THE INTERPRETATION OF BAM FAULT KINEMATICS USING ENVISAT SAR INTERFEROMETRIC DATA

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ABSTRACT

The surface ruptures caused by the 26 December 2003 earthquake which affected the city of Bam (Kerman province, southeast Iran) have already been mapped using interferometric coherence images from Envisat SAR images. The clearly visible traces of these structures in the coherence images allow to prove that the Bam earthquake has been caused by the displacement along a previously unknown fault. Besides the coherence, the SAR interferograms of the ascending and descending orbits present a very complex deformation pattern especially north of Bam. Similar patterns have been observed in two independent datasets (ascending and descending) avoiding misinterpretation as atmospheric errors. Interferograms and derived deformation maps allow to interpret such structures in detail as a system of possible fractures and small faults accompanying the main rupture. Geocoded interferograms allow to trace in detail the direction of these structures, while deformation maps of ascending and descending passes allow the interpretation of their relative movement. The obtained pattern together with the structures mapped from the coherence images gives an opportunity to reconstruct the kinematics of the entire "Bam structure" and find its relation to the kinematics of the major intra-continental strike-slip system of the Gowk fault.

1. INTRODUCTION

Iran is one of the most tectonically active areas worldwide. As the result of Arabia-Eurasia convergence right-lateral faults in central Iran accommodate 15 mm/yr rate of slip [1]. The main recent displacements occur in Eastern Iran along the fault zones surrounding the Dasht-e-Lut desert: the Nayband-Gowk-Subzevaran fault system [2] in the West and the Sistran suture zone in the East. North -South shortening associated with convergence is compensated by left-lateral movement along Dasht-e-Bayaz, Doruneh, and Great Kavir faults [3] trending E-W at the northern edge of Dasht-e-Lut area (Fig.1).



Fig. 1. Location map and tectonical setting of Bam area with the coverage of ASAR Envisat images

The city of Bam is located at the southwestern margin of the Dash-e-Lut desert, 50 km east of the Gowk fault (Fig.1). It is a flat area of a partially cemented aluvial fan system developed northward from Jebal Barez mountains and feeds also from the north, by the hilly area built by Eocene volcanics and Paleogene pyroclastics [4]. The only known tectonic structure of the Bam area was the east-facing fault scarp of 15-20m high located 9 km southeast of the town. This structure, mapped as blind reverse fault active in late Quaternary [4] has been further interpreted as a prominent splay of the Gowk fault system [2]. The Mw ~ 6.6 disastrous 26/12/2003 earthquake which destroyed the city of Bam have no associated large co-seismic surface rupture zone. Preliminary studies suggest that the main slip associated with the earthquake occurre along a previously not known, blind fault extending some 12 km south from the center of the city. Detailed studies of the surface displacements and source parameters shown that the right-lateral slip causing the earthquake occurs along this unknown fault [7] or along the mentioned unknown fault and along the known Bam fault of reverse right-lateral movement [8].

2. INTEFEROMETRIC PROCESSING OF SAR DATA

This study is focused on interpretation of features visible in interferograms north of Bam. These patterns have not yet been analyzed because of their very small contribution to the main co-seismic deformation which was interpreted in previous studies of the Bam earthquake. In the case of individual interferogram analysis these patterns might be simply misinterpreted as phase error of atmospheric of topographic origin. To ensure that only phase contribution due to deformation is present in the interferograms all available inteferometric pairs combinations have been analyzed (Tab.1).

Master (date)	Slave (date)	Btemp (days)	B _l_	ASC/DESC
12.03.2003	02.11.2004	70	2.1 m	DESC* +
12.03.2003	01.07.2003	35	516.3 m	DESC*
06.11.2003	01.07.2004	210	1000 m	DESC*
12.03.2003	06.11.2003	175	-474.3 m	$DESC^{v}$
02.11.2004	01.07.2004	35	516.4 m	DESC^
06.11.2003	02.11.2004	245	474	DESC*
16/11/2003	29/02/2004	105	15.9 m	ASC* +

Tab.1. processed interferometric pairs of Bam earthquake

* co-seismic pair, ^v pre-seismic, [^] post-seismic, + interferograms used for detailed interpretation

The analyzed interferograms have been calculated based on a set of Envisat ASAR data which has been made available by ESA for the scientific community. Short temporal baselines and high correlation due to arid climate allows the generation of unique, very high quality interferograms despite of the long temporal or geometrical baseline. Interferometric processing has been performed using Delft Object - Oriented Interferometric Software DORIS [9].

To remove topographic phase contribution from the interferograms two methods have been applied:

1. Three-pass InSAR processing co-seismic pairs using pre-seismic and post-seismic interferograms

2. Correction with SRTM DEM. For project purposes the SRTM data have been carefully pre-processed with GRASS (Geographic Resources Analysis Support system) software:

A) patching of neighboring SRTM sheets

B) filling the gap areas with interpolation by regularized spline with tension algorithm [10].

C) conversion of SRTM from geoidal (EGM96) heights to ellipsoidal (WGS84 used by SAR orbital geometry). The calculation has been performed based on the geoid EGM96 model provided by GFZ-Potsdam.

The topographic contribution of pre-seismic and post-seismic interferograms has then been examined with SRTM-DEM to exclude possible DEM errors. To test the possible atmospheric contribution the cross-comparison of descending co-seismic interferograms generated from different data sets has been performed. Similar patterns have been found in all interferograms and thus this pattern is not related to atmospheric error [11]. The analysis of interferometric processing concluded with the observation that the identified patterns:

- appear in all processed co-seismic interferograms in the same positions
- appear in both ascending and descending co seismic datasets
- do not appear on pre-seismic and post-seismic interferograms

Based on these observations it might be concluded that the identified deformation pattern is directly related to coseismic surface deformation and this is not caused by phase errors due to coregistration, atmosphere, topography or DEM error.

3. DEFORMATION PATTERN ON SAR INTERFEROGRAMS

For further interpretation purposes the interferograms have been geocoded based on SRTM-DEM to UTM projection and then introduced to GRASS GIS database. The co-registration of interferograms with other data has been improved up to 0.5 pixel based on a set of control points of topographic features visible in the SAR intensity images (e.g. roads, airport, river meanders, rocks etc.). As the reference the Landsat7 ETM+ geocoded image acquired 01 Oct 1999 has been used (courtesy of Global Land Cover Facility at Institute for Advanced Computer Studies).

Previously identified deformation patterns have been carefully mapped by visual inspection of the co-seismic interferograms. For detailed analysis two interferograms have been selected characterized by low temporal and geometrical baselines (see Table1) and thus guaranteed highest quality interferograms.

The selected co seismic interferograms contain many fringes due to co-seismic deformation - i.e. strike slip displacement along the subsurface fault labeled here as co-seismic fringes. In certain parts the gentle deformation pattern is disturbed by a set of small-scale linear structures labeled here as linear structures which were the objectives for this study. The interpretation and mapping follows certain detection criteria (Fig.2):

- parts of co-seismic deformation fringes are shifted, interrupted, or discontinuated

- fringe displacement/interruption occurs along a sharp line

- the same linear structures appear in ascending and descending interferograms at the same location.



Fig.2. Example of the linear structures on descending interferogram detected for interpretation

According to these criteria many prominent structures are excluded from interpretation because they appear only in one set of data. Once interpreted and mapped (Fig. 3), the structures have been checked against the geological map of the Bam area and a Landsat ETM+ image to identify whether any structure is present on the geological map or if it can be traced in the Landsat image. If the structure is found on other datasets it means that it reactivated during earthquake.



Fig. 3. Descending (left) and ascending (right) geocoded interferograms subjected to detailed analysis (see Tab.1) and interpreted linear structures.

4. MODELING AND INTERPRETATION OF SURFACE MOVEMENT

Strike slip faults are commonly surrounded by second-order structures that result from the initiation and the propagation of slip along the fault [12,13]. Second order faults and fractures form the so-called fault damage zone around a fault surface. Detailed studies of the damage zone allows the determination oft the type of slip and its conditions [14]. According to standard geological models the second-order structures should also be initiated or activated during a seismic event caused by slip along the main fault. Thus based on highly coherent co-seismic interferograms, it should be possible to indicate which accompanying structures were active during the earthquake. This concept explains the presence of the linear structures in the ASAR interferograms of the Bam earthquake.

To follow this concept the recognized pattern of linear structures has been first tested against the geophysical models, to verify if similar structures could be simulated according to the model of rectangular dislocation in an elastic half space [15]. To make the modeling more realistic the surficial effect of the main strike slip co seismic dislocation of the Bam earthquake with addition of secondary-order faults has been simulated. The parameters of the main earthquake displacement are applied following Funning et al. [8] which explains the deformation by applying two subparalell faults and a single blind fault proposed by Stramondo et al. [7]. The secondary-order structure has been simulated by a small-scale right-lateral surface fault of 2 cm slip and 5 km of maximal depth. The resulting synthetic interferogram (Fig. 4) presents very similar disrupted fringe pattern to real Envisat interferograms (Figs. 4, 2, 3).



Fig. 4. Simulated interferogram of co-seismic deformation and surface faults

5. THE KINEMATICS AND PRELIMINARY 3-DIMENSIONAL MODEL OF BAM STRUCTURE

According to structural models of strike slip faults, the interpreted deformation structures of the Bam earthquake present an association of low-angle R (Riedel) shears and P-shears [12, 16]. The Bam earthquake has no clear evidence of surface dislocation which may directly be associated with the main fault. The location of main strike-slip fault has been deducted based on results of displacement and source parameters studies [6, 7, 8] which identify the main faults as an unknown blind fault extending some 12 km southward from the city. According to all best-fit model solutions this fault terminates 2 km below the surface. The only surface expression of the fault is the en-echelon association of ruptures identified on interferometric coherence maps [17]. In our structural model this en-echelon pattern represents R-type cracks. Assuming a known location of the main fault and secondary-order R and P shears we tried to reconstruct the entire Bam structure in three dimensions. We used classical models of strike slip fault of Naylor et al. [12] which describe the geometrical relation between R shears and single basement fault at depth, where each shear has a helicoidal or 'plough-shape'. This observation is then linked with the model of the development of strike-slip duplexes by Woodcock and Fisher [16] which describes the inward-dipping geometry of so called flower structures.

In case of the Bam earthquake deformation the detected structures were active only during the very short displacement event so the geometry of the stress field associated with the slip is equal to the earthquake focal mechanism. By applying focal mechanisms for analysis of the distribution of damage zones along the main fault it is possible to explain its asymmetry which is related to the location of extension in the NE and SW quadrants and compression in the NW and SE quadrants. According to this model the majority of identified linear structures is located in extension zones and the previously mapped inverse fault SE of Bam in area of compression. Field observations and displacement models [8] confirm that the inverse fault was active during the earthquake as strike-slip with inverse component.

Applying the Woodcock and Fisher [16] flower structure model to the Bam structure, the northeastern damage zone located in an extensional quadrant could be explained as an extensional duplex of negative flower structure ('tulip structure' – Fig.5) where the southern part of the Bam structure fits to the model of contractional duplex representing a positive flower structure ('palm tree structure' – Fig. 5). The presented model of the Bam structure is very general and needs to be studied further in detail. It is also not clear if the detected structures have been created by the earthquake or only reactivated. In the Bam area the deposition rate of growing alluvial fans seems to be much faster than motion along the faults. However, the thickness of alluvial deposits appears to be much smaller north of Bam where the basement volcanic rocks are more often exposed at the surface and thus the tectonical structures are well-developed. The lack of similarly well developed damage zones in the SW extensional quadrant can be explained by the higher thickness of alluvial deposits which resulted that small scale shears were not able to fully penetrate the partially cemented desert pavement.



Fig. 5. Structural interpretation of Bam structure as extensional (a) and contractional (b) flower structures

6. CONCLUSIONS

We presented the activity of second-order structures associated with earthquake slip along the main fault as interpreted from high quality SAR interferograms. SAR interferometry proves its high sensitivity for detection of surface movement along the subtle structures which might be almost undetectable in the field. The detailed interpretation of secondary-order structures may help understand the kinematics, origin, and extent of the entire Bam structure and give contribution for interpretation of its future development. The obtained results might also be useful for evaluation of hazard for e.g. future investment and safety in the area north of Bam and might also contribute to future field research of seismic risk evaluation. The Bam interferograms are beneficial for structural geological analysis because despite of experiments with physical models (sandbox, clay etc.) it has never been observed in nature which secondary order structures were active at the same time.

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All interferograms have been generated using Delft Object-oriented Interferometric Software (DORIS) and data analysis and interpretation has been performed in Geographic Resources Analysis Support System (GRASS).

8. REFERENCES

- 1. Walker R., Jackson J., Active tectonics and late Cenozoic strain distribution in central and eastern Iran. Tectonics 23, TC5010, doi:1029/2003TC001529, 2004.
- 2. Walker R., Jackson J., Offset and evolution of the Gowk fault S.E. Iran: a major intra-continental strike-slip system. Journal of Structural Geology 24, 1677-1698, 2002.
- 3. Walker R., Jackson J., Baker C., Active faulting and seismicity of the Dasht-e-Bayaz region, eastern Iran. Geophys. J. Int. 157, 265-282, 2004.
- 4. Geological Survey of Iran (GSI), Geological Map of Iran scale 1: 100,000 series, sheet 7648-Bam, 1993.
- 5. Fu B., Ninomiya Y., Lei X., Toda S., Awata Y., Mapping active fault associated with the 2003 Mw 6.6 Bam (SE Iran) earthquake with ASTER 3D images. Remote Sensing of Environment 92, 153-157, 2004.
- Talebian M., Fielding E. J. Funning G. J., Ghorashi M., Jackson J., Nazari H., Parsons B., Pristley K., Rosen P. A., Walker R., Wright T. J., The 2003 Bam (Iran) earthquake: Rupture of a blind strike-slip fault, Geophys. Res. Lett., 31, L11611, doi:10.1029/2004GL020058, 2004.
- 7. Stramondo S., Moro M., Tolomei C., Cinti F. R., Doumaz F., InSAR surface displacement field and fault modelling for the 2003 bam earthquake (southeastern Iran). Journal of Geodynamics 40, 347-353, 2005.
- Funning G. J., Parsons B., Wright T., Jackson J. A., Fielding E. J., Surface displacements and source parameters of the 2003 Bam (Iran) earthquake from Envisat advanced synthetic aperture radar imagery., J. Geophys. Res., 110, B09406, doi:101029/2004JB003338, 2005.
- 9. Kampes B., Hanssen R., Perski Z., Radar Interferometry with Public Domain Tools. In: Proceedings of FRINGE 2003, December 1-5, Frascati, Italy, 2003.
- 10. Cebaucer T., Hofierka J., Suri M., Processing digital terrain model by regularized spline with tension: tuning interpolation parameters for different input datasets. Proceedings of the open Source GIS-GRASS conference, Trento, Italy, 2002.
- 11. Hanssen R. F., Radar Interferometry. Data interpretation and error analysis. Kluwer Academic Press 1-308, 2001
- 12. Naylor M. A., Mandl G., Sijpesteijn C. H. K., Fault geometries in basement-induced wrench faulting under different initial stress states. Journal of Structural Geology 8, 737-752, 1986.
- 13. McGrath A. G., Davison I., Damage zone geometry around fault tips. Journal of Structural Geology 17, 1011-1024, 1995.
- 14. Kim Y.-S., Peacock D. C. P., Sanderson D. J., Fault damage zones., Journal of Structural Geology 26, 503-517, 2002.
- 15. Okada Y., Surface deformation due to shear and tensile faults in a half space, Bull. Seismol. Soc. Am., 75(4), 1135-1154, 1985.
- 16. Woodcock N. H., Fischer M., Strike-slip duplexes. Journal of Structural Geology 8, 725-735, 1986.
- Fielding E. J. Talebian M., Rosen P. A., Nazari H., Jackson J. A., Ghorasi M., Walker R., Surface ruptures and building damage of the 2003 Bam, Iran earthquake. J. Geophys. Res., 110, B03302, doi:10.1029/2004JB003299, 2005.