Co-Seismic Surface Displacement Induced by the Bam Earthquake, Iran (26/12/2003, M=6.6): Insights from InSAR, GPS, SPOT5 Analyses and Levelling

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ABSTRACT: *Co-seismic surface deformation measurements in the vicinity of a ruptured fault provide constraints on detailed fault geometry and slip distribution at depth. Together with seismological data, they give unique insights on the mechanical behaviour of a seismic fault. Three different satellite and ground geodetic measurements of Bam earthquake (Mw 6.6, December 26, 2003) induced surface deformation are presented. Envisat ASAR interferometry provides precise and dense information. However, due to this strike-slip fault orientation, sub-pixel correlation technique applied to Spot-5 images makes more explicit the horizontal component of surface deformation. We complete these oblique and horizontal estimations of deformation with a levelling profile along the main road crossing the rupture from west to east. This geodetic data allows us to propose a dislocation model at depth. The slip vector, on a quasi-vertical fault, slightly dipping towards east, has a strike-slip component as high as 2m, while the dip-slip component appears to be small. We suggest that rupture may have been initiated at depth on the Bam fault and propagated towards surface along this new fault branch. In addition to co-seismic deformation, InSAR analysis and levelling data reveal the presence of a high-rate subsiding zone south-east of Bam city. The phenomenon is likely due to heavy water withdrawal for cultivation purpose or water supply to the Bam and Baravat inhabitants.Ultimately, we present a work in progress involving GPS and InSAR which aims to map post-seismic deformation in the vicinity of Bam. However, technical problems in GPS campaigns and atmospheric artifacts in InSAR acquisitions did not enable us to show any evidence of such a deformation so far.*

Keywords: SAR interferometry; Levelling; Sub-pixel correlation offsets; Dislocation model at depth; GPS

1. Introduction

The *Mw* = 6.6 December 26, 2003 earthquake in eastern Iran destroyed the city of Bam almost completely where a well preserved 2000 year old citadel indicated that no similar event occurred since that time. Despite its relatively moderate size (M_0 = 6.6 1018 *Nm*, US Geological Survey), the earthquake caused a death toll of 30000 people, being the major natural disaster in Iran since the *Mw* = 7.5, 1990 Rudbar earthquake in north-western Iran. This huge human and material disaster results from the conjunction of two factors. First, Bam's buildings were made with compacted-shale bricks, without reinforced structures. Second, the main shock occurred on a blind fault that goes through the city of Bam on its eastern part.

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between central Iran and Afghanistan is well described in literature [1-2]. Recent *GPS* measurements indicate that eastern Iran deforms at a rate of 14*mm*/*yr* [3], see Figures (1) and (2). In agreement with this tectonic setting, the Bam earthquake focal mechanism reveals a rupture on a dextral, vertical strike-slip fault trending north-south.

Satellite imagery has permitted to precisely locate the surface rupture and to accurately map the co-seismic surface deformation all around the city of Bam. The main source of information has been provided by Envisat *ASAR* interferograms (*InSAR*) [4-7]. But this information has been successfully complemented by sub-pixel correlation methods applied to Spot5 images. Finally, one levelling profile across the deformed zone gives a precise estimation of the vertical deformation induced by the earthquake. All these data sets are used as surface constraints for defining a dislocation model at depth.

Apart from this co-seismic deformation, *InSAR* reveals a wide subsiding zone near Narmashir (South-East of Bam). This phenomenon, which occurs continuously over the time of observation, most likely is attributed to heavy water-withdrawal for cultivation purposes or water supply to the Bam and Baravat inhabitants.

Finally, a work in progress is presented in this paper, involving *GPS* and *InSAR* techniques, which aims to map any post-seismic deformation over the Bam neighborhood.

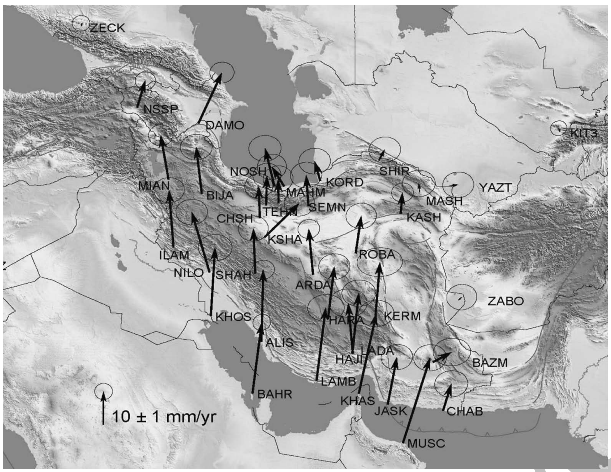

Figure 1. GPS velocity field with respect to fixed Eurasia [3].

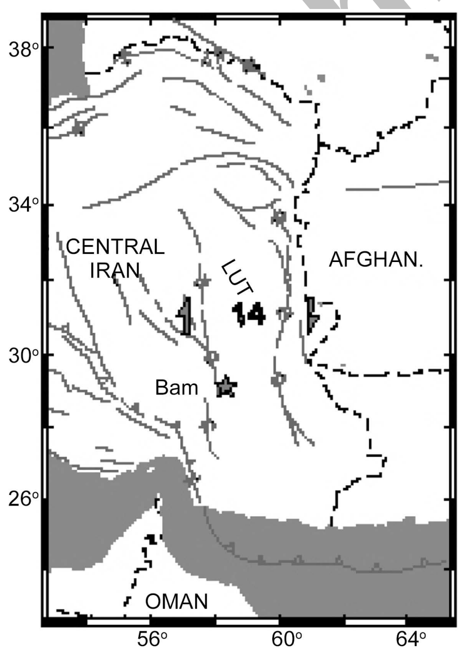

Figure 2. Tectonic setting of eastern Iran. GPS measurements indicate that the eastern Iran deforms at a rate of 14mm/yr.

2. Co-Seismic ASAR Interferograms

The Synthetic Aperture Radar (*SAR*) coverage of the Earth's surface and the related interferometric technique (*InSAR*) has the capability to reveal earth deformation caused by natural events such as glacier motion, volcanoes and earthquakes [8]. On December 3, 2003 and January 7, 2004, the Envisat satellite acquired two descending radar images (*VV* polarization, Swath 2) of the Bam area. Using Single Look Complex (*SLC*) images processed by the European Space Agency, a differential interferogram was computed; see Figure (3) using the *CNES* Diapason software. The phase difference between the two images contains the variation of the satellite-ground distance during the elapsed time, i.e. the

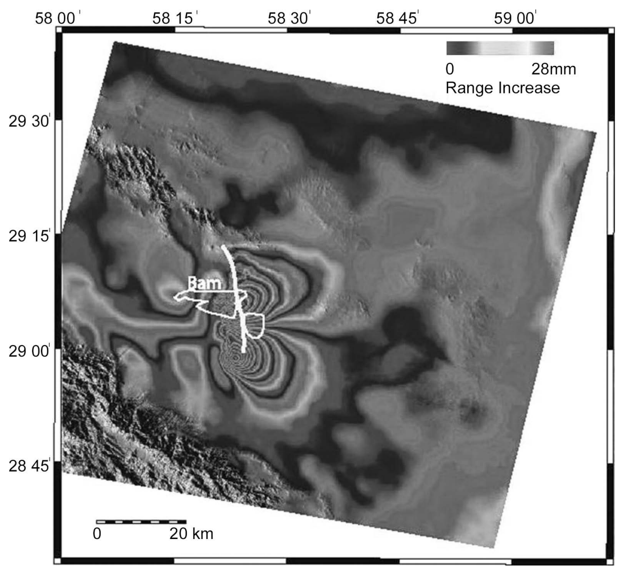

Figure 3. Co-seismic differential ASAR Interferogram in descending orbits [03 Dec 03 - 07 Jan 04], using SRTM dem. The altitude of ambiguity is 20m.

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co-seismic displacement vector projected on the satellite line of sight. Because of the 500*m* track-to-track distance, the geometrical perspective created topographic fringes (one fringe for each 20*m* of elevation change) which were removed using either a precise digital elevation model (dem) provided by the National Cartographic Center of Iran, or the *SRTM* dem. Because the Bam area is almost desert and the time separation of the two SAR images is only one month, the interferogram is highly coherent. This coherence is lost on places where the surface reflectors have experienced significant changes between the two passes, see Figure (5). Indeed, this is the case for the cities of Bam and Baravat, but more unexpectedly, south of Bam along a roughly 10*km* long south-north segment corresponding to the place where the rupture reached the surface. In other respects, the presence of parasitic atmospheric fringes is expected to be limited (lower than one fringe) due to the low temperature in this area in the season and time of the day when the data were acquired. The pair wise analysis of several other interferograms confirmed the presence of atmospheric artifacts, mainly in the south-west part of the co-seismic interferogram (about one fringe).

The interferogram structure is simple with only two major systems of concentric fringes. The phase variation across these two lobes indicated a projected differential motion of ~ 47*cm* along the line of sight. Two smaller phase rings were also present in a symmetrical position to the west. The four lobes localization was consistent with a dextral motion on a north-trending strike-slip fault, roughly passing between east and west lobes i.e. about 4*km* west of the Bam lineament. In agreement with field observation [4] and *InSAR* coherence, phase discontinuity was observed between the lobes South of Bam where the rupture reached the surface.

A co-seismic *ASAR* interferogram has been built using Envisat images acquired in ascending orbits; see Figure (4), resulting in a similar interpretation of the earthquake mechanism.

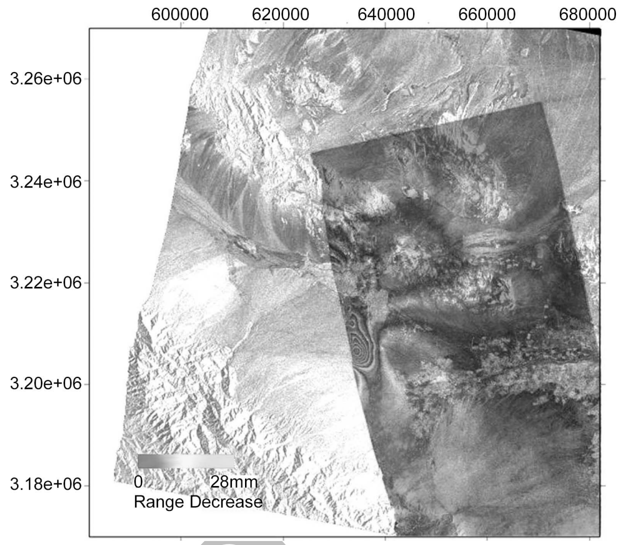

Figure 4. Co-seismic differential ASAR interferogram in ascending orbits [16 Nov 03 - 29 Feb 04], using NCC photogrametric dem. The altitude of ambiguity is 1400m.

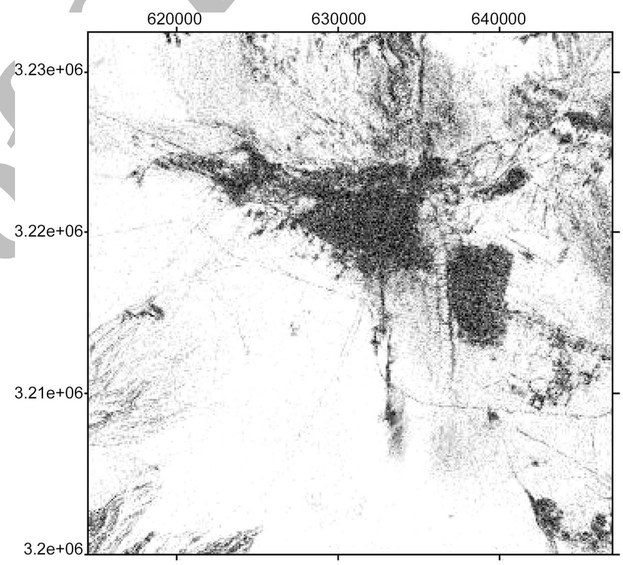

Figure 5. Coherence channel of the co-seismic interferogram. Dark pixels reveal surface changes: damaged urban zones of Bam and Baravat, and, South of Bam, the S-N segment where the rupture reached the surface.

3. Co-Seismic Offsets on SPOT5 Images

InSAR provides measurements of the surface deformation projected along the satellite line of sight. In the case of Envisat swath2, the sub satellite track heading relative to North is -166° for descending orbits and -16° for ascending orbits, while the elevation angle is 23°. This means that (1) we have no direct estimation of each component of the 3D deformation, (2) the sensitivity is higher for vertical displacement than horizontal, and (3) the roughly *S-N* orientation of the fault is poorly adequate to Envisat geometry of acquisition.

One possible way to complement *ASAR* interferograms was to estimate the east-west and south-north components of the surface deformation by computing the sub-pixel offsets between 2 images (optical or radar amplitude) acquired before and after the earthquake. A sub-pixel correlation method developed by Michel and Avouac [9] was applied on two Spot5 images with 2.5*m* resolution cell. A similar processing has been performed by Sarti et al [10] with Envisat *ASAR* complex images obtained

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with a similar doppler centroid and a very small baseline in order to minimize the speckle difference.

The Spot5 images have been acquired on October 10, 2003 and January 28, 2004 with a similar angle of incidence (~left 5°). At large scale, long wavelength artifacts were observed probably due to bad modelisation of the satellite attitude along the orbits. Moreover, on the collapsed urban places, the offset estimator seems to be affected by some bias. Anyhow, if we focus on the ruptured zone, south of Bam, this place seems to be free of any artifacts, see Figure (6).

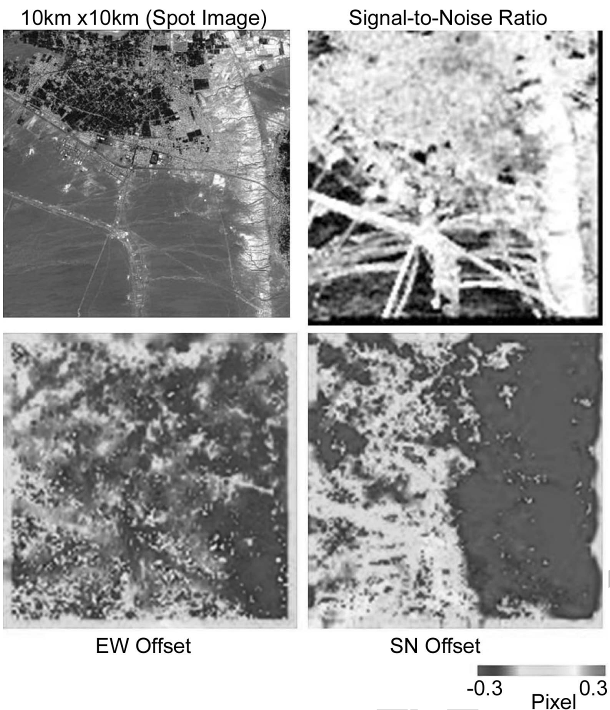

Figure 6. Sub-pixel correlation of Spot5 images over the ruptured zone, South of Bam. a) Spot image, b) The correlation signal-to-noise ratio, c) East-West offsets, d) South-North offsets.

The east-west offsets image does not reveal any significant spatial changes. By contrast, the south-north component is characterized by a steep gradient located along the surface rupture previously mapped by *InSAR*, see Figure (7). This gradient of deformation is about 0.8 *m* (one third of a pixel size) distributed over few hundreds of meters across the fault. This horizontal deformation is significantly higher than the one estimated from ground measurements (0.2*m*) since this deformation mainly occurs without surface rupture.

4. Vertical Co-Seismic Deformation along a Levelling Profile

The main road that crosses the cities of Bam and Baravat from *NW* to *SE* belongs to the first order levelling network of Iran. In order to get a millimetric estimation of the vertical deformation induced by the Bam earthquake, the *NCC* proceeded to the levelling measurement of this profile, see Figure (8). This profile goes through the center of the north-western deformation lobe, then roughly along the symmetry axis of the eastern deformation pattern. The far field has been set to zero deformation, except to the east where it reaches a high rate subsiding zone, see Section 6. Considering its location on the northern part of the quadri-lobes deformation pattern, the shape of this profile is consistent with a dextral strike slip mechanism. Nevertheless, the high amplitude of the relative vertical deformation across the fault (about 20*cm*) suggests some likely thrust component of the rupture.

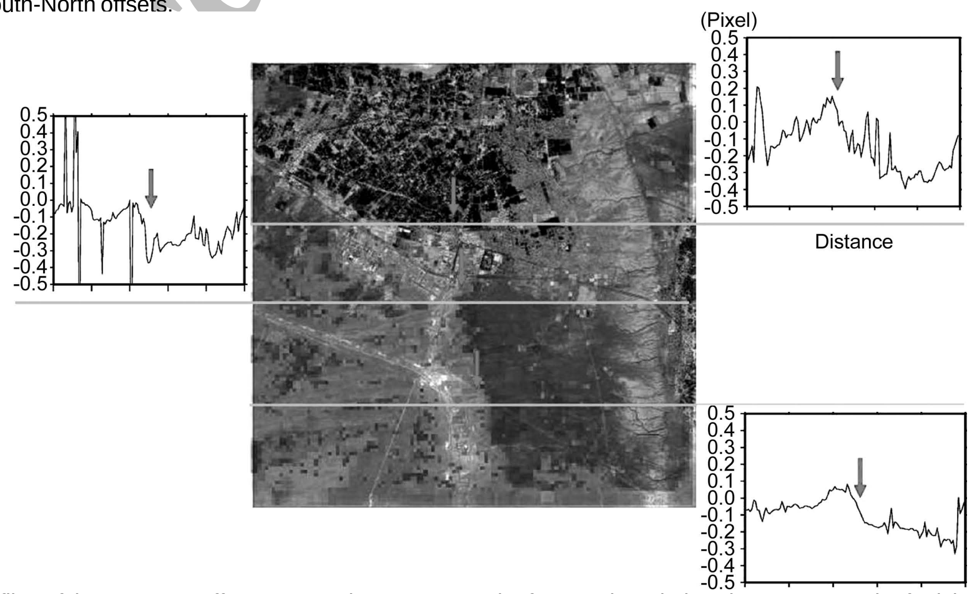

Figure 7. 3 profiles of the S-N Spot offsets across the rupture south of Bam. The relative change across the fault is estimated to one third of a pixel size (~80cm).

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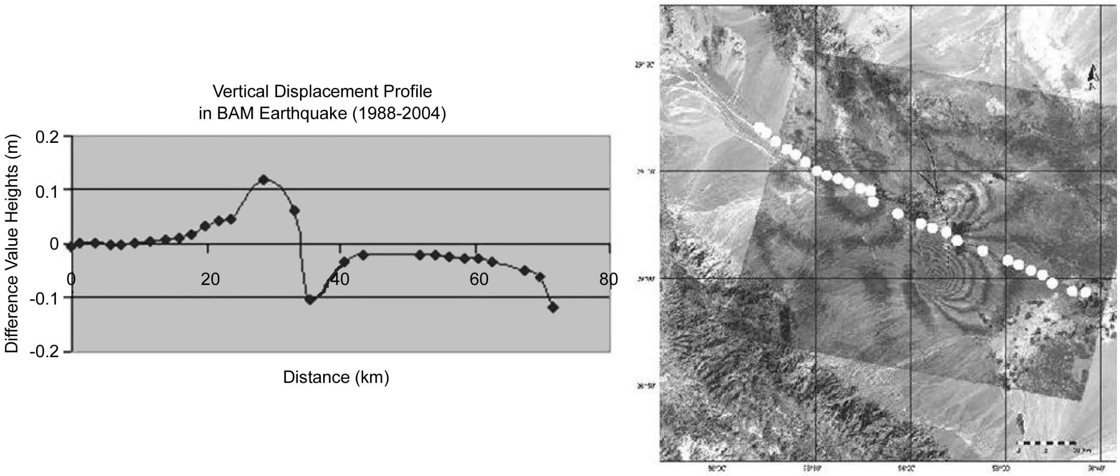

Figure 8. Levelling profile from NW to SE along the main road (white dots superimposed to the co-seismic interferogram).

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5. Model at Depth and Interpretation

The main features (geometry and mechanism) of the Bam earthquake are thus well known: on one hand, surface ruptures appear within the desert north of Bam and along the north trending segment south of Bam as evidenced by *InSAR*, while, on the other hand, all the previous co-seismic surface deformation measurements, in agreement with the focal mechanism, at first order express a right lateral strike slip faulting on a blind fault located about 4*km* west of the Bam lineament.

This lineament is traditionally interpreted as a fault scarp associated with a north trending striking high angle reverse fault (the "Bam fault"). But an *ICG* (International Centre for Geohazards, Norway) reconnaissance mission [11], based on field observations, interpret this morphological feature as an east-facing monocline developed above a steep reverse fault, see Figure (9). This interpretation is reinforced by aftershocks [12] that seem to be aligned along a west dipping plane at depth. Moreover, fissures have been observed along the Bam lineament. So, rupture may have initiated at depth (about 9*km*) on the Bam fault and propagated towards surface along the new branch fault.

Based on these geometrical considerations, slip distribution at depth just on the western fault was first estimated by least-square inversion of *InSAR* data. We used Okada analytic formulations [13] for a rectangular dislocation in an elastic half-space. Then some slip at depth on the Bam fault were added, dipping 80° westward, in a trial-error procedure, to improve the fit between predicted and measured surface deformation, see Figure (10). This leads to a 20*km* fault length with a mean dip of 80° eastward.

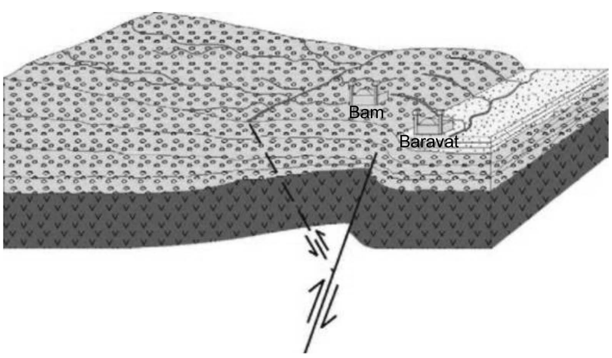

Figure 9. The Bam lineament interpreted as a monocline above a steep reverse fault (ICG Report).

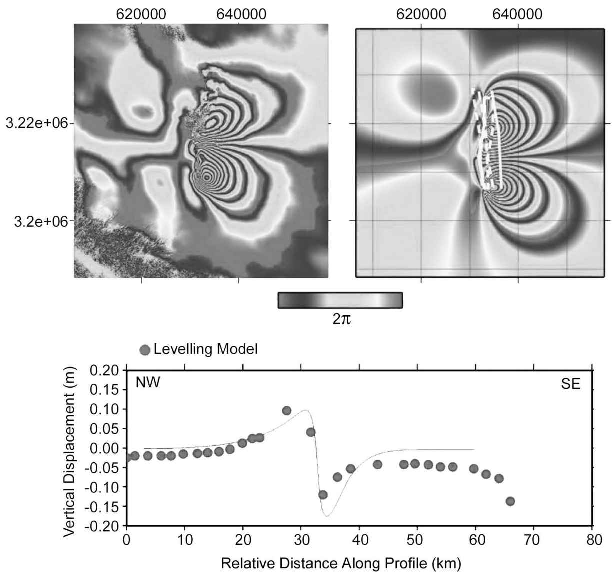

Figure 10. Predicted surface deformation using a dislocation model at depth with the geometry described in Figure (9). a) real interferogram, b) synthetic interferogram, c) vertical deformation predicted along the levelling profile.

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The upper and lower rupture depths are a few hundreds of meters and about 9*km* respectively. The motion has a strike component of 2*m* and a reverse (thrust) component of 0.2*m*. The corresponding geodetic moment is similar to the scalar seismic moment. The addition of a similar slip on the "Bam fault" between 9 and 11*km*, leads to a better fit near the rupture and for the vertical deformation estimated along the levelling profile.

6. Subsidence at Narmashir

Beside the surface deformation induced by the Bam earthquake (co-seismic or possibly post-seismic), *InSAR* reveals a high rate deformation zone (which spatial extend is 15*km* E-W by 10 *km* N-S) south-east of Bam, in the cultivation zone of Narmashir. In addition to the previously described *ASAR* images, we used the Envisat acquisitions of June 2003, March, April and June 2004. All the *ASAR* interferograms constructed from these images reveal the same fringe pattern, see Figure (11). This time permanence rules out any interpretation as atmospheric artifacts. Moreover, the number of fringes associated to this pattern in each interferogram is not correlated with the perpendicular baseline. Therefore, it has to be interpreted in terms of deformation. This deformation appears continuously over the time of observation (June 2003-June 2004). It has, obviously, no tectonic meaning and must be interpreted as a subsidence phenomenon probably due to heavy water withdrawal for cultivation purpose or water supply to the Bam and Baravat inhabitants. Ground-water level drop induces change in effective stress. The pore pressure decrease leads to an increase of the effective stress (increasing compression), so the soil skeleton contracts either in a reversible or irreversible way. The surface deformation is expected to be essentially vertical, even though there is probably a significant horizontal component on the borders of the deformed zone. Assuming pure vertical deformation, the surface deformation could be derived from unwrapped phase, see Figure (12). A peak deformation in the center of the deformed zone by as much as 12*cm* over a one year interval was observed. This deformation revealed by *InSAR* is confirmed by the levelling profile that shows a steep gradient of deformation (subsidence) on its south-eastern end. The origin of this surface motion remains to be confirmed by water-table records over the time interval spanned by *InSAR* images. Moreover, we should be able to check that limits of surface deformation mapped by *InSAR* correspond to some free or confined aquifer contour at depth. Depending on various parameters like compaction index or aquifer thickness, it might be expected that water table has decreased by as much as several meters between June 2003 and June 2004.

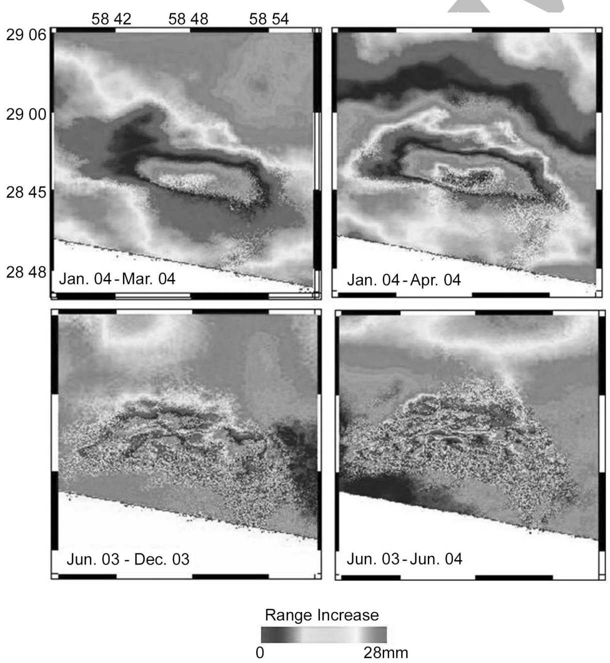

Figure 11. Fringe system associated with the Narmashir deformation zone as observed by 4 differential interferograms in descending orbits. The spatial pattern remains the same, while the number of fringes increases with elapsed time.

7. First Attempts to Measure Post-Seismic Deformation

Even though the magnitude of the Bam earthquake is relatively moderate, it was expected that the

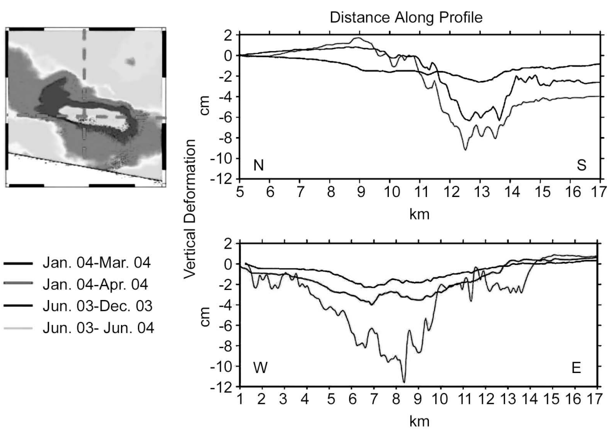

Figure 12. Two profiles (NS and EW) across the deformed zone of Narmashir. The unwrapped phase of 4 interferograms has been converted to deformation making the assumption that its direction is primarily vertical. This subsidence reveals a peak deformation of 12 cm over 1 year.

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post-seismic deformation won't be negligible. Depending on the involved processes (rapid afterslip beneath the ruptured segment, visco-elastic relaxation in the lower crust or poro-elastic rebound), the deformation can occur either in the near field along the ruptured zone, or at larger spatial scale (typically a few tens of kilometers), both at different time-scale (ranging from a few days to several years). The rely was booed on *GPS* and *InSAR* techniques for mapping such a likely deformation.

Less than 3 weeks after the earthquake (January 2-17, 2004), a dense local *GPS* network has been installed and measured, see Figure (13). Its measurement has been reiterated twice: first at the beginning of April, then at mid-June 2004. Unfortunately, the first analysis did not reveal good results because of the short time interval between these first campaigns and the encounter of some technical problems during field measurements. This network will be measured again within the next months.

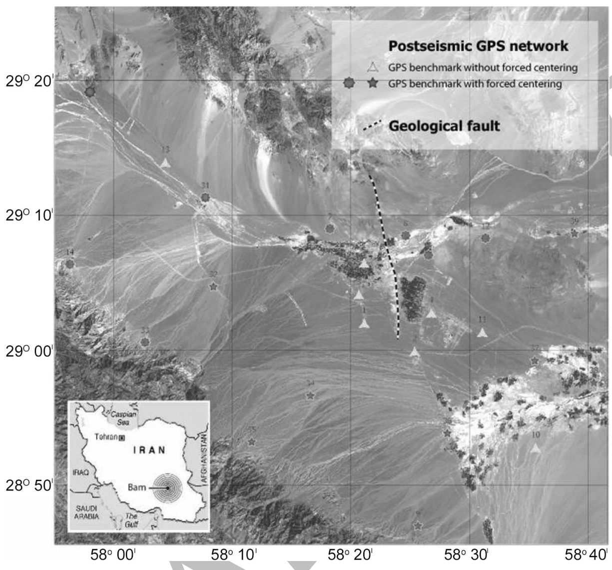

Figure 13. GPS network installed right after the Bam earthquake.

Concurrently, we programmed new Envisat acquisitions. In the interferograms spanning from 1 to 6 months after the earthquake, see Figure (14), the prevailing fringe signature comes from the atmosphere (particularly water vapor content of troposphere). This prevents the detection of any significant fringe patterns that could be assigned to post-seismic surface deformation particularly because their amplitudes are likely to be lower than one fringe. Future acquisitions of Envisat images should help to discriminate fringe patterns which origin would be deformation rather than change in the tropospheric

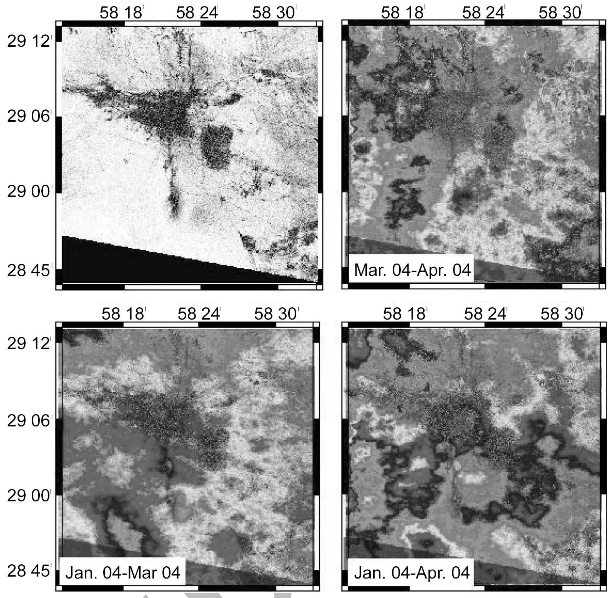

Figure 14. Post-seismic interferograms centered on the co-seismic ruptured zone. The co-seismic coherence image is superimposed to the [17/03/04-21/04/04], [07/01/04-17/03/04] and [07/01/04-21/04/04] differential interferograms. The main contribution to phase signature comes from atmosphere rather than surface deformation.

delay. Indeed, post-seismic surface deformation is expected to be gradual and irreversible in time while change in tropospheric delay is purely random.

8. Conclusions

InSAR technique has proved its ability to map co-seismic surface deformation in arid places accurately, even with moderate magnitude. This information has been complemented with horizontal and vertical estimates of the deformation thanks to, respectively, sub-pixel correlation methods on Spot5 images and levelling. A model of depth has been proposed which predicts surface deformation that fits fairly well with the observations.

This study dedicated to tectonics has revealed the presence in the vicinity of Bam, of a wide subsiding zone, probably due to heavy groundwater withdrawal.

Finally, a dense local *GPS* network around Bam was installed with the objective of measuring any likely post-seismic surface deformation. In the interferograms spanning six months following the earthquake, it was not possible to distinguish any fringe systems that could be associated with deformation.

References

1. Berberian, M. and Yeats, R.S. (1999). "Patterns

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of Historical Earthquake Rupture in the Iranian Plateau", Bull. Seismol. Soc. Am. 89, 120.

2. Walker, R. and Jackson, J. (2002). "Offset and Evolution of the Gowk Fault, S.E. Iran: A Major Intra-Continental Strike-Slip System", *Journal of Structural Geology*, **24**.

3. Vernant, P. Nilforoushan, F., Hatzfeld, D., Abbassi, M., Vigny, C., Masson, F., Nankali, H., Martinod, J., Ashtiani, A., Bayer,R., Tavakoli, F., and Chery, J. (2004). "Contemporary Crustal Deformation and Plate Kinematics in Middle East Constrained by GPS Measurements in Iran and Northern Oman", *Geophys. J. Int.*, **157**.

4. Talebian, M., Fielding, E.J., Funning, G., Jackson, J., Nazari, H., Parson, B., Priestley, K., Qorashi,M. , Rosen, P.A., Walker, R., and Wright, T.J. (2004). "The 2003 Bam (Iran) Earthquake Rupture of 'Truly Blind' Fault", *Geophys. Res. Lett.*, **31**.

5. Fialko, Y., Sandwell, D., Simons, M., and Rosen, P. (2005). "Three-Dimensional Deformation Caused by the Bam, Iran, Earthquake and the Origin of Shallow Skip Deficit", *Nature*, **435**(19).

6. Fielding, E.J., Talebian, M., Rosen, P.A., Nazari, H., Jackson, J.A., Ghoraishi, M., and Berberian, M. (2005). "Surface Ruptures and Building Damage of the 2003 Bam, Iran Earthquake Mapped by Satellite SAR Interferometry Correlation", *J. Geophys. Res.*, **110**(B3).

7. Funning, G.J., Parsons, B., Wright., T.J., Fielding E.J., and Jackson, J.A. (2005). "Surface Displacements and Source Parameters of the 2003 Bam (Iran) Earthquake from Envisat ASAR Imagery", *J. Geophys. Res.*, **110**(B9).

8. Massonet, D., Rossi, M., Carmona, C., Adragna, F., Peltzer, G., Feigl, K., and Rabaute, T. (1993). "The Displacement Field of the Landers Earthquake Mapped by Radar Interferometry", *Nature*, **364**(138).

9. Michel, R. and Avouac, J.P. (2002). "Deformation Due to the 17 August 1999 Izmit Turkey, Earthquake Measured from SPOT Images", *J. Geophys. Res.*, 107 B4, ETG 2-1.

10. Sarti, F., Briole and, P., and Pirri, M. (). "Co-Seismic Fault Rupture Detection and Slip Measurement by ASAR Precise Correlation Using Coherence Maximisation", Application to a North-South Blind Fault in the Vicinity of Bam (Iran), IEEE Geosc. and Remote Sens. Let., In Press.

11. ICG Report 2004-99-1.

12. Tatar, M., Hatzfeld, D., Moradi, A.S., and Paul, A. (2005). "The 26 December 2003 Bam Earthquake (Iran), Mw 6.6, Aftershock Sequence", *Geophys. J. Int.*, 163.

13. Okada, Y. (1985). "Surface Deformation Due to Shear and Tensile Faults in a Half-Space", Bull. Seismol. Soc. Am., **75**, 1135.

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