tion followed the expected variation similar to that of Dst(H) index. The Dst(Z) variations showed a large decrease of –149 nT at 1530 h. The decrease of Z was fairly small at ANN and absent at stations north of ANN. Looking at the temporal variations of Dst(H) index and Dst(Z) at equatorial stations, it can be concluded that the maximum decrease of ΔZ occurs near the middle of the main phase, when the ring current is increasing at the fastest rate.

Even the earliest observations of the geomagnetic fields at Thiruvananthapuram during the IGY had indicated a large range of the solar daily-range of the Z field[7]. The model calculations of vertical field by Yacob[8] and later by Thakur and Rao[9] showed that the $S(q)$ range of Z field is abnormally larger than the theoretical value. Srivastava and Sankar Narayan[10] interpreted the anomaly in terms of ocean effects and the electrical conductivity anomalies in the upper mantle at a depth of 200–800 km. Nityananda *et al.*[11] postulated the presence of a conductor in the upper mantle or lower crust between India and Sri Lanka. Rastogi[5] suggested an additional effect due to the concentration of the induced currents over the extended latitude zones towards the conducting graben in the Palk Strait between India and Sri Lanka. Rastogi[12] has shown that the induction effects in the Z field at electrojet stations in India during solar flares are related to the sharpness of the initial temporal development of the sfe in the H field. Thus the induction is larger and extends to a larger latitude from Thiruvananthapuram northward when the source current develops faster. It is confirmed here too that the induction effects in the Z field during the geomagnetic storms are larger and extend to larger latitudes when the ring current develops faster during the main phase.

This is an account of the disturbance storm-time variations of the vertical component of the geomagnetic field in the Indian electrojet region and needs to be critically studied in relation to other magnetospheric and ionospheric parameters and with the sub-surface geological features in Palk Strait.

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Major lineaments and gravity-magnetic trends in Saurashtra, India

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The lineament map of Saurashtra prepared from false colour, thematic maps indicates four major structural trends. The NE-SW trend reflects the Precambrian Aravalli trend which is dominant in the SE part of Saurashtra and largely represents the basic dykes and plugs exposed in this sector. The ENE-WSW to E-W trend represents the Precambrian trend of Narmada–Son lineament in southern Saurashtra, volcanic pipes of late Cretaceous in central Saurashtra and Gulf of Kutch and Kutch rift basin of Jurassic times, north of Saurashtra. The NW-SE trend parallel to the west coast of Saurashtra is possibly related to coastal tectonics which evolved during late Jurassic due to the break-up of Africa from India. The N-S to NNE-SSW trends prevalent in the eastern and the central parts of Saurashtra are parallel to the Cambay rift basin which evolved during late Cretaceous, due to interaction of the Reunion plume with the Indian lithosphere. It is significant to note that N-S trends occur in pairs, indicating fracture zones. The Bouguer anomaly map also reflects similar structural trends in different parts of Saurashtra, where individual trends are predominant compared to the others. Some of the N-S structural trends coincide with gravity gradients or linear gravity anomalies, indicating fracture zones/faults which may be important for groundwater exploration. Besides, the Bouguer anomaly map has also delineated six circular gravity 'highs' of 40–60 mGal over the volcanic plugs/stocks. The large wavelength gravity 'low' over the Jasdon

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plateau is partly caused by thickening of the crust due to isostatic compensation and a part of this anomaly may also be caused by some deeper sources. The total intensity magnetic map depicts well-defined pairs of magnetic lows and highs of approximately 500–1000 nT over the volcanic plugs, which belong to the Deccan eruption. The same order of gravity and magnetic anomalies observed over the volcanic plugs suggest almost similar bulk composition for them, although large variations in compositions are reported from the exposed rock types. It also suggests that there must be mafic/ultramafic components under all the pipes, though they are reported mainly from the Junagadh pipe.

THE west coast of India and adjoining regions have been affected by three major tectonic events during the Mesozoic period, after the break-up of Gondwanaland[1], which include: (i) Break-up of Africa from India along the west coast of India during middle to late Jurassic[1]; (ii) Break-up of Madagascar along the west coast of India during middle to late Cretaceous[1]; (iii) Break-up of Seychelles–Mascarene plateau from the Indian plate[1] and eruption of Deccan Trap from the Reunion hotspot during late Cretaceous[2].

These events have affected the adjoining coastal areas in various ways, the most important being the development of structural trends, rift basins and different kinds of igneous intrusions. The coast of Saurashtra is affected mostly by the first event, as the other two events were located south of Saurashtra. The break-up of Africa from India along the west coast of India is associated with large-scale volcanic eruption over Africa and Antarctica in form of Karroo volcanics and Ferrar volcanics, respectively[3]. Some volcanic rocks of Mesozoic period have also been reported from bore-wells in Saurashtra[4]. The break-up of Madagascar from the west coast of India during 80–90 Ma is related with the Marion hotspot[5]. The break-up of Seychelles and eruption of Deccan flood basalt from Reunion hotspot during late Cretaceous has been most significant and widespread over the Indian continent[2,6]. Due to the vast coverage of Deccan Trap over the western part of the Indian continent, signatures of the previous events are covered under the Deccan Trap and cannot be accessed directly in the field. The Saurashtra Peninsula is mostly covered by Deccan Trap (Figure 1) which represents flows of tholeiitic basalt with several intrusions of acidic, alkaline and mafic/ultramafic rocks[7]. Deccan Trap of Saurashtra is presumed to be one of the earliest products of magma differentiation due to Reunion hotspot during late Cretaceous, as indicated by occurrences of picritic basalt, gabbro and alkaline rocks in this area[8] and serpentinization of basic igneous rocks of Girnar hills[9]. Some volcanic plugs are also reported (A–C in Figure 1), out of which the one at Junagadh (A in Figure 1) is the one best-studied[10,11]. It consists of ring complex with an assemblage of rocks types varying in composition from acidic, alkaline to mafic/ultramafic. B and C are similar volcanic plugs known as Barda and Alech plugs. The exposed rocks of these plugs are predominantly acidic in composition. Some stocks/plugs are also reported from the south-eastern part of Saurashtra around Vallabhipur, Palitana and Rajula, which are basically alkaline and acidic in composition[12]. There are dyke swarms oriented NE-SW in the SE part of Saurashtra, which are basically mafic/ultramafic belonging to Deccan Trap activity (Figure 1). There are some east-west oriented dykes in the central part of the Saurashtra near Rajkot and Jasdon (Figure 1). Some NE-SW lineaments around Rajula are reported[13]. Figure 1 also shows tertiary sediments along the coasts and mesozoic sediments to the north of Chotila in the NE corner of the Saurashtra Peninsula. In order to delineate major structural trends and their inter-relationship, the gravity and the magnetic data from this area are studied in conjunction with the lineament map prepared from satellite images of Landsat-TM data acquired during February 1995 which are described and discussed below.

Figure 2 shows the major and minor lineaments of Saurashtra prepared from false colour composite, thematic maps obtained from NRSA on 1 : 250,000 scale. This lineament map shows dense concentration of lineaments along the coast and in areas adjoining it, while the central part shows relatively less number of lineaments. This suggests the marked influence of coastal tectonics in the development of lineaments in this area. The following four major structural trends are clearly visible in the map, which dominate in different regions of Saurashtra.

(i) NE-SW trend is present in almost the total area. However, it is predominant in the SE part of Saurashtra, coinciding with intense dyke swarms of Deccan volcanism and is almost parallel to the coast of Saurashtra with the Gulf of Cambay, in this sector.

(ii) ENE-WSW to E-W trend is the another dominant trend over entire Saurashtra Peninsula. The ENE-WSW trend in the southern section represents the trend of the Narmada–Son lineament, which is a Precambrian trend in this region. However, towards the north, the E-W trend coincides with the volcanic plugs of Junagadh, Barda and Alech (A–C in Figure 1) and some basic dykes of Deccan volcanism in central Saurashtra. Further north, the Gulf of Kutch and the Kutch rift basin display ENE-WSW to E-W trend which is considered as Jurassic rift basin[14].

(iii) NW-SE trend, parallel to the west coast of Saurashtra, is predominant in the coastal part and in adjoining areas. It indicates their interrelation-

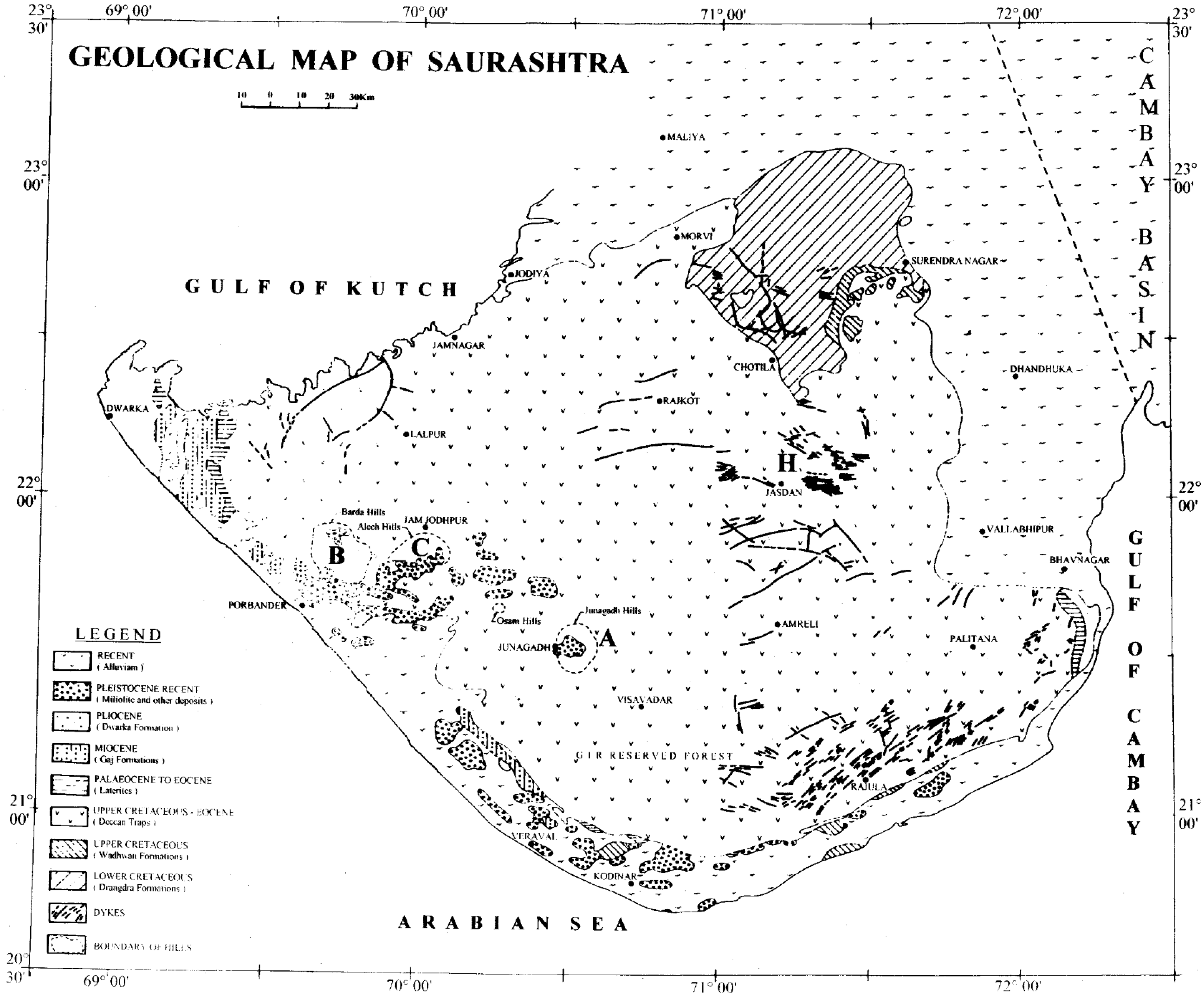

Figure 1. Geological map of Saurashtra which is primarily covered by Deccan Trap eruption of late Cretaceous. A, B and C are volcanic plugs known as Junagadh, Barda and Alech, respectively. Some plugs and dykes of Deccan eruption are also reported from SE part of Saurashtra around Palitona and Rajula.

ship with the evolution of the coastline. This is a Precambrian Dharwarian trend of the Peninsular shield of India, which might have been reactivated during middle–late Jurassic due to break-up of Africa from the Indian plate.

(iv) NNE-SSW to N-S trend is predominant in the eastern part, which is likely to have been influenced by the Gulf of Cambay and the Cambay rift basin located east of Saurashtra. In this regard, the occurrence of these trends in pairs (L1–L7) is quite remarkable. They are visible in pairs as linear zones with contrasting tonal and texture characteristics.

The present-day drainage pattern in Saurashtra (Figure 3) is radial, suggesting a domal uplift around Jasdon coinciding with the Jasdon plateau. However, it is mainly E-W and N-S, which are comparatively younger trends, controlled by volcanic plugs and Cambay basin of late Cretaceous. This suggests that the corresponding structural trends of N-S and E-W are also reactivated in the recent times and may represent the youngest events in this area.

The published Bouguer anomaly map of Saurashtra[15,16] shows only one circular gravity 'high' covering the major portion of western Saurashtra and a gravity 'low' over the Jasdon plateau (H in Figure 1) which may be due to large data gaps in this sector. Therefore, some additional gravity stations were recorded (approx. 1000 in number) in western Saurashtra along profiles I, II, III and IV and some data around Junagadh. The new gravity data are acquired using Lacoste Romberg gra-

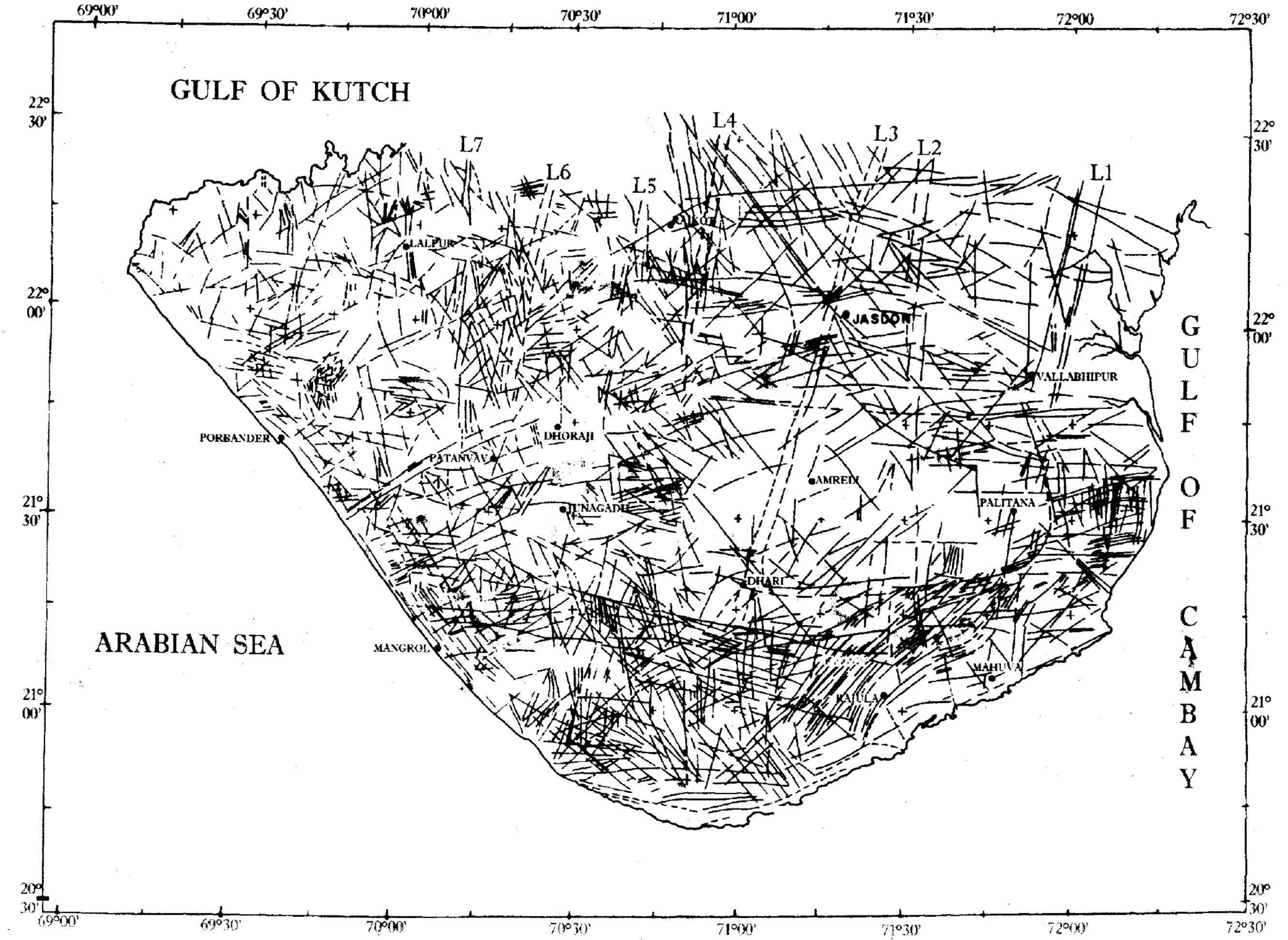

Figure 2. Lineament map of Saurashtra based on false colour, thematic maps from Landsat-TM data acquired during February 1995. L1–L7 are pairs of NNE-SSW to N-S lineaments parallel to the Gulf of Cambay.

vimeter of 0.01 mGal accuracy and the elevation is controlled by geodetic levelling, providing an overall accuracy of 0.3–0.5 mGal for the computed Bouguer anomaly. The new and the old data are processed together using IGSN 1971 for a density of 2.67 for the Bouguer slab. The resulting map is presented in Figure 4, which shows following significant features:

(i) Gravity highs of 40–60 mGal corresponding to volcanic plugs of Junagadh, Barda and Alech in western Saurashtra are marked as A, B and C, respectively. The gravity anomaly A is circular in nature and coincides with the Junagadh plug, while the gravity anomalies B and C are individually circular, but together they are oriented E-W indicating a fracture zone occupied by these volcanic plugs.

(ii) Three similar circular gravity highs of almost the same amplitude are also delineated in the SE part of Saurashtra near Vallabhipur, Palitana and Rajula marked as D, E and F, respectively. These highs are individually circular in nature, but together are aligned in NE-SW direction indicating a large fracture/fault zone, which may form the western margin of the Cambay rift basin[17]. They coincide with the exposed volcanic plugs/stocks which are mainly alkaline in nature.

(iii) A broad gravity low (H in Figure 4) over the Jasdon plateau in eastern Saurashtra is delineated, a part of which might be due to isostatic compensation.

(iv) There are several other small wavelength gravity highs and lows, especially in the northern part of Saurashtra, which are caused by subtrappean shallow sources.

Besides these major gravity anomalies, most of the major structural trends observed in the lineament map (Figure 2) are also present in the Bouguer anomaly map (Figure 4), which are marked as double-sided arrows

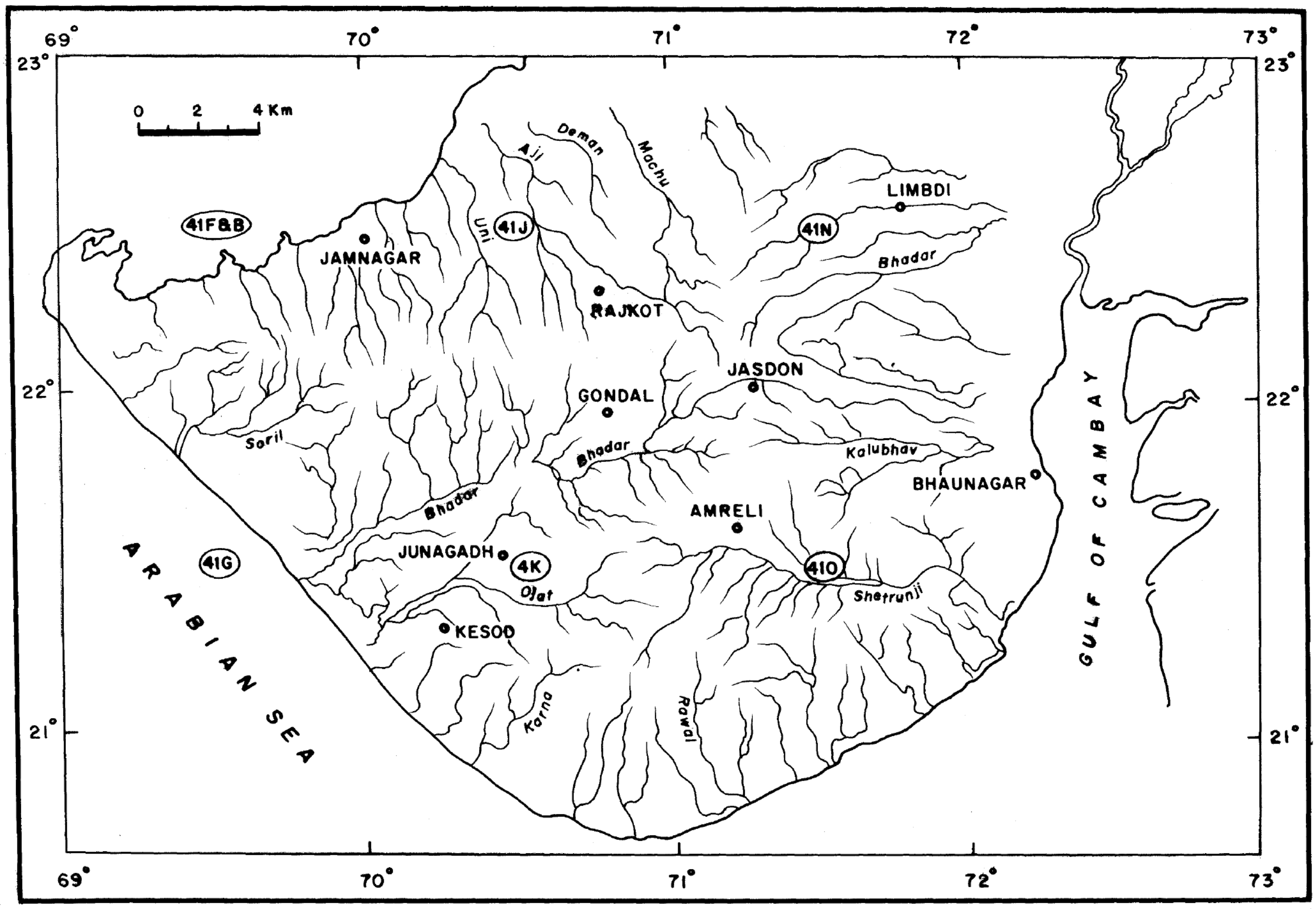

Figure 3. Drainage map of Saurashtra showing radial drainage pattern originating from areas around Jasdon which form an elevated part known as Jasdon plateau. There are two primary components to it, namely E-W and N-S.

based on the contour patterns. These are prevalent in different parts of Saurashtra such as (i) NE-SW trend in the SE part; (ii) E-W trend in the central part of the western Saurashtra; (iii) NW-SE trend along the west and the north coast of Saurashtra; and (iv) N-S to NNW-SSE trend in the central part. It is interesting to note that the linear gravity gradient G (Figure 4) coincides in part with the N-S lineament L4 inferred from satellite data (Figure 2). They are indicative of fractures/fault zones.

An east-west profile XX′ across Saurashtra (Figure 4) showing elevation, free-air and Bouguer anomaly is given in Figure 5. There is a good correlation between free-air and Bouguer anomaly over Jasdon plateau, which is opposite to the regional elevation. This indicates isostatic compensation for this plateau. The zero value of free-air anomaly indicates isostatic compensation, which can be used to estimate its effect in the Bouguer anomaly[18]. ZF marked on the Bouguer anomaly profile (Figure 5) indicates the effect of isostatic compensation in the present case, which is approximately –15 mGal. The elevation profile shows a higher elevation of approx. 300 m over the Jasdon plateau (H), which implies a crustal thickening of approximately 2 km for isostatic compensation. A crustal thickening of 2–3 km is also suggested by seismic investigations[19], which show a crustal thickness of 38 km towards the west and 40–41 km towards the east under the Jasdon plateau. This crustal thickening produces an anomaly of –15 to –20 mGal as discussed above, as effect of isostatic compensation, while the observed gravity low is approximately –35 mGal. Therefore, the difference between the observed and the effect of isostatic compensation, viz. approximately –15 to –20 mGal is produced by other subsurface low density sources. However, as it is a regional large-wavelength anomaly, it might be caused due to some deep-seated body in the upper mantle[16].

A magnetic survey has been conducted along roads and tracks at approximately 1.5–2.0 km interval, using proton precision magnetometers with an accuracy of 1 gamma, in parts of Saurashtra where the Bouguer

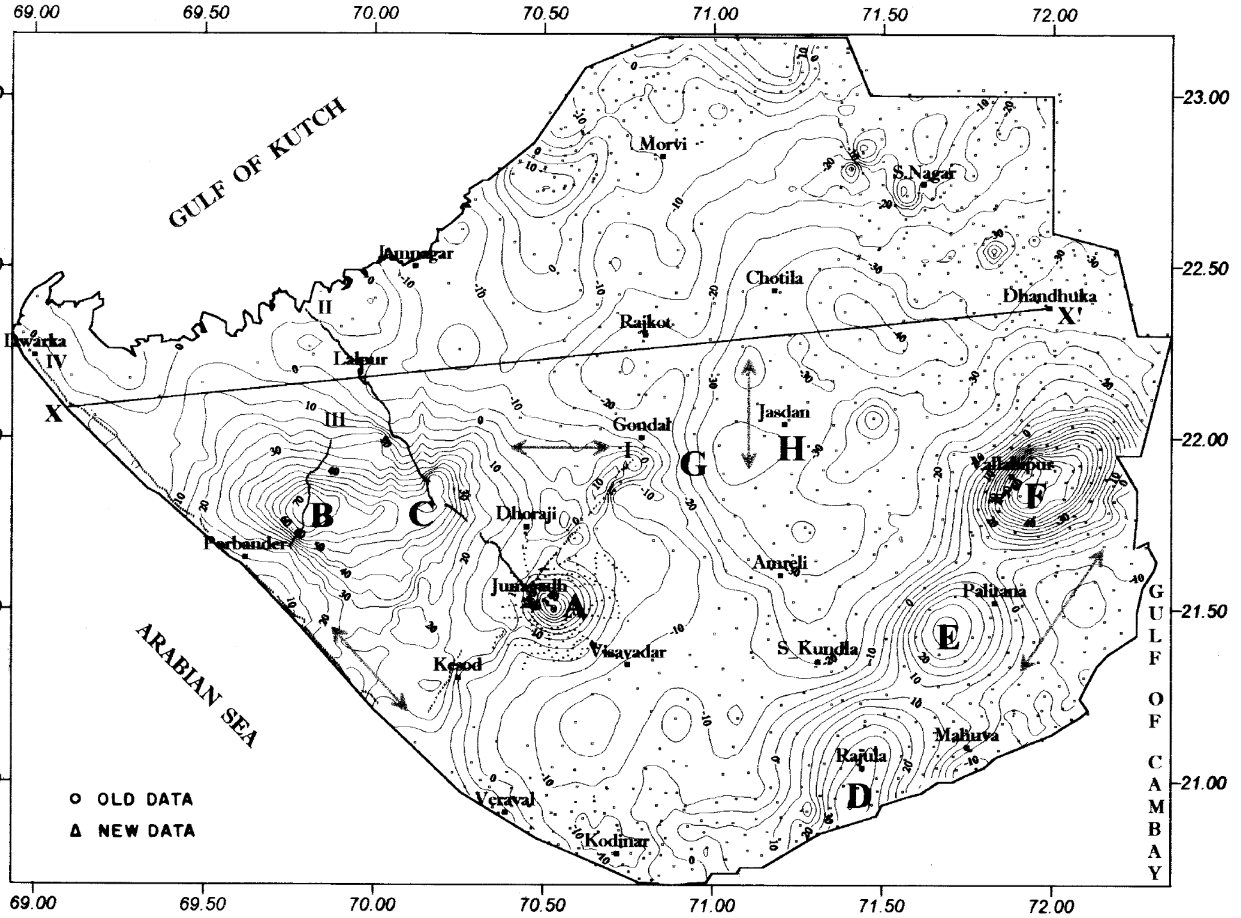

Figure 4. Bouguer anomaly map of Saurashtra. A–F are circular gravity highs reflecting volcanic plugs/stocks. G is a prominent gravity gradient around Jasdon plateau and H denotes the gravity low observed over it. Double-sided arrows indicate contour pattern and the structural trends in different parts of Saurashtra.

anomaly has indicated the presence of volcanic plugs, as described above. The recorded data are corrected for diurnal variation and the IGRF and the resulting total intensity map is shown in Figure 6. As the exposed rock is Deccan Trap, there is considerable variation in the magnetic field due to lateral inhomogeneity of the magnetic minerals. Laboratory measurements have also indicated considerable variations in the susceptibility of different samples of Deccan Trap and volcanic plugs from this area, varying between 10^{-3} and 10^{-5} CGS units[20]. Normally the magnetic surveys in such cases over the trap covered provinces record noisy data and do not provide any systematic anomaly. However, the total intensity magnetic map (Figure 6) depicts well-defined sets of magnetic lows and highs, marked as A–F, corresponding to gravity highs of volcanic plugs marked by the same letters in Figure 4. The magnetic anomalies in the surrounding regions are irregular and do not show any significant pattern, which can be attributed to lateral inhomogeneity of magnetic minerals in the exposed Deccan Trap. This clearly indicates that the magnetic characteristics of volcanic pipes are different compared to the Deccan Trap encompassing them. Normally, a body magnetized in the present-day geomagnetic latitudes for this area will produce a magnetic low accompanied by a small high towards the north due to induced magnetization and the amplitude of magnetic high will be approximately 10–20% that of the magnetic low. However, in the present context the nature of magnetic anomalies shows large magnetic low accompanied by a significantly large magnetic high, suggesting the presence of strong remanent magnetization corresponding to their period of evolution, namely the Deccan Trap volcanism. Figure 6 also shows NE-SW trend in the S-E part of Saurashtra which corresponds to exposed basic dykes and volcanic plugs inferred, based on gravity anomalies in this region. The other prominent trends are EW and NW-SE in the western Saurashtra, which correspond to volcanic plugs of Junagadh, Barda and Alech and coastal tectonics along the west coast of Saurashtra, respectively.

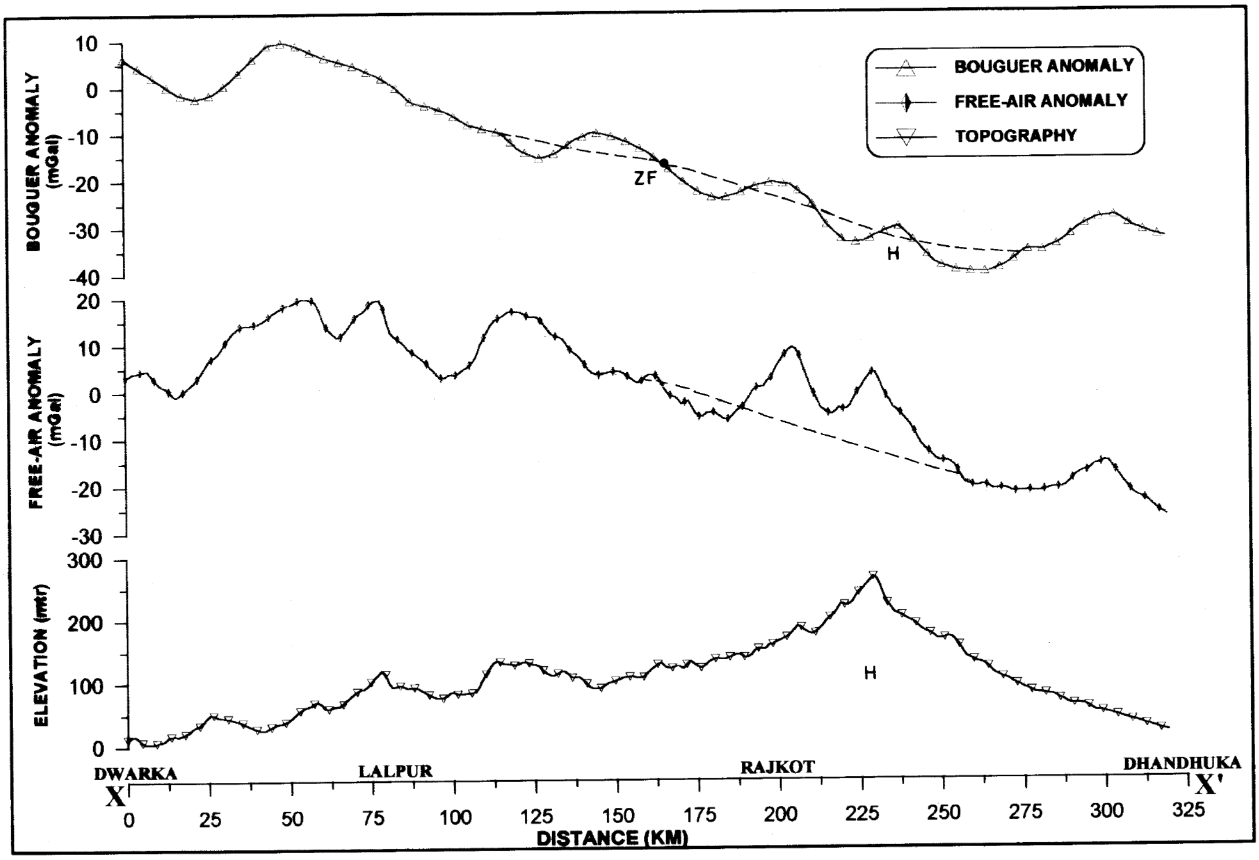

Figure 5. Gravity profile XX′ (Figure 4) presenting elevation, free-air and Bouguer anomaly. The trend in the free air and the Bouguer anomaly is opposite to the regional elevation of the Jasdon plateau (H), indicating isostatic compensation. ZF corresponds to the zero free-air on Bouguer anomaly profile, representing the gravity effect due to the compensating mass.

The major structural trends delineated from satellite data in Saurashtra are also observed in the regional Bouguer anomaly map, which shows their region-wise dominance. Four such major trends are deciphered from these maps:

(i) NE-SW trend is a Precambrian Aravalli trend and is observed in the entire Saurashtra Peninsula, but is more predominant in the SE part of Saurashtra. The Bouguer anomaly map in this section also presents similar oriented trends. NE-SW-oriented dykes of Deccan volcanism are also exposed in this region and are almost parallel to the coast of Saurashtra with the Gulf of Cambay. This indicates that the older Aravalli Precambrian structural trend might be in the form of fractures in this section, which were reactivated during late Cretaceous due to Deccan Trap eruption.

(ii) ENE-WSW to E-W trend represents the Precambrian Narmada–Son lineament trend in the southern part of Saurashtra. However, it is present in the entire region of Saurashtra and is occupied by volcanic plugs in the central part and is represented by the Gulf of Kutch and the Kutch basin north of Saurashtra. Among these structural trends, the Bouguer anomaly map reflects only E-W trend in central Saurashtra, suggesting that it represented fracture zones occupied by volcanic plugs. The Kutch rift basin also follows the older Precambrian trend of Delhi group, which is NE-SW and takes E-W trend, east of Kutch rift basin.

(iii) NW-SE trend, parallel to the west coast of Saurashtra, is visible over the entire Saurashtra Peninsula. However, it is more dominant in the western and the northern parts close to the coast and is also reflected in the corresponding sector of the Bouguer anomaly map. It may represent the tectonics responsible for the evolution of the coast in this area, namely the break-up of Africa from the Indian plate during late Jurassic.

(iv) N-S to NNE-SSW trend is dominant in the eastern part of Saurashtra close to the Cambay basin, which is a tertiary rift basin with similar orientation and therefore appears to be related to tertiary rifting. Some of these structural trends coincide with gravity gradients such as L4 (Figure 2),

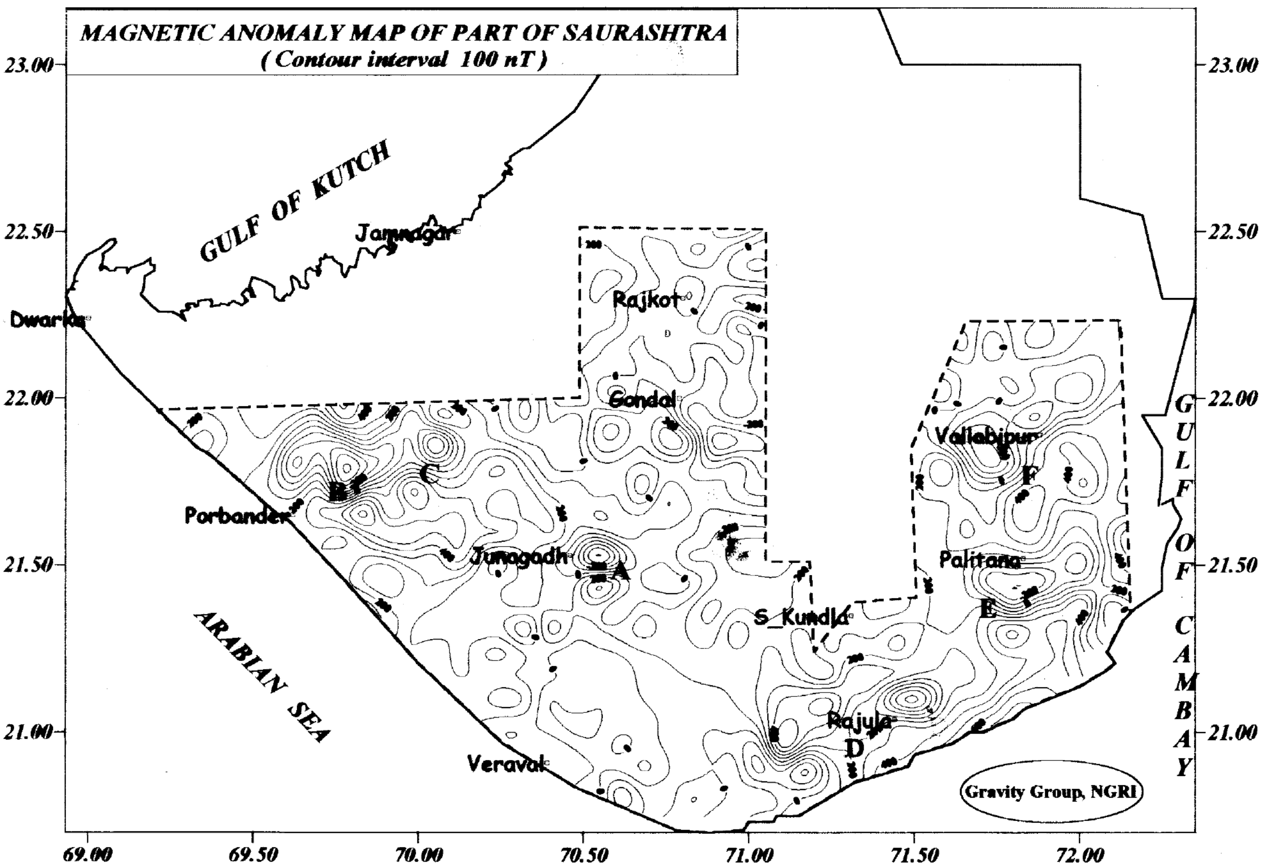

Figure 6. Total intensity magnetic map of the part of Saurashtra where gravity anomalies due to volcanic plugs are delineated. A–F are pairs of magnetic anomalies corresponding to volcanic plugs reflected in the Bouguer anomaly map (Figure 4) referred to by the same letters.

coinciding with G (Figure 4) or small-wavelength linear gravity anomalies implying a fault/fracture zone, which might be suitable for groundwater exploration.

Besides these major structural trends, the Bouguer anomaly map has delineated circular gravity highs of 50–80 mGal corresponding to six volcanic plugs/stocks (A–F in Figure 4). It is interesting to note that the largest gravity anomaly of 70 mGal is recorded over the volcanic plug at Barda (B in Figure 4), which is largely reported as felsic in composition, based on exposed rock types[12]. The volcanic plug at Junagadh (A in Figure 4) is reported to consist of more mafic/ultramafic components; however, only 50 mGal gravity anomaly is recorded over this pipe. This shows that there must be large subsurface mafic/ultramafic (high density) components in the volcanic plug at Barda (B) to give rise to gravity anomaly of larger amplitude compared to that of the volcanic plug at Junagadh (A). It has also delineated several small and large wavelength gravity lows corresponding to shallow and deeper mass deficiencies. The large-wavelength gravity low over Jasdon plateau is partly due to crustal thickening caused by isostatic compensation and partly due to some deep-seated sources, probably in the upper mantle. The volcanic plugs are also characterized by pronounced pairs of magnetic lows and highs of 500–1000 nT which appear to have been caused by remanent magnetization. Almost the same order of gravity and magnetic anomalies observed over the six plugs suggest the presence of mafic/ultramafic components in all the pipes, though they have been primarily reported from the Junagadh pipe.

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A note on palaeomagnetic evidence to show tectonic deformation in the Deccan Volcanic Province of Saurashtra, western India

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A long curved dyke with peculiar vertical layering, in the Deccan Volcanic Province of Saurashtra, was palaeomagnetically investigated. Palaeomagnetic measurements clearly indicate that the curved character of the dyke is due to some kind of tectonic drag deformation. Such deformation could have possibly developed in case the Saurashtra Peninsula has moved northwards along the Cambay Basin fault. There is a possibility that the horst in the southern part of Saurashtra may have been originally the continuation of the Satpura horst.

IN the central and south-eastern parts of Saurashtra, there are a large number of prominent dykes that often stand out as ridges. Majority of the dykes are dolerites, although an ankaramite dyke and a stock-like body of essexite have also been encountered in the area between Rajkot and Amreli. South of Amreli, in addition to the dolerite dykes there are a few rhyolitic quartz porphyry dykes. The dykes north of Amreli trend E–W, while south of Amreli they trend NE–SW. One prominent dyke (Figure 1) north of Amreli (68 km from Rajkot on road to Bhavnagar) trends E–W and can be traced for more than 50 km along the length and has a width of 10 to 15 m. This dyke is distinctly curved in the eastern part of the outcrop to trend NW–SE and has a T-shaped extension (penetration of the magma along an intersecting fracture) that can be traced for 15 km in length trending NE–SW. Petrography and petrochemistry of this dolerite, along with layering seen in this dyke, have been described earlier[1]. Dextral displacement of the dyke along N–S fractures can be observed at various places along the length of the dyke, but such displacements have been considered earlier as possibly due to intrusion along *en echelon* fractures[1]. Palaeomagnetic study was carried out on this dyke to ascertain whether the curved nature of the dyke is due to intrusion along a curved fracture or the curving is a later tectonic phenomenon.

The curved dyke was sampled at five different places along the length of the dyke. Sample locations are shown in Figure 1. Samples S II and S III were collected from the western straight part of the dyke. At both these locations four separate oriented samples were collected. Similarly, samples S IV and S V were collected from the eastern curved part of the dyke. At each of these latter locations three oriented samples were collected. S VI was collected from the 'T' branch of the dyke at the eastern end, where four separate oriented samples were collected. The oriented samples were mounted in cement and core specimens of 2.5 cm diameter and about 2.2 cm length were prepared for each sample. Three to fourteen specimens were prepared for samples of each locality.

The NRM measurements were made for all the specimens using the astatic magnetometer (LAM-24 manufactured by Geofyzika n.p. Brno, Czechoslovakia). Alternate field demagnetization was carried out starting at 50 Oe and going up to 1000 Oe, in increments of 25, 50, 100 and 200 Oe, on two to three pilot specimens for each of the locations. Similarly, thermal cleaning was carried out on a pilot basis starting at 100°C, going up to 600°C, in increments of 50 to 100°C. Thermal cleaning was carried out in a magnetic vacuum using MAVACS (magnetic vacuum control system).

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