INSAR ANALYSIS OF THE ABSHERON PENINSULA AND NEARBY AREAS, AZERBAIJAN

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Abstract A set of Synthetic Aperture Radar (SAR) data covering the Absheron Peninsula is processed using interferometic synthetic aperture radar (InSAR) to generate a detailed digital elevation map of the region and to measure possible surface deformations. The dataset includes eight ERS-1 and ERS-2 scenes from 1996 though 1999 and images Radarsat images from 1999. The radar has a wavelength of 5.66 cm allowing theoretical resolution along the line of sight to the satellite of surface deformations on the order of mm. Possible causes of surface deformation are earthquakes, mud volcanism, groundwater changes, and hydrocarbon withdrawal. We also use optical satellite images (Advanced Spaceborne Thermal Emission and Reflection - ASTER) and ground truth data. Initial InSAR processing used a digital elevation model (DEM) based on the combination of a global DEM with a high resolution DEM derived from ASTER stereo optical data. This DEM was then refined with radar pairs possessing short temporal baselines. Correlation over the area was fair with moderate to low correlation over a time period of 2 years. Preliminary results show no clear indications (> 10 cm line-of-sight) of large deformation over known mud volcanoes during the periods spanned by the interferograms. Preliminary modeling of likely fluid movement associated with the mud volcanoes indicates that it should be possible to estimate the depth of increased pressure and determine constraints on chamber size using InSAR. Modeling of the two large (M_w 6.8 and 6.5) earthquakes near Baku in November 2000 using global catalog locations and focal mechanisms indicates that the deformation from these events should be observable onshore using InSAR.

Keywords: Azerbaijan,interferometric synthetic aperture radar, mud volcanoes

1. Introduction

The mud volcanoes of the Absheron Peninsula, Azerbaijan are the most spectacular examples of onshore mud volcanism in the world [Jakubov et al., 1971; Hovland et al., 1997]. As well as being fascinating and occasionally dangerous structures, these volcanoes are of interest for the clues they provide to sub-surface fluid flow and stress. In general, sub-surface fluid flow is poorly understood but important in many applications, including hydrocarbon extraction. Mud volcanism can also pose a natural hazard, not only to onshore facilities and people but also to offshore facilities and drilling. With increases in population and urban development in areas of mud volcanism, a better understanding of the mechanics underlying eruptions is needed.

Recent studies based on 3D seismic data [Cooper, 2001] suggest that at least some offshore mud volcanoes in the South Caspian region possess shallow mud chambers which refill prior to eruption. This raises the possibility that inflation of the chamber may produce measurable surface deformation. Similar techniques have been used successfully to detect precursors to magmatic volcanism (e.g. [McGuire et al., 1995]). Some data from leveling lines also supports deformations related to mud volcanism [Sinelnikov and Svistun, 1980] Recently, interferometric synthetic aperture radar (InSAR) has been used to monitor magmatic volcanoes. In this work we explore the use of InSAR for investigating onshore mud volcanism and in particular the potential for monitoring subtle changes due to sub-surface fluid flow.

2. Method

InSAR relies on measuring the phase difference between two (or more) images from satellite based radar to construct an image of the surface deformation between satellite passes. It provides very accurate measurements (mm scale resolution with pixel size on the order of 10's of m) of the relative surface deformation over a wide area (typical scenes are 100 km square). The exact measurement is along the satellite line-of sight, which for the ERS satellites is at an average (scene center) angle of 23^o. Consequently, the technique is most sensitive to vertical motion. The method has been used successfully to image a wide range of deformations including those due to earthquakes, groundwater extraction, and volcanic activity (see [Hanssen, 2001] or [Burgmann et al., 2000] for a review).

However, limitations exist with InSAR data. These limitations include limited data coverage, decorrelation, and artifacts due to topography or atmospheric propagation. For the South Caspian region, perhaps the most substantial difficulty is the limited data. Only a few radar scenes suitable for interferometry currently exist, which make a thorough data analysis difficult. However, sufficient data does exist to assess the potential use. Another difficulty is decorrelation, which refers to the loss of phase stability between pixels and can be caused by surface slope or changes in the ground surface. Decorrelation increases with time but the rate of temporal decorrelation varies greatly from region to region [Zebker and Villasenor, 1992]. Urban areas tend to retain correlation well while vegetated areas rapidly decorrelate. Surface topography also creates a phase change between images that depends on the distance between the satellites (baseline) at the time of imaging and which requires an accurate knowledge of the topography to remove. Excessive topography also creates features such as layover or shadowing due to the radar imaging geometry. In general, these effects are best compensated for with the use of an accurate digital elevation model. Another potential difficulty is phase changes due to variations in atmospheric water content, either laterally or vertically in combination with topography [Delacourt et al., 1998; Hanssen, 2001], which can easily distort observed signals [Rigo and Massonnet, 1999]. The proximity to the Caspian Sea suggests that such effects could easily occur and create substantial gradients in atmospheric water vapor. Groundwater or extraction of hydrocarbons changes can also cause surface elevation changes [Bawden et al., 2001; Galloway et al., 1998]. The best way to identify and compensate for these possible artifacts is through use of multiple data sets over the same area.

Modeling of possible deformation. A crude estimate of the expected deformation prior to an eruption can be made by assuming a spherical pressure source embedded in a homogenous half-space [Mogi, 1958]. The depth of the chamber must be much greater than the radius. Figure 1 shows the amount of vertical deformation expected from a sphere with radius of 250 m and a pressure change equivalent to 82,000 m^3 at depths of 3 km and 1 km. This roughly corresponds to the amount of mud expelled from the recent eruption of Lokbatan. Larger quantities have been recorded during other eruptions [Jakubov et al., 1971]. This should be considered as a lower bound, as it does not include the large quanities of gas that escape.

Consequently, any measured deformation can be used to place constraints on the depth, size, and shape of the chamber (and pressure change). Shallow chambers produce a high amplitude signal while deeper chambers will produce a longer wavelength but low amplitude signal.

Remote sensing data. A suite of radar imagery as well as selected optical imagery was collected (Table 1). The optical data was from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite, which has a resolution of 15 meters at optical and near-infrared wavelengths [Abrams et al., 2001]. The ASTER satellite also collects stereo pairs, which are useful for the construction of elevation models. The DEM had a nominal resolution of 30 m.

For optimal use in interferometry, the two pairs of radar images should be within several hundred meters of each other in the respective orbits, which

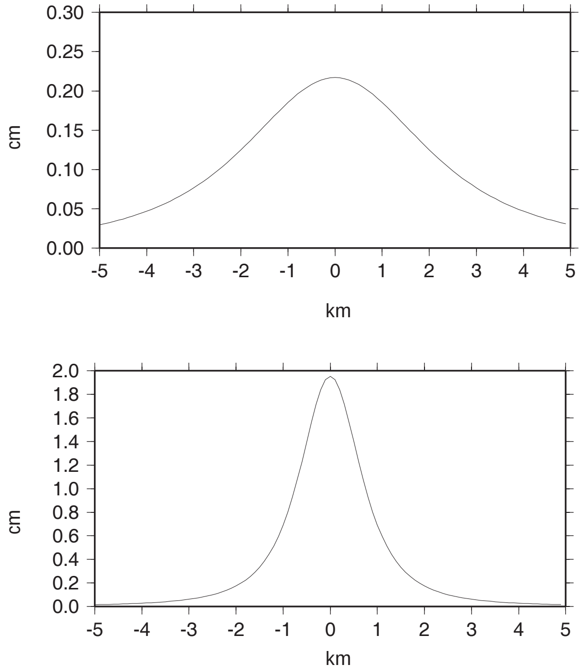

Figure 1. Cross-sections of expected deformation assuming a spherical pressure source with a radius of 250 m at a depth of 1 and 3 km. A pressure change equivalent to a volume change of 82,000 m^3 is used.

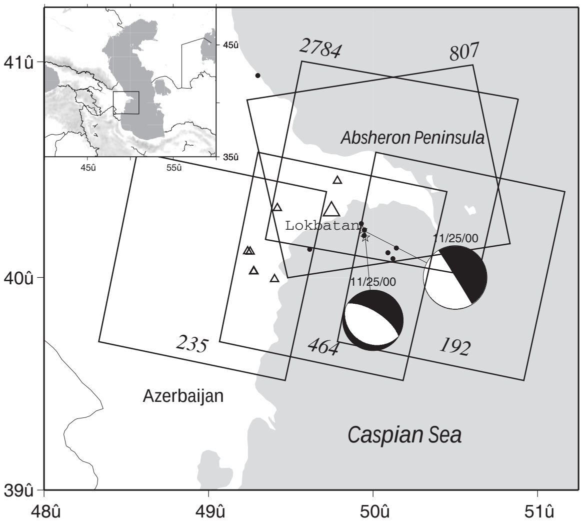

Figure 2. Map of data showing locations of radar scenes and focal mechanisms and locations of November 2000 events.

places considerable constraints on the available data (Table 1). Data from both the ERS and Radarsat satellites was collected. The general procedure used the pairs with longer spatial baselines but shorter temporal span to generate the topographic corrections. Pairs with short baselines were used to observe deformation.

Table 1. Radar data used in this study. The radar data shows the pairs and baselines. Pairs marked with an asterisk were used to generate DEMs.

Sat.	*Track*	*Frame*	*Date 1*	*Sat.*	*Date 2*	*Perp. Base.*	*Days*	*Corr.*
ERS-1	192	2781	1996/05/12	ERS-2	1996/05/13	-156	1	good
ERS-2	192	2781	1996/05/12	ERS-2	1998/10/05	124	876	poor
ERS-2	192	2781	1998/10/05	ERS-2	2000/12/18	-217	805	poor
ERS-2	464	2799	1998/08/15	ERS-2	1999/03/15	36	210	good
ERS-1	235	2799	1998/08/15	ERS-2	1999/05/16	-528	934	poor
ERS-2	235	2799	1996/05/16	ERS-2	1999/05/06	234	1120	poor
ERS-2	235	2799	1996/05/16	ERS-2	1999/06/10	-137	970	poor
ERS-2	235	2799	1996/05/06	ERS-2	1999/06/10	-378	35	good
RSAT	807	26083	2000/10/09	RSAT1	2000/11/02	63	24	good
RSAT	2784	25690	2000/10/06	RSAT1	2000/10/30	488	24	poor

Track 192. This track covered the Absheron Peninsula and provided the only data that spanned the earthquakes of 25 November 2000. A pair of scenes with a time gap of 1 day (tandem pair) was available for elevation correction, which is minimal for the relatively flat peninsula. Unfortunately the data had relatively poor correlation due to a relatively long time span and does not cover many mud volcanoes. Nevertheless, fringes possibly due to the earthquakes of 25 November 2000 are apparent on the pair spanning October 1998 to December 2000.

Track 235/464. These scenes cover the Absheron Peninsula as well as much of the coast south of Baku. Similar to Track 192, the length of time covered make deformation determinations difficult but is excellent for elevation models. Track 464 has only one pair but with a short baseline and spans 210 days.

Track 807/ 2784. These data were recorded by the Radarsat satellite in October 2000 and covered only a short time period (24 days) immediately prior to the earthquakes. No obvious signs of deformation are visible. Track 807 has a short baseline (67 m) and therefore well suited to measure deformation. Track 2784 had a much longer baseline and showed considerable decorrelation.

3. Results

The combination of the various data sets has allowed the construction of a DEM, which is a necessary first step. The DEMs have been compared with

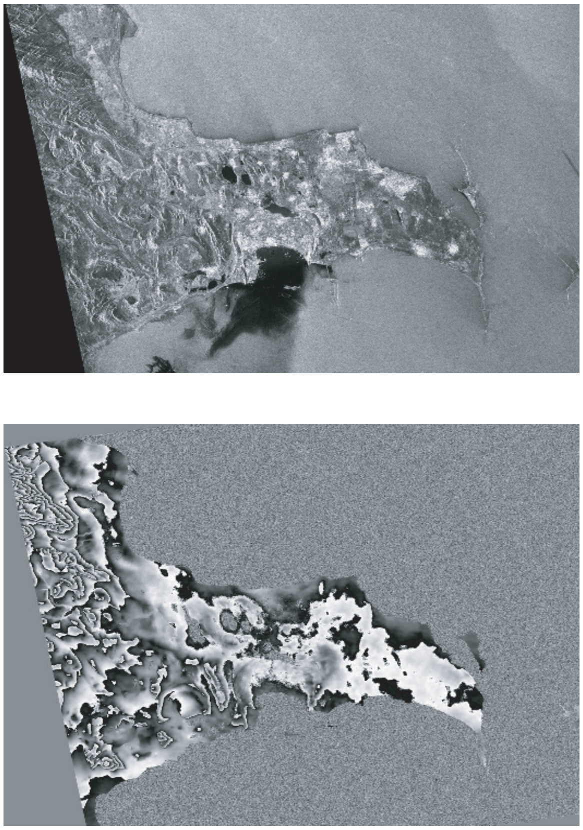

Figure 3. Examples of amplitude (top) and phase data (bottom) for radarsat (track 807).

topographic maps and with independently derived topography (Figure 1). Correlation is fair and appears to be retained for up to roughly two years, with isolated patches of longer-term coherence in urban areas. The offshore platforms also retain coherence, which allows the potential for limited measurement offshore as well.

Nov. 25, 2000 earthquakes. On November 25, 2000 two large (M_w 6.8 and 6.5) earthquakes occurred within minutes of each other offshore Baku. One pair (track 192 1998-2000) spanned the time of the events. Although coherence was low, some fringes were observed on the Absheron Peninsula although it is possible that these may be contaminated by orbital or atmospheric errors.

Due to the poor coverage and multiple number of events, it was impossible to determine a seismic mechanism from the InSAR data alone. However the InSAR does serve to place constraints on the depth and location.

Modeling was performed to estimate the amount of expected surface deformation using the available seismic data (Figure 4). The modeling was per-

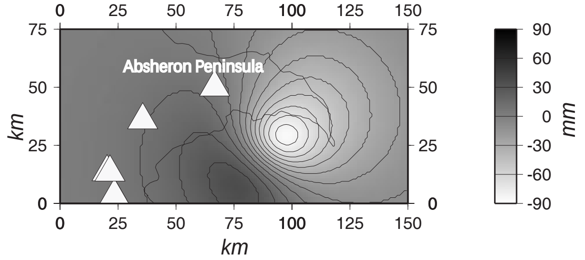

Figure 4. Model of estimated deformation from the November 2000 earthquakes. A finite fault in an elastic half-space is assumed, with slip scaled to fault dimensions. Focal mechanism is from Harvard CMT (e.g. [Dziewonski and Woodhouse, 1983]) with depth and location from the ISC [ISC, 2001].

formed using a finite fault in an elastic half space [Okada,1995], as implemented by [Fiegl and Dupre, 1999]. Fault size was scaled to the moment and slip scaled to length using standard relationships. The fault was assumed to be square. This model predicted a high spatial deformation along the south side of the Absheron Peninsula, which was not observed. Therefore the model was revised to use a deeper depth that was consistent with the body-wave solution. Even increasing the depth to 50 km still predicted more fringes than observed, and it may be that the ISC (global) location is in error. Shifting the location farther offshore would help resolve the differecnes.

Mud volcanoes. Observation of mud volcanoes has been focused on the area around Lokbatan due to the possibility of observing deformation prior to the 2001 eruption (Figure 3). No large-scale movement is observed so far but work is still in progress.

Conclusions and future work. Preliminary results suggest that InSAR is feasible for longterm monitoring of mud volcano activity but more work needs to done on estimating errors. Coherence in the area is good for periods of up to two years at the wavelengths used for the ERS and Radarsat satellites (5.66 cm). The data was suitable to construct a good quality DEM, which will be useful for future analysis and monitoring. No clear signals have been observed yet associated with the mud volcanoes however fringes representing deformation from the November 2000 earthquake may be visible on pairs spanning the time of the earthquake. Coherence is fairly good for up to two years and longer in urban areas.

To reduce the error, two suggestions are made. Combining InSAR with GPS monitoring would enhance the results of both, as has been shown in other areas [Bawden et al., 2001]. While GPS is spatially limited to a few points, it is relatively immune to variations in atmospheric water vapor due to the use of two wavelengths. The GPS sites could also be used to identify fixed points with known elevations for use in orbital corrections. In additional, the collection of a long series of InSAR data is possible with the new Envisat satellite which would be highly useful. This would allow careful monitoring of the possible signals.

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