**InSAR maps and time series observations of surface displacements of rock salt extruded near Garmsar, northern Iran**

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**Abstract:** A large allochthonous sheet of Eocene rock salt is forming the Eyvanekey plateau west of Garmsar along the northern periphery of the Great Kavir basin. This salt extruded over the central plains of Iran, where the southward advancing front of the Alborz Mountains is offset by the NE–SW-trending Zirab–Garmsar strike-slip fault. Based on nine descending Advanced Synthetic Aperture Radar images, produced by the European Space Agency’s ENVISAT satellite from 2003 to 2006, we used interferograms to map the displacement over 22 increments ranging in time from 2 to 18 months. To study the surface deformation at high temporal and spatial resolution, a small subset of interferograms was used to map the mean velocity of surface deformation. The results suggest that the top of the salt is subsiding continuously at rates that depend on the season. The surface displacement rate throughout the region ranges from subsidence of −40 to −50 mm a−1 to uplift of 20 mm a−1. The agricultural lowlands, where groundwater extraction for irrigation exceeds recharge, are subsiding faster than the salt sheet. Correlation of surface displacements with active folds and seismic faults around the salt sheet also suggests that the study area is undergoing active deformation.

**Supplementary material:** Interferogram for the period 19.08.2003–14.02.2006 is available at http://www.geolsoc.org.uk/SUP18383.

The deserts of Iran are suitable natural laboratories for studying hundreds of subaerial salt extrusions that are usually submarine or subsurface elsewhere (Talbot 1998). The c. 200 salt extrusions emergent in the Zagros Mountains are of Infracambrian to Cambrian age (Hormoz salt). The other extrusions of the central plateau of Iran in the fore-deep of the Alborz Mountains consist of Early Oligocene to Miocene salt. Most Iranian salt extrusions, both Hormoz and Tertiary, can be considered as natural models of diapirs that extrude nappe piles consisting of normal upper crustal rocks. The shape of these diapirs is controlled by the rate of extrusion, lateral spreading, and rate of erosion.

Unlike most Iranian salt extrusions that probably gravity-spread for tens or hundreds of millennia from diapirs that reach the surface along faults (Talbot et al. 2000), the salt sheet that underlies the 20 km × 10 km × 0.32 km area of the Eyvanekey plateau differs in having been squeezed to the surface as the Alborz mountain front advanced southward over the Garmsar basin. In recent reviews this body of rock salt has been referred to as the Garmsar salt nappe and quoted as an example of a sheet of allochthonous salt that extruded along a mountain front before undergoing open-toed advance (Hudec & Jackson 2006, 2007). The main aim of the present study was to check whether this mountain front and its associated salt extrusions are still active.

Extrusion and dissolution rates of Hormoz salt have been constrained by analytical (Wenkert 1979; Talbot & Jarvis 1984) and numerical modelling (Talbot et al. 2000), and by repeated direct ground measurements of markers fixed on the salt (Talbot & Rogers 1980; Talbot et al. 2000; Bruthans et al. 2006, 2007). Similar studies of extrusions of Tertiary salt are more limited. Safaei (2001) related large elastic strain, measured on southward facing salt faces in the Garmsar hills, to contemporaneous temperature changes via the thermal expansion of dry salt. Talbot & Aftabi (2004) investigated strain of an extrusion near the city of Qom, and Talbot (2000, 2004) and Schleder & Urai (2007) described some of the structures and microfabrics that help to explain strain softening of the salt in the Eyvanekey plateau. All of these ground measurements, however, monitor surface strain only at particular points on single salt bodies.

Recent improvements in interferometry of synthetic aperture radar (SAR) images have reached the stage where the surface strain over the entire bodies of the Iranian salt extrusions can be routinely and remotely mapped and monitored. Weinberger et al. (2006a,b) used time series interferograms, checked by precise ground levelling, to demonstrate that different parts of the top of Mount Sedom in Israel rose at steady rates between 5 and 9 mm a−1 since its top was truncated by a precursor to the Dead Sea at 14 ka.

InSAR (SAR interferometry) uses the phase difference between two SAR images of the same area acquired at different times to map either a digital elevation model (DEM) for the area or its surface displacement in the line of sight (LOS) of the satellite. For this study, data for the salt extrusions north and west of Garmsar (Fig. 1) were collected by the European Space Agency’s Environmental Satellite ENVISAT, which imaged the area between December 2003 and June 2005.

We analysed nine ASAR (Advanced Synthetic Aperture Radar) images spanning these 18 months to characterize the surface displacements for the area indicated in Figure 1 before using 22 interferograms for more detailed analyses of the deformation over distinct time intervals and finally using time
series data to calculate the rates of LOS surface deformation of localities representative of different geological units.

**Geological background**

Diapirs of Tertiary salt are forming topographic highs in the Great Kavir basin and in several of its sub-basins such as Qom, and the Garmsar basin. Tertiary salt dissolved from these topographic highs collects as brines in downslope topographic lows where it is often reprecipitated as modern salt.

The Garmsar basin (Figs 1 and 2) is one of a series of basins in the foredeep of the Alborz Mountains forming an embayment in the northern periphery of the Great Kavir basin, from which it is separated by the Kuh-e-Gachab and Dulasian swell (Fig. 3b). The oldest Tertiary strata in the region are marine Eocene sediments associated with volcanic rocks resting unconformably on folded Mesozoic strata. The initial thickness of the evaporite-bearing sequence is not clear because of its strong subsequent distortion but probably exceeded 8000 m (Jackson et al. 1990).

The age of the evaporitic sequence is unclear because of the lack of fossils. However, lithological similarities to rocks from Qom Kuh and the diapirs in the Great Kavir basin (Jackson et al. 1990) suggest that the Garmsar rocks include evaporites of both late Eocene and Oligocene age.

Some salt in the Garmsar basin could still be in place beneath the Mesozoic rocks in the deformation front of the Alborz Mountains. Other salt strata were extruded to the surface in the form of small diapirs along faults in the foothills without significant spreading over the surface (Safaei 2001; Fig. 1). However, it is likely that most of the salt overridden by the southward advance of the Alborz deformation front was expelled over recent sediments of the Great Kavir basin (Figs 1 and 3) to the south and/or west. This salt is now present as a huge sheet of allochthonous salt that forms what we will call here the Eyvanekey plateau (Figs 1 and 3c). Smaller extrusions of salt in the hills north of Garmsar mark where the Alborz deformation front is offset about 9 km by the 130 km long SW–NE-trending Zirab–Garmsar dextral fault. The latter is not a pure strike-slip but a transtensional fault.

The overridden salt is overlain by a mechanically significant roof, rafts of which are detached from the leading edge of the roof behind the extrusive toe. Huge rafts of the Alborz Mountains collapsed southward into the salt, whereas others were carried several kilometres southward along transfer strike-slip faults, or were rotated about steep axes. Given that the salt in the Eyvanekey plateau, situated west of Garmsar, was initially extruded southward from the line of diapirs emergent in the hills along the southern edge of the Alborz north of Garmsar, the Eyvanekey plateau might have been dextrally displaced for c. 9 km along the Zirab–Garmsar fault to its current position (Fig. 2). Whether the Zirab–Garmsar fault is still active will be constrained by future global positioning system (GPS) studies.

The Eyvanekey plateau rises above the surrounding irrigated farmlands (Fig. 3), and the smaller Garmsar salt extrusions fringing the Alborz front consist predominantly of salt and gypsum rock with subordinate marl, calcareous marl, shale and sandstone, together with inclusions of mafic volcanic rocks.

The present surface of the plateau is barren and the salt is covered by several metres of residual insoluble soils after dissolution of the salt by rain (Talbot 2004); most of these are light green to pale brown gypsum with subordinate marl and calcareous marl (Amini & Rashid 2005).

Natural outcrops of salt are rare, but halite is accessible in many salt quarries and a few mines, most of which were opened in the last 10 years. Most of the salt is white and fine grained with a strong subhorizontal mylonitic foliation (Schleder & Urai 2007) but some is red and some has been subjected to what looks like static grain growth. The bedding in the salt sheets is generally subhorizontal but displays refolded recumbent folds exposed in steep north–south- and west–east-trending quarry faces (Fig. 4a and b). The fine-grained salt is mechanically very weak (Schleder & Urai 2007) but it is unknown whether any of the salt in Garmsar is still moving today (Talbot 2000).

**Methods of study**

Interferometric analyses of SAR images have become a widespread, valuable technique to measure subtle displacements of the ground surface (e.g. Massonnet & Feigl 1998). When two radar images are made at different times from the same viewing window, the images are degraded by systematic and random factors due to the sensors, sea states, atmospheric conditions, and other factors. These factors have a strong effect on the coherence of the images and hence the interferometric analysis.
angle, a small change in the position of the target (ground surface) may create a detectable change in the phase of the backscattered signals. This difference of phase is expressed in an interference map (interferogram). The resulting fringe pattern reflects the ground displacement that occurred between the two acquisitions, and the product is referred to as a ‘change interferogram’. Rather than using the primary data to generate our own DEM, we used the DEM provided by the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 90 m.

For the ENVISAT SAR satellite each fringe or colour cycle in a change interferogram corresponds to a map contour of displacement equivalent to half the radar wavelength. The mean incidence angle of this satellite is 25°. Thus, in the case of pure vertical movement, one fringe cycle represents 31.4 mm of displacement.

The phase change in the interferogram is the sum of topographic information, \( \phi_{\text{topo}} \), surface displacement between the two acquisitions, \( \phi_{\text{disp}} \), atmospheric delay, \( \phi_{\text{delay}} \), and noise, \( \phi_{\text{noise}} \):

\[
\phi = \phi_{\text{topo}} + \phi_{\text{disp}} + \phi_{\text{delay}} + \phi_{\text{noise}}.
\]

Successful InSAR generation requires the removal of the topographic phase contribution so as to isolate the ground displacement component. \( \phi_{\text{topo}} \) can be simulated and eliminated by introducing DEM information. The atmospheric component, \( \phi_{\text{delay}} \), is primarily due to fluctuations of water content in the atmosphere between the satellite and the ground. The atmospheric delay can be identified using the fact that the fringe structure is independent over several interferograms; alternatively, it can be modelled by using data from a GPS network. It is also possible to reduce the atmospheric disturbance to the displacement phase term by using the ‘interferogram stacking technique’. The atmospheric effect can be estimated by plotting the phase against the height for each pixel; it is strong if there is a good correlation between height and phase. Maps displaying the mean displacement velocity were produced using MATLAB software.

**Data**

The data for the present study were collected by the European Space Agency (ESA) Environmental Satellite ENVISAT, which imaged the study area between December 2003 and June 2005. The normal orbital cycle for this satellite is 35 days. To check if any surface displacement is recognizable in the study area, we constructed a preliminary interferogram using two descending ENVISAT images acquired in August 2003 and February 2006. This interferogram shows large areas of coherent signal on the bedrock and salt and some fringes on the margins of the salt sheet, thus encouraging further detailed investigations.

Subsequently we acquired nine descending images from the ESA (Table 1 and Fig. 5) and generated change interferograms for different periods that vary between 2 and 18 months between 2003 and 2005 (Fig. 6). As listed in Table 2, we generated 22 differential interferograms from the ESA data using GAMMA software (supplied by the Remote Sensing Group, Geological...
Fig. 3. Simplified regional setting of Garmsar hills, Eyvankey plateau and surroundings. (a) Regional location map. (b) Tertiary evaporites on the surface in the Garmsar and Great Kavir basins (Jackson et al. 1990). (c) Simplified geological setting of Garmsar hills and Eyvankey plateau after geological map of Amini & Rashid (2005). (d) Lithostratigraphic column of the Garmsar basin after Jackson et al. (1990). The Eocene–Oligocene rock salt is the main source for the extrusions of the Garmsar salt nappe and the diapirs in the hills to the north of the Garmsar NE–SW cross-section. The latter cuts through the Garmsar salt nappe as shown in (c) (modified after Amini & Rashid 2005).
The effect of topography was removed from each interferogram using the DEM with a spatial resolution of 90 m provided by the SRTM. The InSAR technique maps surface deformation along the LOS of the ENVISAT satellite.

Most of the surface displacement plotted in Figure 8 can be assumed to be near vertical. Constructing interferograms for neighbouring pairs in a series of acquisitions for the same area produces a time series of the surface deformation rate over the entire deformed area.

Results

One of our interferograms shows colour fringes on the steep slopes of the margins of the small salt extrusion in the Garmsar hills and around the large salt sheet beneath the Eyvanekey plateau (see the Supplementary Material). These fringes indicate a rate of surface displacement of the western margin of this salt body of c. 1 cm a\(^{-1}\). More detailed information on the displacement rate results from interferograms spanning shorter increments than 12 months. Twenty-two interferograms were prepared and analysed for each pair of images for 22 epochs listed in Table 2, which ranged in length from 2 to 18 months.

Because the topographic phase has been removed from these flattened interferograms, the colours record mainly the surface deformation in the near-vertical satellite LOS. Areas undergoing subsidence during this period are indicated by warmer colours. Such sinking areas are present in all interferograms, but with different magnitudes of displacement. NE–SW- and NW–SE-
trending profiles were prepared to show the rate of fluctuation of the surface displacement inside the extruded salt and its surroundings (Figs 6 and 7).

To highlight the major deformation features and relate variations in the LOS surface displacement rates to seasonal parameters, such as temperature and amount of precipitation, as well as seismic data, maps of the mean displacement velocity (Fig. 8) were produced for four of the interferograms chosen from the 22 periods. The mean displacement velocity is plotted against the distance along the NE–SW- and NW–SE-trending profiles, respectively (Fig. 9; for location of the profiles see Fig. 8). Most of the time series data suggest that subsidence increases continuously from the top of the salt sheet downslope toward the agricultural lowlands. Most of this subsidence can probably be attributed to salt dissolution by the annual rainfall, the latter being in the range of c. 100 mm a⁻¹. The spatial changes in the magnitude of subsidence and subsidence rate might be controlled by the distribution of agricultural wells, the degree of mining activity in the margin of the salt glacier (Fig. 4c) and the presence of mechanical weak planes such as faults and fractures.

Fig. 5. Eighteen points (images) were acquired in the first search for overlapped images in Track 106 descending images, so nine points (images) have a good relation on temporal and perpendicular baselines (the curve shows the relations of perpendicular and temporal baselines of nine descending radar images).

Fig. 6. Four representative differential interferograms chosen from the 22 interferograms to show seasonal impacts on topography. The date of each interferogram is indicated. Scaling of colour bars is in centimetres.
Discussion

InSAR provides continuous maps of the surface displacement rather than displacements at a few discrete points as are usually obtained by precise ground measurements. The two orbital tracks of the satellite have to be within a few hundred metres for the signal to preserve coherence. This limits the number of interferograms that can be produced from satellite image pairs. Changes in the orbital geometry of the two acquisitions probably generally degrade the coherence in interferograms generated with longer baselines.

In the present study only 22 interferograms are considered, which have been processed from the nine image pairs out of the potential 36 pairs generated by the ENVISAT satellite from 2003 to 2005 (Fig. 5). Local loss of coherence in the interferograms may be related to vegetation, sudden changes in ground conditions such as those caused by cultivation or changes in near-surface water, or slope instability.

Along the LOS the surface displacement in each interferogram, shown in Figure 6, ranges from several millimetres to centimetres. Below we discuss some of the factors that may control the surface deformation of the salt extrusion and the surroundings, which include both barren areas and farmlands.

Fig. 7. Fluctuation in vertical height along profiles indicated in the differential interferograms shown in Figure 6.

Local uplift rates of c. 10 mm a\(^{-1}\) are compatible with the rate of 10 mm a\(^{-1}\) measured for the uplift of the central Alborz Mountains in GPS studies (Masson et al. 2002). It has to be emphasized that Masson et al. (2002) expected this rise to occur along major faults, whereas our work indicates that movement in the Garmsar area is dispersed among many minor faults but is mainly related to folding. Rather than swelling by further extrusion of salt from deeper structural levels, or degrading by dissolution, the Garmsar salt nappe appears to be affected by folding, which is related to north–south shortening.

Given that shortening rates are between 1 and 11 mm a\(^{-1}\), anticlines above a detachment should rise at rates of 10 mm a\(^{-1}\) whereas synclines should subside at rates greater than c. 3.3 mm a\(^{-1}\) (Vita-Finzi 1986, p. 139). These values are broadly consistent with the 8 ± 2 mm a\(^{-1}\) north–south shortening rate across the central Alborz as indicated by GPS studies (Vernant et al. 2004b). The GPS data further show that recent deformation seems to extend southwards beyond the piedmont area. InSAR cannot be used to constrain the sinistral shear along the range-parallel strike-slip faults inside the belt. The rate of this strike-slip has been determined at 4 ± 2 mm a\(^{-1}\) (Vernant et al. 2004a).
Seasonal effects on surface displacement

Garmsar is the largest town in the study area. It is situated at c. 825 m above sea level on the northern edge of Dasht-e Kavir, which is the largest desert on the central plateau of Iran. Garmsar means ‘hot place’ in Farsi and the climate is characteristically dry and cloudless throughout the year with minimal rainfall (e.g. 100 mm a⁻¹) and temperatures ranging from −10 °C in winter to 40 °C in late summer. The farmlands on the plains overlooked by the Eyvanekey plateau and to the south of Garmsar are cultivated by extraction of groundwater, particularly in spring and summer. Four change interferograms for periods between 2 and 18 months were chosen from the 22 interferograms to constrain the impact of seasonal parameters on the surface displacement rates. Surface LOS displacement rates on these four interferograms were plotted along NE–SW and NW–SE profiles, respectively along and across the likely transport direction of the salt in the Eyvanekey plateau (Fig. 6).

It is obvious that in the period from 5 March to 14 June, the uplift rate increased from NE to SW along the extruded salt sheet of the profile (Fig. 7a). However, although InSAR observations show that large sections of the salt in the NE Garmsar hills subsided (c. −2 cm), the distal SW margin of the plateau was lifted up as much as 2 cm.

The NE–SW profile along the Eyvanekey salt sheet indicates that the surface of its NE edge in the Garmsar hills subsided at −2 cm (Fig. 7a). This subsidence in the salt extrusion zone diminishes to the SW, where the salt surface increasingly rose, reaching a value of c. 1.5 cm at its distal southern edge.

The NW–SE profile across the Eyvanekey salt sheet shows a small rise (0.2 cm) in its centre that falls off to c. −1 cm at its margins (Fig. 7b). This profile fits the dimensionless profile for a

| Image identification | Epoch date | Perpendicular baseline (m) | Temporal baseline (days) |
|----------------------|------------|----------------------------|--------------------------|
| A                    | 02 12 2003 to 10 02 2004 | 46                         | 70                       |
| B                    | 02 12 2003 to 29 06 2004 | 674                        | 210                      |
| C                    | 02 12 2003 to 03 08 2004 | 154                        | 245                      |
| D                    | 02 12 2003 to 16 11 2004 | 288                        | 350                      |
| E                    | 02 12 2003 to 21 12 2004 | 90                         | 385                      |
| F                    | 03 08 2004 to 29 06 2004 | 828                        | 35                       |
| G                    | 03 08 2004 to 16 11 2004 | 442                        | 105                      |
| H                    | 03 08 2004 to 21 12 2004 | 244                        | 140                      |
| I                    | 03 08 2004 to 01 03 2005 | 100                        | 210                      |
| J                    | 16 11 2004 to 21 12 2004 | 198                        | 35                       |
| K                    | 10 02 2004 to 21 12 2004 | 44                         | 315                      |
| L                    | 10 02 2004 to 01 03 2005 | 100                        | 385                      |
| M                    | 29 06 2004 to 16 11 2004 | 290                        | 140                      |
| N                    | 29 06 2004 to 21 12 2004 | 584                        | 175                      |
| O                    | 16 11 2004 to 05 04 2005 | 91                         | 140                      |
| P                    | 21 12 2004 to 14 06 2005 | 135                        | 175                      |
| Q                    | 01 03 2005 to 16 11 2004 | 342                        | 105                      |
| R                    | 01 03 2005 to 21 12 2004 | 144                        | 70                       |
| S                    | 01 03 2005 to 05 04 2005 | 433                        | 35                       |
| T                    | 01 03 2005 to 14 06 2005 | 5                          | 105                      |
| U                    | 05 04 2005 to 21 12 2004 | 289                        | 105                      |
| V                    | 05 04 2005 to 14 06 2005 | 428                        | 70                       |
viscous droplet spreading under gravity seen in former salt fountains in the Zagros mountains (Figs 6 and 7; see also Talbot 1998, fig. 3) The agricultural lands adjoining the NW margin of the Eyvanekey plateau and south of Garmsar subsided as much as 3 cm. Putting these two profiles together suggests that salt may have risen into the head of the Eyvanekey salt sheet and flowed to the SW, and spread under gravity away from a NE–SW axis.

The NW–SE profile across the salt sheet for 105 days, from 3 August to 16 November, indicates that these trends are reversed (Fig. 7c). Both the salt sheet and farmlands subsided c. 4 cm, whereas the top of the salt plateau subsided only c. 0.5 cm.

The equivalent NE–SW profile (Fig. 7d) for the period from 29 June to 16 November reveals changes in rising and sinking from the highest part of the salt sheet in the north toward the central parts of the salt sheet. Moreover, it shows a rise of up to 2 cm in the steepest slopes above the southern margin whereas the surrounding agricultural lands subsided more than 5 cm.

The NE–SW- and NW–SE-trending profiles shown in Figure 7 have similar shapes but different ranges. The depth to the groundwater table is likely to be close to stable over the winter when the farmers have no need to extract ground water. On the other hand, there was no subsidence in winter. The head of the salt sheet in the SW subsided relative to that in the NE (Fig. 7e).

Structural effects on the deformation mechanisms

The southern prolongation of the Zirab–Garmsar strike-slip fault cuts through the Eyvanekey salt sheet extruded over the central Iranian plateau (Fig. 2). The surface traces of many minor faults that are subparallel to this major fault are shown in Figure 8. The pattern suggests local disturbance along such minor faults, which is obvious, for example, along the southeastern edge of the salt plateau (Figs 8 and 9). The lineaments correlate well with active faults; the epicentres of earthquakes recorded from 2003 to 2006 (m_b = 2 and 3) are also shown in Figure 8. These faults, however, may separate distinct units with different mechanical properties, so that the differential surface deformation (e.g. of the salt compared with the surrounding plain) may record differential dissolution, thermal expansion, gravity flow, etc.

Some of the most obvious lineaments on the interferograms correlate well with the margins of the salt sheet beneath the Eyvanekey plateau. These lineaments may reflect localized dissolution or downslope flow of rock salt along the steep salt margins (Figs 8 and 9).

InSAR time series observations

The interferograms record the incremental ground deformation between their acquisition dates. It is possible to produce a time series of the total surface displacement in the LOS between the starting time and each acquisition date.

As there are as many linearly independent interferograms as acquisition dates in an unbroken chain in our study, it is possible to use a least-squares inversion to map or obtain the surface deformation for each time covered by the data (Berardino 2002; Biggs & Wright 2004). The resulting mean displacement velocity map and plots (Figs 9 and 10) indicate that the surface of the

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![Image](image-url)
Eyvanekey plateau and of the surrounding agricultural lowlands subsided continuously from 2003 to 2006. The maximum surface deformation rate is estimated to have been near 20 mm a\(^{-1}\) in farmlands and 5 mm a\(^{-1}\) in the centre of the sheet of allochthonous salt.

As shown by small dots in Figure 8, a large number of water wells are used to irrigate the farmlands to the west and east of the Eyvanekey plateau, particularly in the spring and summer. We found 503 wells in the west and 181 wells in the east (some dots are outside the study area). There is an obvious correlation between these wells and the area of maximum subsidence near Garmser east of the plateau and some of the wells west of the plateau (Figs 8 and 9), suggesting that the surface subsides where the water table is significantly lowered by water extraction. Wells that cluster in areas of maximum subsidence appear to be over-exploiting the available groundwater. Wells in areas undergoing less subsidence may be fed more efficiently by water draining from the Alborz.

The graphs in Figure 10 indicate that the subsidence rate is high along the eastern margin of the salt sheet and increased continuously from 2003 to 2006. This observation could be related to downward flow of the salt along the steep eastern margin, where it was undergoing dissolution, or brittle downslope sliding could be aided by daily elastic thermal strains and by the spoil heaps of the 20 active quarries situated along this margin.

On the other hand, Figure 10 shows unsteady surface displacement along the southern margin of the salt sheet. Two points underwent a sharp decrease in subsidence rate from the beginning to the middle of 2004 followed by a steady increase to the middle of 2005, after which the decrease slowed again. We attribute this observation of enhanced subsidence to fluid-controlled strain softening of rock salt by increasing the rates of dissolution–precipitation in winter when the salt is wet. The opposite case occurs in summer when the salt is dry and thus much stronger.

**Conclusion**

The results of the present study demonstrate the capability of InSAR to monitor displacements of the ground surface on a regional scale. InSAR measurements were used to map and calculate the rates of near-vertical displacement in the Garmser area. Nine ASAR images acquired during 2003–2005 were used to identify the main areas of subsidence and uplift in this area.

These interferograms show organized phase differences as colour fringe patterns for epochs ranging in time from 2 to 18 months. The surface displacement rate throughout the region ranges from subsidence of −40 to −50 mm a\(^{-1}\) to uplift of 20 mm a\(^{-1}\).

The most obvious seasonal effects are that the farmlands around the Eyvanekey plateau subside rapidly in spring and summer when they are irrigated by the extraction of groundwater that is not replenished at the same rate. The surface of the Eyvanekey plateau subsides at the beginning of each year and then recovers throughout the remainder of the year. We attribute this to the water table falling as a result of extracting groundwater for irrigation.

The uplift rate is faster in the southern part of the Eyvanekey plateau than in more northern areas, whereas the steep margins of the Eyvanekey plateau subside rapidly. Subsidence increases locally along seismically active faults in the plains that are thought to control fluid flow in the region. Such fluid migration is compatible with fractional volume decrease in materials along the fault and subsidence along its surface trace. Our time series analyses indicate slow subsidence over the entire area with minor seasonal effects.

The maximum subsidence rates (40–50 mm a\(^{-1}\)) occur east and west of the Eyvanekey plateau, where the agricultural lands are irrigated each spring and summer by wells extracting shallow groundwater. A steady increase of subsidence rate in the farmlands (outside the salt plateau) is recorded from 2003 to 2006.

Recently the national government started to control the rate of groundwater extraction in Iran, especially during the dry seasons. InSAR maps like that shown in Figure 10 should aid such management by distinguishing areas where current rates of pumping groundwater exceed the natural recharge rates from those where the same density of wells appears to be sustainable.

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