CFB magmatism. Thus it is important to work on the temporal relationship between ACICs and CFBs, which may certainly play an important role for understanding the origin of ACICs.

The majority of carbonatite occurrences worldwide are Cretaceous in age (< 200 Ma)[1] and are temporally linked to the formation of large igneous provinces immediately prior to the break-up of the supercontinent Pangea. The exact timing of this alkaline–carbonatite magmatism globally is critical in evaluating the details of magmatic processes operating within mantle plumes and could provide a detailed record of the break-up history of the supercontinent Pangea.

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ACKNOWLEDGEMENTS. We are grateful to Dhirendra Kumar, Atomic Minerals Division for his valuable guidance and suggestion for completing the fieldwork around Jasra. CSIR is acknowledged for financial assistance (24(0251)/01/EMR-II).

Received 11 September 2001; revised accepted 24 December 2001

Estimates of coseismic displacement and post-seismic deformation using Global Positioning System geodesy for the Bhuj earthquake of 26 January 2001

Sridevi Jade*, Malay Mukul, Imtiyaz A. Parvez, M. B. Ananda, P. Dileep Kumar and V. K. Gaur

CSIR Centre for Mathematical Modelling and Computer Simulation, Belur Campus, Bangalore 560 037, India

The $M_w = 7.6$ Bhuj earthquake of 26 January 2001 that occurred in the Kachchh Rift Basin (KRB) was felt over a wide area in the country. Global Positioning System (GPS) measurements were made at eleven sites in the epicentral area and at Jamnagar, south of the KRB to estimate the total residual displacements at these sites as a result of this earthquake. During the survey, seven Great Trigonometrical Survey (GTS) points (1857) were reoccupied using GPS. An additional five GPS points were established by C-MMACS for post-seismic studies. The Jamnagar site was measured earlier in 1997 while the seven GTS sites are those established during the GTS, 144 years ago. Comparison of GPS (1997) and GPS (2001) coordinates at Jamnagar gives the coseismic displacement vector of 16 ± 8 mm at N35°E for the four-year period (1997–2001); this is the only GPS–GPS based estimate of coseismic slip of the Bhuj earthquake. Comparison of GTS (1857) and GPS (2001) coordinates at 7 GTS sites yields upper bounds on the displacements suffered by these sites as a result of the co-seismic slip of major events that occurred in the intervening period. GTS (1857)–GPS (2001) baselines oriented at low angles to the NNE–SSW compression or transport direction have shortened in length, while those oriented at high angles have been elongated. The two epochs of measurements at the five GPS sites in KRB and Jamnagar during February and July 2001, yield post-seismic displacement rates averaging about 1 mm/month at these sites. GPS (February 2001)–GPS (July 2001) baselines, on the other hand, have shortened in length irrespective of their orientation relative to the NNE–SSW transport direction.

AN earthquake of moment magnitude $M_w = 7.6$, rocked the Rann of Kachchh and adjoining areas at 8 h 46 min (IST) on the morning of 26 January 2001 (Figure 1). This is the second catastrophic earthquake to have occurred in Kachchh, 181 years after the *M* 7.5 (ref. 1) earthquake of June 1819 which destroyed the towns of Bhuj and Anjar and created an 80-km-long fault scarp and a natural dam (Allah Bund) uplifted at its crest by

*For correspondence. (e-mail: sridevi@cmmacs.ernet.in)

6.5 m, on the northern edge of the Rann of Kachchh. The death toll of this earthquake already exceeds 10 times that of the 1819 event because of increased population, making it the most lethal of Indian earthquakes so far. The earthquake affected a large area with a heavy toll of life (officially 20,005) and property estimated at Rs 21,262 million (www.ndmindia.nic.in/eq2001/sit.html).

Palaeoseismic indicators reveal that severe earthquakes have repeatedly occurred in this region over the past thousand years[1]; the oldest evidence pointed to an earthquake inferred to have occurred 800–1000 years ago. The major Kachchh earthquakes of 1819 and 2001 also happen to be the two largest historical events to have occurred anywhere within the continent. The 1819 event was the first major intra-continental earthquake for which crustal deformation was quantified[2,3]; the earthquake was inferred to have occurred along a steep 80-km-long NNW–SSE reverse fault dipping at 55 ± 5°N with slip of 11 ± 2 m (ref. 4). The epicentre of the 2001 earthquake lies about 70 km SSE of that of the 1819 event.

The history of the Kachchh Rift Basin (KRB), the site of the 2001 Bhuj earthquake, began at about 150 Ma, with initial opening of the Kachchh rift and continued to widen. During all this time the KRB was subjected to extensional stresses and inversion from extensional to compressional tectonics occurred around 20 Ma (refs 5 and 6) by which time the basin was subjected to NNE–SSW directed compression[7]. North-dipping Kathiawar fault and south-dipping Nagar Parkar fault are extensional faults that form the southern and northern boundaries of the KRB, respectively. The NNE–SSW compression has resulted in the formation of two systems of thrust faults within the KRB. The northern Allah Bund system of thrust faults are NNE-dipping, with transport direction from NNE to SSW, whereas the southern Kachchh Mainland Fault system of faults dip to the SSW and have SSW to NNE transport direction. The zone of transition between the two systems of faults lies almost entirely in the Great Rann. The entire KRB has been seismically active; the 1819 earthquake occurred in the northern system of faults, whereas the 1956 Anjar and the 2001 Bhuj earthquakes occurred in the southern system of faults. The Bhuj earthquake was initially thought to have originated on the Kachchh Mainland Fault (see ref. 8); subsequent analysis of aftershocks and geology has indicated that the hypocentre of the 2001 earthquake was located in the footwall of the Kachchh Mainland Fault probably along a blind thrust, dipping 40°–50°S and trending ENE–WSW and parallel to the Kachchh Mainland Fault[9].

Several interpretations of the Bhuj earthquake[10] have been proposed based on teleseismic waveform modelling. These embrace a range of rupture areas, epicentral locations and slip vectors. Geodetic measurements in the epicentral region offer an alternative and potentially less ambiguous interpretation of the rupture parameters of the recent earthquake. Keeping this in mind, CSIR

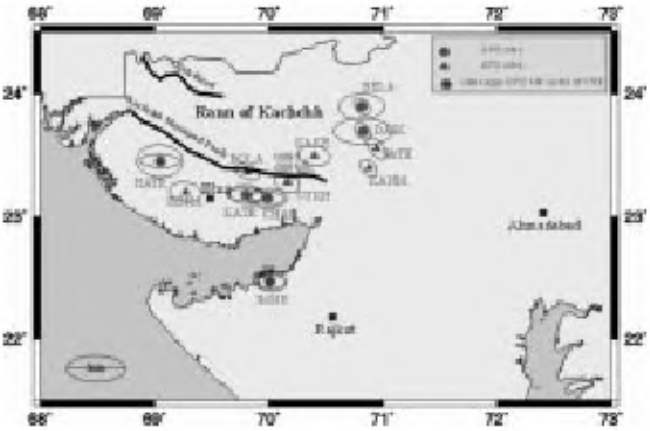

Figure 1. Sites measured using GPS geodesy along with error ellipses associated with the estimation of their coordinates from GPS data.

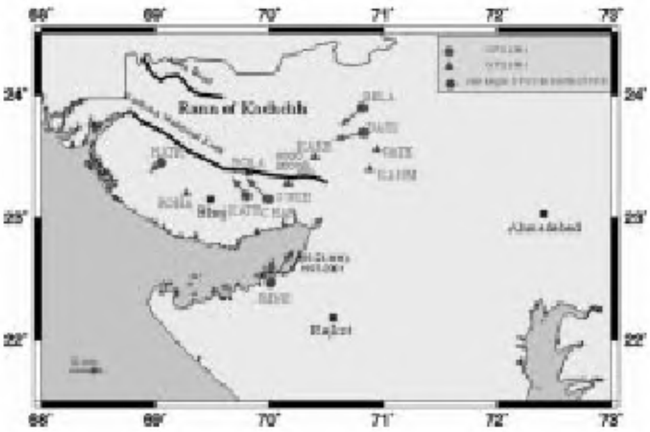

Figure 2. Coseismic and post-seismic displacement vectors at the GPS sites of Bhuj GPS campaign.

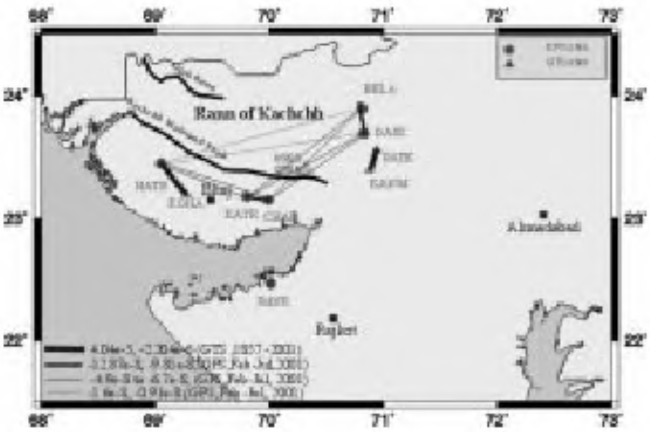

Figure 3. Elongation (+) and shortening (–) of the GTS/GPS baselines.

Table 1. Bhuj GPS campaign sites

Station	Four-letter code	GTS/GPS	Latitude	Longitude	Number of epochs of measurement
Jamnagar	JMNR	GPS	22.47	70.01	3 (1997, 2001)
Hathria	HATR	GTS/GPS	23.45	69.05	2 (2001)
Charakda	CHAR	GPS	23.15	69.98	2 (2001)
Khatrod	KATR	GPS	23.18	69.80	2 (2001)
Bela	BELA	GPS	23.89	70.81	2 (2001)
Dajka	DAJK	GPS	23.69	70.83	2 (2001)
Boladi	BOLA	GTS	23.37	69.81	1 (2001)
Kakarwa	KAKR	GTS	23.49	70.39	1 (2001)
Roha hill	ROHA	GTS	23.20	69.27	1 (2001)
Kanmer	KANM	GTS	23.39	70.87	1 (2001)
Pata-e-Shah	PATE	GTS	23.56	70.94	1 (2001)
Sukhpur	SUKH	GTS	23.28	70.16	1 (2001)

Centre for Mathematical Modelling and Computer Simulation (C-MMACS), Bangalore launched a GPS campaign in the KRB to estimate coseismic displacements as well as post-seismic visco-elastic deformation expected to reflect the visco-elastic relaxation. Figure 1 shows the seven Great Trigonometrical Survey (GTS) points (1859) that were reoccupied using GPS along with the five GPS (Global Positioning System) points (Hathria, Charakda, Khatrod, Bela and Dajka) established by C-MMACS for post-seismic studies. Table 1 gives details about the sites measured in the KRB using GPS geodesy and their approximate location. All the sites were measured using either Trimble SSE or SSI receivers and SSE geodetic antennas with ground planes. Each site was occupied for a minimum of 48 h and maximum of 72 h, except for Jamnagar site which was run continuously for 10 days during the first epoch of measurements. Since Jamnagar was measured in 1997 as a part of country-wide GPS campaign launched by C-MMACS, the recent measurements there have helped us to constrain the displacement suffered by this site during the four-year period. This displacement in the Indian reference frame would be mainly the result of coseismic slip associated with the Bhuj earthquake, thereby providing the upper bound to the coseismic slip-related displacement at this site. The GTS–GPS displacement at the seven GTS sites pertaining to the 144-year period (1857–2001) would, of course, include the displacement related to the coseismic slip of the 2001 earthquake in addition to those resulting from other moderate earthquakes of this period, as well as the accumulated aseismic displacement over the 144-year period. This number, therefore, would also provide an upper bound to the displacement related to the coseismic slip for the 2001 earthquake, although the associated uncertainties would be high. However, in the absence of pre-quake GPS data from the KRB region, this would be a useful number to constrain the coseismic slip on the 2001-rupture plane. Two epochs of measurements of the 5 GPS sites in KRB and Jamnagar in February and July 2001 give the post-seismic deformation information. This communication presents the results of the measurements described above.

The GPS data of the occupied sites have been processed using Bernese 4.2 software. The GPS site at the Indian Institute of Science (IISc), Bangalore, which is a part of GPS global tracking network (International GPS service, IGS station), has been taken as the reference point. The coordinate and the velocity of IISc are known very precisely in the International Terrestrial Reference Frame (ITRF). Precise orbit files of the GPS satellites have been used for data processing. Coordinates of the sites in the Bhuj region have been estimated by tightly constraining the IISc site to its ITRF coordinate. This strategy was adopted, because the absolute ITRF velocity of the Indian plate (~ 55 mm/yr) is high when compared to the relative displacements in the campaign region. Moreover, as the campaign region is well within the Indian plate, constraining the displacement of these sites with other IGS stations (which are not in the Indian plate) will introduce errors related to the plate movements. The distance of the other IGS stations from the campaign area is quite large and so it does not make any sense to include them. The errors involved in the estimation of the coordinates are expressed in the form of two-dimensional error ellipses and plotted in Figure 1.

The displacement suffered by GTS and GPS sites in the north and east directions are given in Table 2. The changes in the 2001 GPS-derived baseline lengths relative to the GTS baselines measured in 1857 are given in Table 3 along with the changes in the baseline length between the five GPS sites for the two epochs (February and July 2001) of measurements. The displacement vectors at GPS sites in the Indian reference frame are plotted in Figure 2, which also shows the coseismic displacement suffered by Jamnagar due to the 2001 earthquake. The GTS/GPS baselines are shown in Figure 3 along with the changes in baseline length for the periods 1857–2001 and February–July 2001.

Table 2. Absolute displacement in north and east directions of the GTS/GPS sites

Station	GTS/GPS	Period	North	East
Jamnagar	GPS	1997–2001	16.80 cm	17.57 cm
		February–July 2001	2.11 cm	1.44 cm
Hathria	GTS/GPS	1857–2001	18.53 m	116.06 m
		February–July 2001	1.0 cm	1.11 cm
Charakda	GPS	February–July 2001	2.0 cm	0.778 cm
Khatrod	GPS	February–July 2001	1.89 cm	1.00 cm
Bela	GPS	February–July 2001	0.778 cm	0.778 cm
Dajka	GPS	February–July 2001	1.11 cm	0.556 cm
Boladi	GTS	1857–2001	19.83 m	117.20 m
Kakarwa	GTS	1857–2001	21.39 m	119.02 m
Roha hill	GTS	1857–2001	18.81 m	116.89 m
Kanmer	GTS	1857–2001	18.53 m	116.06 m
Pata-e-Shah	GTS	1857–2001	21.24 m	117.97 m
Sukhpur	GTS	1857–2001	21.24 m	117.87 m

Three epochs of GPS measurements at Jamnagar (22.5°N, 70°E; Figure 1), i.e. one measurement prior to and two measurements after the 2001 event, give both the coseismic displacement (1997–2001) and post-seismic displacement (February–July 2001). The displacement vector (Figure 3) obtained from GPS–GPS comparison of the Jamnagar site for the four-year period (February 1997–February 2001) is 24.3 ± 1 cm at N46°E. In the Indian reference frame, assuming a maximum of 3 ± 2 mm/yr shortening at N45°E within the Indian plate[11], the minimum coseismic displacement vector at Jamnagar is 16 ± 8 mm at N35°E. Two epochs of GPS measurements made at Jamnagar after the 2001 event give the post-seismic displacement vector of 7.9 ± 5 mm (N).

Displacements between GPS-derived positions of the seven GTS points and published triangulation data (GTS) measured in 1857 have also been estimated (see Table 2). However, direct comparison of latitudes and longitudes turns out to be problematic because of uncertainties in orientation and translation between coordinates of the Everest Spheroid[12] and the GPS coordinate systems. For example, the GTS–GPS displacement (Table 2) of all the seven GTS sites over the 1857–2001 period is found to be approximately 19 m (N) and 117 m (E) from its published position, even after correction for the 1856 longitude for Chennai[13]. This number, however, includes the effect of aseismic strain accumulation in the region along with coseismic slips of previous and the 2001 event, as well as uncertainties in the longitude correction. However, the northern component of this displacement does yield an upper bound to the northward motion suffered by this site as a result of the coseismic slip of the major events in the region during the past 144 years.

Comparison of GTS (1857) and GPS (2001) baseline lengths (Table 3, Figure 3) seems to make more sense, as systematic errors in the coordinates of the GTS points are not included in the baseline lengths. Given this, change in the baseline lengths over a 144-year period for Hathria–Roha hill baseline is 1.47 m and Kanmer–Pata-e-Shah baseline is –0.20 m, which corresponds to an elongation of 4.0436×10^{-5} (strain rate of 2.81×10^{-7}/year) and shortening of 2.204×10^{-6} (strain rate of -1.53×10^{-8}/year) approximately across and along the NNE–SSW compression or transport direction as indicated by their azimuths (Table 3).

Post-seismic (February–July 2001) GPS–GPS displacement suffered by the five GPS sites computed in the Indian reference frame near the epicentre indicates displacement rates averaging 1 mm/month (Figure 2). Baseline lengths involving the five GPS points within the KRB measured in February and July along with the difference in baseline lengths are listed in Table 3 and plotted in Figure 3. All the baselines, irrespective of their azimuths, have shortened in length; the magnitude of shortening is highest along the Charakda–Khatrod baseline (shortening of 1.2873×10^{-7} at strain rate of 3.09×10^{-7}/year) and lowest for the Hathria–Bela baseline (shortening of 0.9097×10^{-8} at strain rate of 0.2183×10^{-7}/year). Given that the azimuth of the Charakda–Khatrod baseline is 98.98° and that of the Hathria–Bela baseline is 76.02° (Table 3), the latter is closer to the regional NNE–SSW compression direction and hence should be exhibiting maximum rather than minimum shortening. However, the Hathria–Bela baseline is farthest from the epicentre and the Charakda–Khatrod line is the closest. This indicates that the minimum and maximum shortening of the Hathria–Bela and Charakda–Khatrod baselines is directly related to their distance from the epicentre and, therefore, is probably controlled by post-seismic deformation rather than the NNE–SSW regional compression.

In summary, the coseismic displacement during the Bhuj earthquake of 26 January 2001 could be estimated best from GPS (1997)–GPS (2001) measurements at Jamnagar, which is south of the KRB, and lies on the hanging wall of the thrust fault on which the earthquake

Table 3. GTS/GPS baseline lengths and their corresponding changes

Baseline	GTS/GPS 1857/February 2001 baseline length (m)	GPS baseline length (m) July 2001	Change in baseline length	Azimuth degrees	Elongation (+)/ shortening (–)
Hathria–Roha hill	GTS, 1857 (36434.1126)	36435.5858	1.47 m (1857–2001)	132.00	4.04×10^{-5} (1857–2001)
Pata-e-Shah–Kanmer	GTS, 1857 (18919.5974)	18919.3979	–0.20 m (1857–2001)	022.81	-2.204×10^{-6} (1857–2001)
Charakda–Khatrod	GPS, February 2001 19419.7047	19419.7022	–2.5 mm (February–July 2001)	98.98	-12.87×10^{-8} (February–July 2001)
Bela–Dajka	GPS, February 2001 22420.6154	22420.6132	–2.2 mm (February–July 2001)	176.64	-9.812×10^{-8} (February–July 2001)
Charakda–Bela	GPS, February 2001 117828.7032	117828.6953	–7.9 mm (February–July 2001)	47.96	-6.705×10^{-8} (February–July 2001)
Charakda–Dajka	GPS, February 2001 104466.8687	104466.8622	–6.5 mm (February–July 2001)	57.08	-6.222×10^{-8} (February–July 2001)
Hathria–Charakda	GPS, February 2001 102213.5558	102213.5495	–6.3 mm (February–July 2001)	107.83	-6.16×10^{-8} (February–July 2001)
Khatrod–Bela	GPS, February 2001 130130.5550	130130.5475	–7.5 mm (February–July 2001)	54.78	-5.763×10^{-8} (February–July 2001)
Khatrod–Dajka	GPS, February 2001 119004.0008	119003.9940	–6.8 mm (February–July 2001)	63.42	-5.714×10^{-8} (February–July 2001)
Hathria–Khatrod	GPS, February 2001 83135.3146	83135.3105	–4.1 mm (February–July 2001)	109.90	-4.93×10^{-8} (February–July 2001)
Hathria–Dajka	GPS, February 2001 183660.2854	183660.2823	–3.1 mm (February–July 2001)	82.37	-1.687×10^{-8} (February–July 2001)
Hathria–Bela	GPS, February 2001 186880.0925	186880.0908	–1.7 mm (February–July 2001)	76.018	-0.9097×10^{-8} (February–July 2001)

occurred. The coseismic displacement vector (16 ± 8 mm at N35°E) obtained at Jamnagar site for the four-year period (1997–2001) is the only GPS–GPS estimate of coseismic slip of the 2001 Bhuj earthquake. This displacement at Jamnagar is consistent with elastic models of the Bhuj earthquake (using slip parameters estimated from teleseismic data) which indicate that displacements of 2–5 cm may have occurred at this location (Bilham Roger, pers. commun., 2001). This suggests that pre-seismic strain rates applied to the Kachchh region were not excessive compared to those prevailing in central India. The uncertainties observed with all the seven GTS sites reoccupied after the 2001 Bhuj earthquake indicate that computation of GTS–GPS displacement vectors is best avoided and only GTS–GPS baseline lengths between stations should be compared. Comparison of GTS (1857) and GPS (2001) baselines along and across the NNE–SSW compression or transport direction reveals shortening of 2.204×10^{-6} and elongation of 4.0436×10^{-5}, respectively. The post-seismic displacement vectors at the five GPS sites in the KRB and Jamnagar indicate that the displacement related to the post-seismic rheological reworking of the lower crust is superposed on the deformation related to the thrusting in the KRB. Baseline lengths involving the five GPS points within the KRB have shortened irrespective of their orientation relative to the NNE–SSW compression direction, indicating that post-seismic deformation controls this shortening.

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ACKNOWLEDGEMENTS. This work was funded by a special grant from the Director General, CSIR, Government of India. We have benefitted a great deal from discussions with Roger Bilham, University of Colorado. Excellent critical reviews by two anonymous reviewers helped greatly to improve the quality of this paper.

Received 20 April 2001; revised accepted 3 January 2002