Geophys. J. Int. (2001) 146, 827–832

Geomagnetic coast and other effects deduced from the new observatory at Visakhapatnam, India

B. J. Srivastava,[1,*] Habiba Abbas,[1,†] T. RamaGopal,[1] D. R. K. Rao[2] and B. M. Pathan[2]

[1] National Geophysical Research Institute, Hyderabad 500 007, India
[2] Indian Institute of Geomagnetism, Colaba, Mumbai 400 005, India. E-mail: dkrao@iig.iigm.res.in

Accepted 2001 May 2. Received 2001 March 16; in original form 2000 September 5

SUMMARY

Coastal effects observed in the long-period Sq Solar quist day ranges and short-period changes over 30 min intervals during magnetic substorms (bays), as recorded at a new magnetic observatory at Visakhapatnam, on the east coast of India, during 1995 in the *H*, *Z* and *D* elements, are analysed and the preliminary results are discussed. The results are compared with those from Alibag and Hyderabad (located more or less at the same latitude) based on simultaneous 1995 records. Short-period induction vectors are computed and the arrows presented and discussed at the three locations.

While the enhancement associated with close proximity to the coast in Sq (*Z*) at Alibag on the west coast compared to the central inland station of Hyderabad (enhancement of 17–37 per cent) is quite prominent in all three seasons of the year, at Visakhapatnam it is only marginally observed during the d-season. At bay frequencies, medium-sized induction arrows point towards the nearest deep-sea conductive body at both Alibag and Visakhapatnam, while it is towards the southeast with a considerably reduced magnitude at Hyderabad. These induction arrows and the effects on Sq (*Z*), Sq (*H*) and Sq (*D*) ranges are discussed in conjunction with the Parkinson arrows and Sq (*Z*), Sq (*H*) and Sq (*D*) ranges from Margao (west coast)–Dharwar–Bellary–Mahanandi–Chirala (east coast) at the latitude of the 16°N profile of an earlier array experiment, and the two are interpreted together.

Key words: channelling, coast effect, electromagnetic induction, Sq variation.

1 INTRODUCTION

A new geomagnetic observatory has been established in the Andhra University campus at Visakhapatnam (geographical latitude 17.67°N, longitude 83.32°E; geomagnetic latitude 7.95°N, longitude 155.77°) by the Indian Institute of Geomagnetism (IIG) for marine geophysical studies in the Bay of Bengal region. It is located on the east coast of India, close to the geographical latitude of both the Alibag (geographical latitude 18.62°N, longitude 72.87°E; geomagnetic 9.84°N, 145.84°, west coast) and the Hyderabad (geographical latitude 17.42°N, longitude 78.55°E; geomagnetic 8.09°N, 151.15°, central inland) observatories and lies outside the influence of the daytime equatorial electrojet. It is equipped with a set of Quartz (IZMIRAN) *D*, *H* and *Z* variometers, a Vector proton magnetometer and a declination–inclination magnetometer for absolute controls. Srivastava *et al.* (1974a,b) discussed the geomagnetic variation anomalies based on special magnetic observations at 20 temporary mobile stations along the Alibag–Hyderabad–Kalingapatnam profiles in two stages (Alibag–Hyderabad in May–July 1970 and Hyderabad–Kalingapatnam in February–March 1973), using a mobile unit of Askania *H* and *Z* variographs with a visual ink recording system and a set of QHM and BMZ instruments. They compared the diurnal and short-period variations at Alibag and other field stations with those from Hyderabad to derive coastline-associated induction anomalies.

The Alibag coastal effect in short period variations such as SSCs (Storm Sudden Commencements), SIs (Sudden Impulses) over a few minutes and bays of duration 1–2 hr, as recorded on the Askania variograph was found to disappear near Pune about 110 km from the west coast off Alibag. However, in the case of long-period daily variations of *H* and *Z*, the coast effect was found to extend (with diminishing magnitude) up to 185 km from the west coast. The Sq (*Z*) ranges at Alibag were found to

* Now at: 104, Sumedha Apts, st#2, Habshiguda, Hyderabad 500 007, India.
† Now at: 22-2-532, Darushifa, Hyderabad, 500 024, India.

be enhanced 1.66 times compared to those at Hyderabad during May–July 1970, while at Kalingapatnam, located on the east coast about 150 km to the northeast of Visakhapatnam, the Sq (Z) ranges were 1.49 times those of the Hyderabad ranges during February–March 1973, and this east coast effect extended only up to 70 km, tapering off further inland. However, the Sq (H) was only very slightly reduced at Alibag as well as at Kalingapatnam. These results were based on absolute observations of H and Z with QHM and BMZ instruments four or five times during a day at the field stations as the Askania diurnal records showed temperature effects.

The northernmost profile, along 16°N geographical latitude, of a magnetometer array experiment in southern peninsular India carried out during the period December 1979–March 1980 passed through Margao (on the west coast), Dharwar, Bellary, Mahanandi and Chirala (Srivastava *et al.* 1982). Chirala is located about 385 km southwest of Visakhapatnam. The ratios of ranges of Sq (at each of the southern peninsular stations) with respect to similar ranges at Hyderabad were computed for the H, Z and D elements and were depicted in Figs 1, 2 and 3, respectively, of Srivastava *et al.* (1982) and Figs 2, 3 and 4 of Srivastava 1992). The Sq (H) range ratios with respect to Hyderabad at all five stations as well as at Adilabad, located north of both Alibag and Hyderabad, were of the order of 1.0 (the same as the Hyderabad values), indicating that the stations were free from the influence of the daytime equatorial electrojet, as is the case for Hyderabad. The Sq (Z) range ratios with respect to Hyderabad were, respectively, 1.29, 1.23, 1.08, 1.04 and 1.32; the Sq (D) range ratios with respect to Hyderabad were 1.42, 1.31, 0.96, 1.16 and 1.39. Thus, the Sq (Z) range at Margao (on the west coast) and Dharwar (about 100 km inland) definitely showed the coast effect as observed at Alibag, and the Sq (Z) range ratio at Chirala located on the east coast showed a similar effect. The Sq (D) range ratios with respect to Hyderabad at Margao and Dharwar also showed a coast effect, similar to that at Mahanandi (150 km inland from the east coast) and Chirala (located on the east coast), with enhanced Sq (D) range ratios with respect to the Hyderabad values. Srivastava (1992) has also ruled out any influence of the daytime equatorial electrojet on the Sq values recorded north of 16°N latitude, especially during the period 1980–2000, when the dip equator in the Indian region was drifting southwards.

With the continuous operation of a new geomagnetic observatory at Visakhapatnam and the availability of hourly mean values of the D, H and Z elements for 1995, it was felt that it would be interesting to compare the Sq (D), Sq (H) and Sq (Z) ranges at Visakhapatnam during 1995 with those simultaneously recorded at Alibag and Hyderabad for the five international quiet days of every month. Furthermore, D, H and Z amplitudes of about 45 prominent night-time substorm (bay) events simultaneously recorded with durations of 1–1.5 hr each at the three observatories were also scaled over time intervals of about 30 min and the data were used to derive the induction vectors at the three stations.

The goal of this paper is to examine the geomagnetic field records of Visakhapatnam, both in the long-period Sq variations and in the short-period changes such as bays so as to ascertain the coast effect and other conductivity anomalies, if present. These results from Visakhapatnam are also compared with the previously published electromagnetic induction results from the Alibag and Hyderabad observatories as well as from nearby southern array stations.

2 ANALYSIS AND RESULTS

2.1 Solar quiet day (Sq)

Mean hourly values of H, Z and D from the three observatories at Alibag (ABG), Hyderabad (HYB) and Visakhapatnam (VSK) for 1995 have been used. The present computations are based on the daily ranges of H, Z and D obtained as the differences in nanotesla between the maximum (around midday) and minimum (near midnight) hourly values in H on each of the five international quiet days (Sq) for every month of 1995 at the three stations. It would have been more appropriate to define the Sq range as the difference between midday and midnight values. However, this would result in very little change in the magnitudes. Ratios of Sq (H), Sq (Z) and westerly Sq (D) ranges were computed at Alibag and Visakhapatnam with respect to Sq range values on the same quiet day from Hyderabad, the central inland reference station, assumed to be free from anomalous induction effects, there being no significant conductive or resistive deep geological structures in its vicinity, and also its being located far from either of the coasts. Monthly means and the seasonal (d, e and j) means of their ratios are computed. These results are given in Tables 1 and 2, respectively.

2.2 Short-period substorm (bay) data

The amplitudes of H, Z and D changes (ΔH, ΔZ and ΔD, all in nanotesla) during 45 well-defined substorms (bays) were measured from the bay commencement trace levels to the peak values in the three elements as recorded at Alibag, Hyderabad and Visakhapatnam in 1995, there being only one set of ΔH, ΔZ and ΔD values for each bay at each observatory. Table 3 gives the amplitudes of two typical bays at the stations to demonstrate the order of the quantities involved in the computation. Fig. 1 shows the same two substorm events as recorded at the three observatories in India along with the recording at Nagpur observatory (geographical latitude 21.10°N, longitude 79.00°E; geomagnetic 11.72°N, 151.93°).

Following Untiedt (1970) induction vectors are determined at the Alibag, Hyderabad and Visakhapatnam stations using the following equation:

$$\Delta Z = A\Delta H + B\Delta D + \bar{\epsilon} \quad (1)$$

Coefficients A and B use real-valued coefficients of a linear regression found by least-squares functions and $\bar{\epsilon}$ is a small constant (error term). The induction vector with magnitude S is defined as

$$\mathbf{S} = -iA - jB, \quad (2)$$

where i and j are unit vectors in the magnetic north and east directions. The azimuth of the induction vector as measured clockwise from the magnetic north is given by

$$\theta = \tan^{-1}(B/A) \quad (3)$$

Finally, the Parkinson vector is given by

$$\mathbf{P} = \mathbf{S}/\sqrt{1+|S|}^2 \quad (4)$$

In eq. (1), the entire ΔZ (station) is assumed to be anomalous, while ΔH and ΔD are treated as normal values.

Table 1. Mean monthly and seasonal values (d: Jan., Feb., Nov. and Dec.; e: Mar., Apr., Sept. and Oct.; j: May, Jun. and Aug.) of the Sq range in nT based on daily Sq range values on five international quiet days of each month at Alibag, Hyderabad and Visakhapatnam during 1995.

1995	Sq (*H*) range (nT)			Negative Sq (*Z*) range (nT)			Westerly Sq(*D*) range (nT)		
	ABG	HYB	VSK	ABG	HYB	VSK	ABG	HYB	VSK
Jan	20	23	23	18	15	17	22	26	28
Feb	35	37	34	15	12	15	15	17	18
Mar	49	54	55	22	21	24	30	29	31
Apr	42	49	55	32	26	23	42	45	50
May	36	42	39	30	22	15	48	50	53
Jun	44	49	45	37	20	14	59	62	63
Jul	46	50	45	33	26	15	51	53	61
Aug	41	43	41	31	29	21	54	50	52
Sept	32	36	33	32	26	15	51	52	54
Oct	38	42	42	18	18	13	22	22	24
Nov	35	39	41	16	15	13	16	18	20
Dec	25	29	29	15	14	14	17	24	26
d-season	29	32	32	16	14	15	18	21	23
e-season	40	45	46	26	23	19	36	37	40
j-season	42	46	43	33	24	16	53	54	57

Table 2. Mean monthly and seasonal ratios based on ratios of daily Sq ranges on five international quiet days of each month at Alibag, Hyderabad and Visakhapatnam during 1995.

1995	Sq (*H*) range		Sq (*Z*) range		Sq (*D*) range	
	ABG/HYB	VSK/HYB	ABG/HYB	VSK/HYB	ABG/HYB	VSK/HYB
Jan	0.94	0.98	1.11	1.26	0.84	1.10
Feb	1.01	0.97	1.28	1.20	0.83	0.95
Mar	0.91	1.01	1.05	1.19	1.02	1.09
Apr	0.85	1.06	1.30	0.93	0.92	1.09
May	0.85	0.93	1.33	0.67	0.96	1.07
Jun	0.90	0.96	1.64	0.77	0.97	1.02
Jul	0.92	0.92	1.37	0.60	0.98	1.05
Aug	0.94	0.95	1.12	0.75	1.08	1.06
Sep	0.88	0.91	1.26	0.57	0.98	1.05
Oct	0.89	0.97	1.08	0.94	1.02	1.21
Nov	0.91	1.08	1.07	1.03	0.88	1.07
Dec	0.86	1.00	1.27	1.02	0.74	1.08
d-season	0.93	1.01	1.18	1.13	0.88	1.05
e-season	0.88	0.99	1.17	0.91	0.99	1.11
j-season	0.90	0.94	1.37	0.70	1.00	1.08

In our computations, ΔZ amplitudes at the coastal stations of Alibag and Visakhapatnam are treated as anomalous and are coupled with ΔH and ΔD amplitudes of simultaneous Hyderabad events, which are considered as normal.

Table 3. Amplitudes over 30 min time intervals to peak values of two typical bays [(i) on 01 June 1995 at 1520–1640 UT and (ii) on 27 September 1995 at 2020–2120 UT] as recorded simultaneously at the three observatories in the three magnetic elements.

		ΔH (nT)	ΔZ (nT)	ΔD (nT)
Alibag	i	31	−8	−7
	ii	60	−16	−12
Hyderabad	i	35	4	−10
	ii	59	6	−16
Visakhapatnam	i	31	13	−5
	ii	63	23	−16

The following results have been obtained and the values of S, θ and P are computed using eqs (2), (3) and (4):

Alibag	$A = -0.146$,	$S = 0.224$
	$B = 0.170$,	$\theta = 319°$
	$\bar{\epsilon} = 0.781$ nT,	$P = 0.218$
Hyderabad	$A = 0.044$,	$S = 0.062$
	$B = -0.044$,	$\theta = 135°$
	$\bar{\epsilon} = 1.602$ nT,	$P = 0.062$
Visakhapatnam	$A = 0.313$,	$S = 0.341$
	$B = -0.135$,	$\theta = 113°$
	$\bar{\epsilon} = 0.394$ nT,	$P = 0.322$

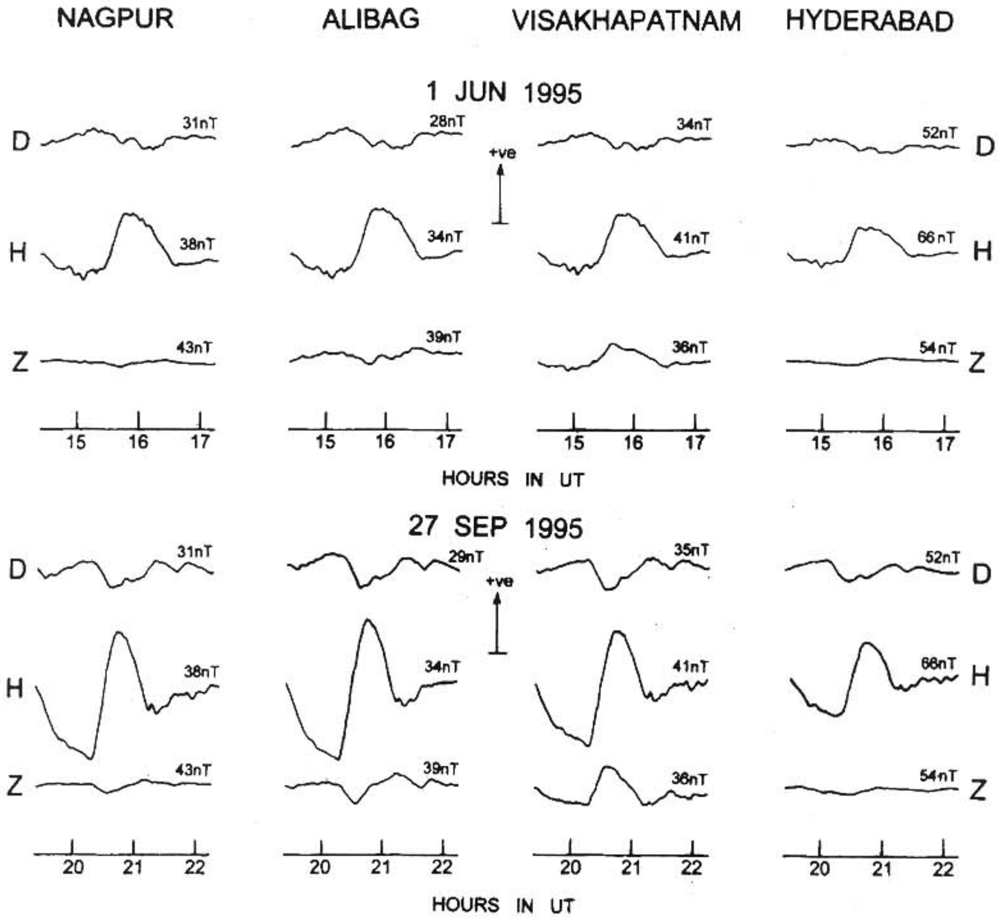

Figure 1. Tracings of magnetograms recorded at four Indian observatories on 1 June and 27 September 1995 showing typical substorm (bay) events. The sensitivities corresponding to the lengths of the arrows are shown on the right-hand side of each trace.

The induction arrows thus determined at the three stations are shown in Fig. 2.

3 DISCUSSION

An examination of Table 1 shows that the seasonal mean values of Sq (*H*) at Alibag are slightly reduced compared to those at Hyderabad, while no definite trend emerges at Visakhapatnam. For Sq (*Z*) ranges, the Alibag values are enhanced compared to those from Hyderabad in all three seasons. However, the Sq (*Z*) values at Visakhapatnam are rather reduced compared to those at Hyderabad, except for the months of January, February and March, when they are enhanced (19–26 per cent), which needs further investigation. As regards the Sq (*D*) ranges observed at the three observatories, those from Alibag and Hyderabad are comparable and those from Visakhapatnam are only marginally enhanced in all three seasons. It is noted that the characteristics of the daily variations of the *H*, *Z* and *D* traces at the three stations are similar.

Table 2 shows the same results as ratios of the Sq values observed at Alibag and Visakhapatnam with respect to Hyderabad for the three seasons. The Sq (*Z*) enhancement at Alibag is 20–40 per cent but the Sq (*H*) reduction at Alibag turns out to be only 10 per cent of the Hyderabad values. At Visakhapatnam, however, the Sq (*Z*) is only marginally enhanced in the winter months (d-season) but reduced in the equinoctial and summer months (e- and j-seasons). The Sq (*H*) ranges at Visakhapatnam are comparable with those at Hyderabad. Although it is not possible to confirm the earlier results entirely, based on QHM and BMZ observations (because the Askania field records were affected by temperature changes) and Sq ranges derived from maximum and minimum at mobile stations along the Alibag–Hyderabad–Kalingapatnam profiles (Srivastava *et al.* 1974a,b), the Kalingapatnam Sq (*Z*) were found to be enhanced during the winter months (January, February and March), as observed at Visakhapatnam.

According to the National Institute of Oceanography Regional Centre at Visakhapatnam, vast deposits of limestone have been discovered recently in the Bay of Bengal off Visakhapatnam continental shelf about 15 km from the seashore and extending up to 25 km at sea depths of 60–600 m along a 50 km stretch of the coastline from near Anakapalle to Kalingapatnam. Apparently this vast and relatively deep resistive body may not allow the Sq induced currents in the seawater to concentrate near the Visakhapatnam coast. In the case of Alibag on the west cost, however, such induced Sq currents in the Arabian sea do concentrate along the coastline and the continental margins and give rise to enhanced daily ranges in *Z* and reduced daily ranges in *H* and *D* as compared to those at the Hyderabad station.

An examination of Fig. 2 shows medium-sized induction arrows nearly perpendicular to the coastline at the two coastal

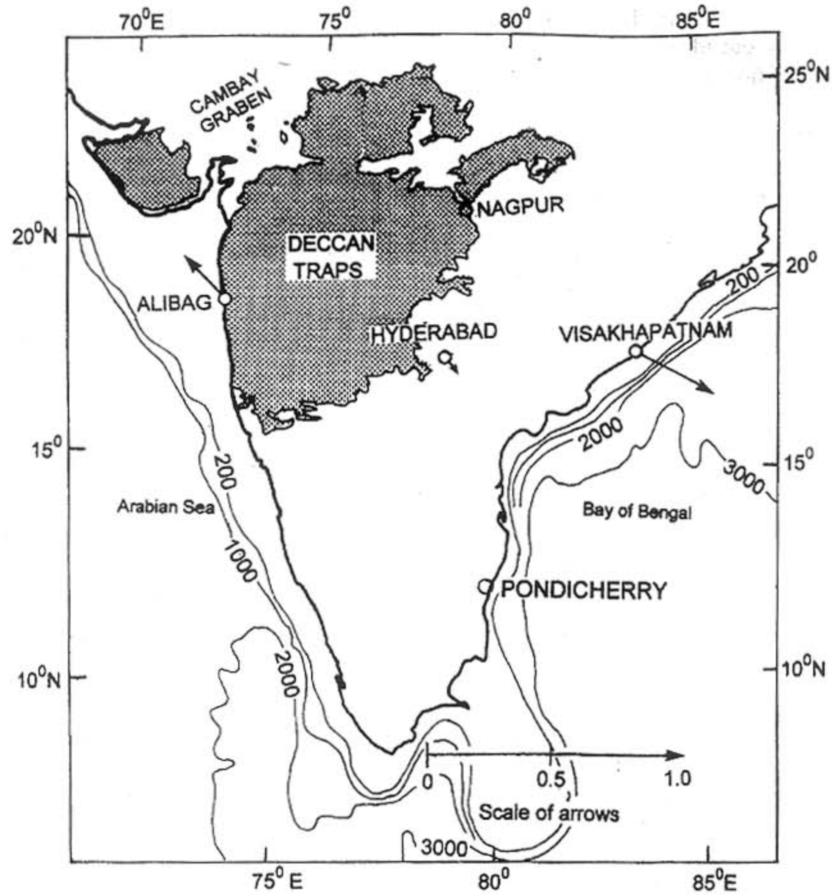

Figure 2. Map showing the locations of the three observatories, at Alibag, Hyderabad and Visakhapatnam, in peninsular India. The induction arrows corresponding to bay frequency at these stations are shown at the respective stations. Contour lines for sea water depths (bathymetry) are also shown.

observatories of Alibag (deflected due to conductive crustal bodies at the Cambay graben) and Visakhapatnam, pointing towards the respective deep seas, while a short vector is seen at Hyderabad, which is typical of an inland station (Parkinson 1959, 1962; Schmucker 1964; Srivastava & Habiba Abbas 1980). The directions of the arrows at Alibag and Hyderabad are nearly the same for bays as obtained earlier by Singh *et al.* (1977).

With the commissioning of a few new magnetic observatories in the last decade at Visakhapatnam and Pondicherry (geographical latitude 11.92°N, longitude 79.92°; geomagnetic 2.50°N, 151.97°) on the east coast and a centrally located observatory at Nagpur, enigmatic changes in the geomagnetic variations can be further probed. The example of substorm signatures that were simultaneously recorded at Nagpur is included in Fig. 1, along with the other three stations. The diurnal variations at all the northern hemisphere observatories, south of Sq focal latitude, record a noon-time maximum in H and a depression of the field (nearly minimum) in Z. This is the case with all the observatories in the Indian region, irrespective of their locations either on the east or west coasts or far inland. Although the variations in H and Z at diurnal frequencies are of opposite sign, the H and Z variations at shorter periods (1–2 hr) such as bays, SIs and SSCs (1–10 min) have the same sign at the eastern coastal stations, especially Pondicherry and Visakhapatnam. At Alibag, the H and Z variations have opposite signs at all frequencies. Asinkar *et al.* (1999) have identified the frequency of transgression of phase changes to be 341–284 min from diurnal to short-period variations between H and Z components at the eastern coastal observatories, and attributed this short-period feature to possible electromagnetic induction effects in Z associated with an extended tectonic feature such as the 85°E ridge in the southwestern Bay of Bengal, as indicated by the induction arrows shown in Fig. 2.

On the other hand, Srivastava & Habiba Abbas (1980) have reported short-period fluctuations such as bays with negative (upward) vertical field changes for positive horizontal component changes and negative D changes at Alibag on the west coast. They also postulated a system of induced currents concentrating along the coast and the wide continental shelf during substorm events with two branches, one in the Bay of Bengal north to south along the east coast, passing through the Palk Strait and turning northwards, and the other in the Arabian sea waters, again north to south along the Alibag coast, and the two branches meeting and turning westwards north of Surathkal (Mangalore) and south of Margao as a diffuse east–west sheet current. Earlier Srivastava & Prasad (1974) discussed the possible role of the Deccan traps in the reversal of short-period Z variations at Alibag as compared to Hyderabad. We note (see Figs 1 and 2) that during substorm events negative Z changes are still observed at Nagpur on the eastern fringe of the Deccan Traps north of Hyderabad, although very much reduced as compared to Alibag. These changes in Z turn positive at Hyderabad just outside the Traps. The role of the Deccan Traps in the induction problem is yet to be fully understood.

Thakur *et al.* (1986) provided the Parkinson arrows at the southern peninsular Indian magnetometer array stations (December 1979–March 1980). Again we refer to the northernmost (16°N latitude) profile of the array passing through Margao (west coast)–Dharwar–Bellary–Mahanandi and Chirala (east coast) (their Fig. 1). The bay-type fluctuations at Margao and Bellary were similar to those at Alibag. The medium-sized real induction arrow for 37 min period at Margao points westwards to the Arabian Sea, and it becomes shorter inland at Bellary with smaller Z amplitudes on the southern edge of the Traps along the west coast. Alibag-type negative Z changes for substorms at Margao and Bellary (inland), just outside the Traps, indicate the southern extent of such changes ($\sim 16°$N).

Mareschal *et al.* (1987) discussed the induction models for the southern Indian region with simple tests and showed that even though a conductor is required in the Indo-Ceylon graben to explain the geomagnetic variations, its integrated conductivity need not be that selected by Ramaswamy *et al.* (1985). The graben conductor coupled with a conductor located underneath the Comorin ridge or thereabouts provides a better 3-D model for the observed bay variations of the geomagnetic field in this region. An extension of the southern Indian region modelling technique to latitudes further north (with the availability of high-quality data from a dense network of recently commissioned observatories) will shed more light on this complex induction problem.

ACKNOWLEDGMENTS

The authors are grateful to Prof. H. K. Gupta, Director NGRI, Hyderabad, India, and Prof. G. S. Lakhina, Director, IIG, Mumbai, India, for the data from their observatories and various other facilities provided at the two Institutes during this investigation.

REFERENCES

Asinkar, R.L., Pathan, B.M. & Rao, D.R.K., 1999. Enigmatic signatures of the geomagnetic field at the eastern coastal regions of India, *36th Ann. Convention Mtng Indian Geophys. Un.*, Pondicherry University, pp. 108–109 (abstract).

Mareschal, M.G., Vasseur, G., Srivastava, B.J. & Singh, R.N., 1987. Induction models of southern India and the effect of off-shore geology, *Phys. Earth planet. Inter.*, **45**, 137–148.

Parkinson, W.D., 1959. Directions of rapid geomagnetic fluctuations, *Geophys. J. R. astr. Soc.*, **2**, 1–14.

Parkinson, W.D., 1962. The influence of continents and oceans on geomagnetic variations, *Geophys. J. R. astr. Soc.*, **6**, 441–449.

Ramaswamy, V., Agarwal, A.K. & Singh, B.P., 1985. A three dimensional numerical model study of electromagnetic induction around the Indian peninsula and Sri Lanka Island, *Phys. Earth planet. Inter.*, **39**, 52–61.

Schmucker, U., 1964. Anomalies of geomagnetic variations in the southwestern United States, *J. Geomag. Geoelectr.*, **15**, 193–221.

Singh, B.P., Nityananda, N. & Agrawal, A.K., 1977. Induced magnetic variations in the Indian peninsular, *Acta Geodet. Geophys. Montanist.*, **12**, 65–72.

Srivastava, B.J., 1992. New results of the dip equator and the equatorial electrojet in India, *J. Atmos. Terr. Phys.*, **54**, 871–880.

Srivastava, B.J. & Habiba Abbas, 1980. An interpretation of the induction arrows at Indian stations, *J. Geomag. Geoelectr.*, **32**, SI187–SI196.

Srivastava, B.J. & Prasad, S.N., 1974. Role of the Deccan Volcanics in the reversal of short-period geomagnetic variations at Alibag, *Phys. Earth planet. Inter.*, **9**, 157–160.

Srivastava, B.J., Bhaskara Rao, D.S. & Prasad, S.N., 1974a. Geomagnetic variation anomalies in the Koyna and Bhadrachalam seismic areas in peninsular India, *J. Geomag. Geoelectr.*, **26**, 247–255.

Srivastava, B.J., Bhaskara Rao, D.S. & Prasad, S.N., 1974b. Geomagnetic induction anomalies along the Hyderabad-Kalingapatnam profile, *Tectonophysics*, **24**, 343–350.

Srivastava, B.J., Prasad, S.N., Singh, B.P., Arora, B.R., Thakur, N.K. & Mahashabde, M.V., 1982. Induction anomalies in geomagnetic Sq in peninsular India, *Geophys. Res. Lett.*, **9**, 1135–1138.

Thakur, N.K., Mahashbde, M.V., Arora, B.R., Singh, B.P., Srivastva, B.J. & Prasad, S.N., 1986. Geomagnetic variation anomalies in peninsular India, *Geophys. J. R. astr. Soc.*, **86**, 839–854.

Untiedt, J., 1970. Conductivity anomalies in central and southern Europe, *J. Geomag. Geoelectr.*, **22**, 131–149.