Reports

Seasonal Movements in a Salt Glacier in Iran

Abstract. *The philosophy of the storage of high-grade radioactive wastes in salt seems to be based on the assumption that the salt glaciers of Iran are no longer moving. Monitoring the movements of markers painted onto one of the salt glaciers suggests that the glacier deforms elastically as a result of temperature changes most of the time but flows plastically when it is sufficiently wet during each annual rainy season.*

Sixty or so diapirs of Hormuz (Infracambrian) rock salt emerge at the surface in southern Iran (*1*). A few tens of these diapirs have associated with them extrusive sheets of salt (*2*) which have been known as salt glaciers since they were first described over 50 years ago.

Knowledge of the rate of any flow of salt under surface conditions is very important to the philosophy of radioactive waste storage (*3*). Gussow has argued (*4*) that the salt glaciers originally extruded rapidly as hot (~ 300°C) lavalike flows and that they have not moved since cooling to ambient temperatures. Our results seem to rule out this idea and substitute a pattern of continuing seasonal flow.

We report here the movements of markers painted onto the halite of one of the most spectacular salt glaciers, that on the northern side of Kuh-e-Namak (Dashti) at 28°17′N, 51°43′E. Our monitoring program, which began in January 1977, was terminated unexpectedly (*5*), but our results, even without the intended coverage for 1 or 2 years, strongly suggest that this glacier flows plastically during the brief annual rainy season between October and February [mean annual rainfall, ~ 28 cm (*6*)].

Markers were painted on the eastern edge of the salt glacier (3000 m long, 3500 m wide, and ~ 50 m thick) along two lines of sight controlled by an alidade which fitted into mountings permanently cemented onto appropriate outcrops of country rock. Subsequent positions of the markers are reported as distances from the fixed lines of sight which were perpendicular to the edge of the salt body (*7*). On some days of our field program, we recorded only the 0800-hour position of each marker on the shorter of the two survey lines while on our way to make geological observations (*8*). On other days we measured the temperatures and the position of one or more markers at 15-minute intervals throughout the daylight hours.

Our short survey line consisted of two markers, a marginal station 6 m onto the southeastern flank of the salt about 1000 m from the snout and a median station 40 m onto the salt. The alidade was mounted 9 m from the edge of the salt, and the short survey line was therefore 49 m long. Figure 1 illustrates the movements of these two stations during 3 days when the salt glacier was deforming elastically. Records are available for other days and parts of days, but we chose those included in Fig. 1 to illustrate the full range of movements and to show that the relationship between the movement and temperatures depends on whether the salt was wet or dry. Throughout the 3 days represented in Fig. 1, the median station moved alternatively down- and upstream over a range of a few centimeters whereas the marginal station moved more or less in sympathy over a range only one-third or one-fourth as large.

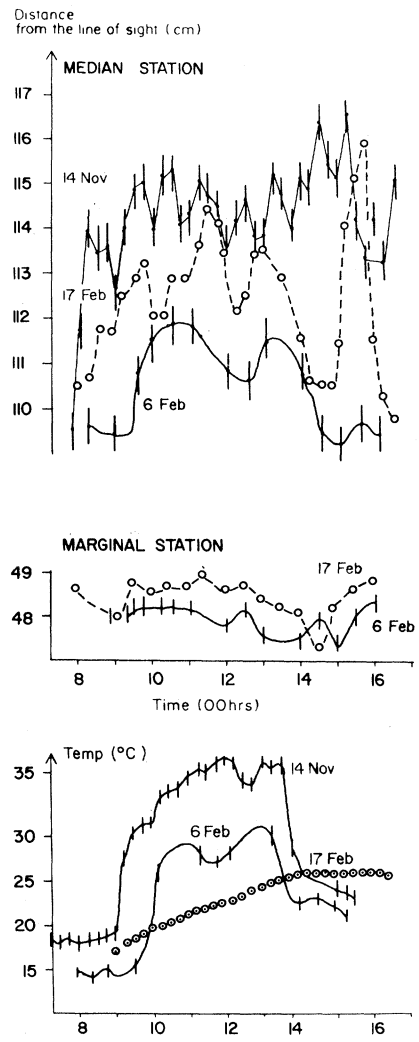

Fig. 1. The movements of the two stations of the short survey line on three particular days. Surface temperatures are shown for 6 February (at the alidade) and 14 November (at the median station); temperatures shown for 17 February were recorded behind 20 cm of salt at the median station.

On days when the surface of the salt was dry (*9*), several back-and-forth movements occurred (for example, on a cycle of 50^{+40}_{-20} minutes), and these showed little correlation with the fluctuations in surface temperature. Indeed, the most marked movements occurred on hot days (for example, 17 February) after the sun had set on the median station, when the salt approximately 20 cm deep was hottest (*10*). When the salt was wet (and the air temperature was usually cooler), the two survey stations moved downstream only when the surface temperatures rose and moved upstream in immediate response to decreases in temperature (see the record for 6 February in Fig. 1).

The volume of halite changes almost 1 percent in the temperature range from 0° to 100°C (*11*). We consider the movement of the stations illustrated in Fig. 1 (and others like them) to indicate that the sun induces measurable elastic strains in the salt glacier. When the surface of the salt was dry, significant downstream movements before the sun shone on the median station (see the record for 14 November in Fig. 1) suggest that thermal strains can be transmitted hundreds of meters through dry salt in a few minutes from surfaces already in the sun.

The pattern of daily movements typical of the dry season appears to depend not only on the surface temperatures but also on the thermal gradients in the salt mass. These, in turn, depend upon the dampness of the salt.

Figure 2a (on a smaller scale than Fig. 1) shows all our records of the movements of the short survey line. These two stations were painted onto the salt in a fixed line of sight on 28 January 1977, about a week after the last heavy rains of the preceding rainy season. On our first return visit (30 January) we found the median station 95 ± 1 cm downstream of the line of sight. The markers must have

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continued to move downstream for some time after that measurement, for in subsequent monitoring we found them further downstream but retreating back upstream. Interpolation between our measurements suggests that the maximum downstream advance of both these stations occurred on or about 1 February. The salt seems to have ceased flowing then and to have shrunk as it dried, for both stations then retreated upstream for about 4 days. However, not all the preceding downstream advance was recovered and a permanent downstream movement must have occurred in the first 2 days of our monitoring program. After 5 February, the salt around the short survey line began to deform as an elastic solid and presumably did so for the remainder of the 1977 dry season.

We returned to the salt glacier in early November, about a week after a rainstorm which marked the beginning of the next rainy season at an unusually early date. From 6 to 9 November, the two markers of the short survey line retreated almost but not quite back to where they had been in February. The glacier had dried out during this period and deformed elastically again. The rain between 12 and 17 November appears to have been insufficient to cause flow to recommence, but a small permanent advance of 2 cm at the median station appears to have been associated with the wetting in early October.

Figure 2b shows our records of the movements of six markers on our main survey line approximately 850 m upstream of the short survey line. Although 300 m long over the salt, this survey line still stretched only a tenth of the width of the salt glacier. The patterns of movement of most of these markers are similar to those of the short survey line for the same period, but they occurred over larger distances. Their relative downstream displacements indicate a nonlinear strain gradient across the line of sight. Such differential movements, and the continued downstream movement of station 2 long after the others had partially retreated, corresponded to both a flow bulge in the color bands between stations 1 and 4 and a surface stream flowing over this bulge throughout our monitoring program.

What we consider to be the simplest interpretation of the movements recorded in Figs. 1 and 2 is that both our survey lines were established on the salt glacier when it was still flowing downslope while it was sufficiently damp from the preceding rainy season. Within a few days of our painting the markers, the salt glacier shrank as it dried but recovered only a small fraction of the downstream movement we had already recorded. We infer that we recorded only a small fraction of the total permanent downstream flow accumulated during the 1976–1977 rainy season and that such plastic flow occurs at surface temperatures and pressures for several weeks each year. Periods of flow are assumed to occur when the salt is sufficiently wet for the yield point of the salt mass to be exceeded (*12*). Such periods of plastic flow are interspersed with dry periods when the salt glacier deforms as an elastic solid.

Halite has long been known to soften dramatically on wetting (the Joffée effect) (*13*). The salt glacier we studied may be considered a massive field experiment confirming this fact.

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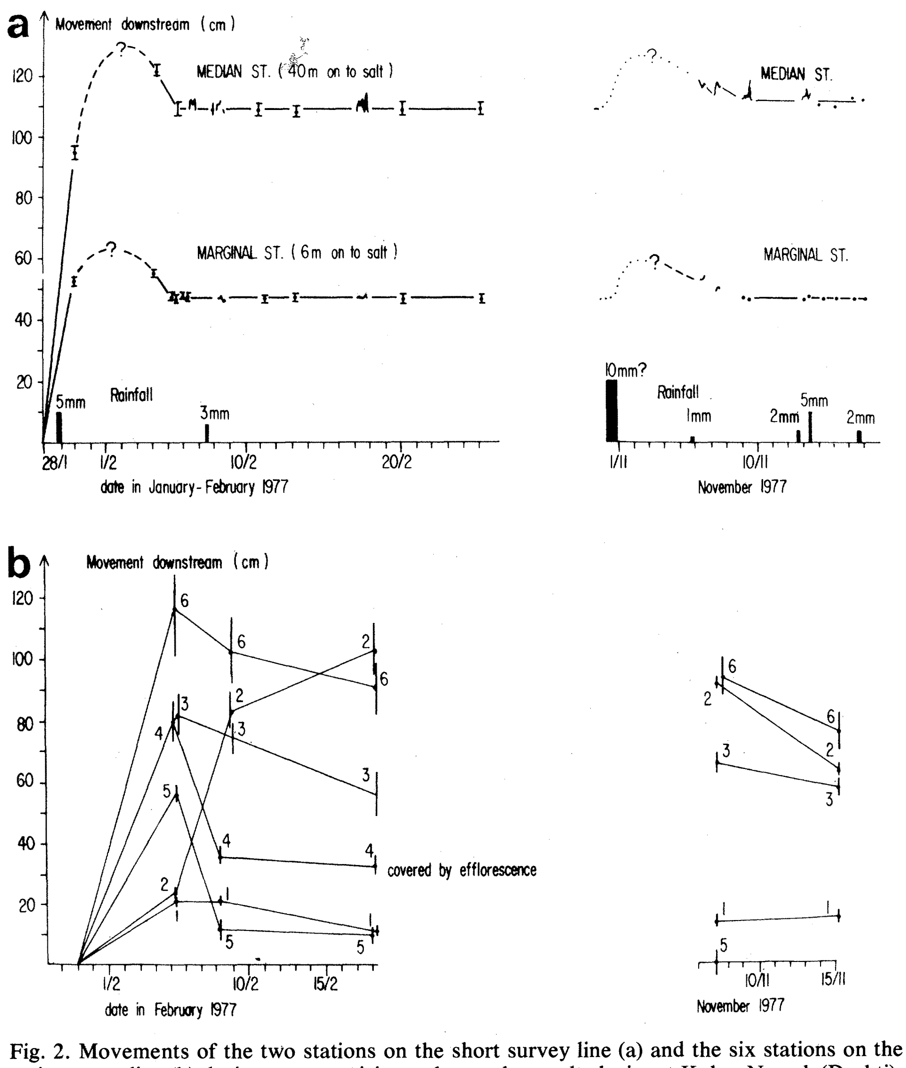

Fig. 2. Movements of the two stations on the short survey line (a) and the six stations on the main survey line (b) during our two visits to the northern salt glacier at Kuh-e-Namak (Dashti). Our rainfall records are also shown and represent the end of one rainy season (December 1976 to February 1977) and the beginning of the next (November 1977 to February 1978). Stations 1 through 6 on the main survey line were, respectively, 80, 100, 120, 150, 190, and 300 m from the southeastern edge of the salt glacier, 1850 m behind its snout. The alidade was located 50 m from the edge of the salt. The error bars on the data from station 6 indicate an accuracy of ± 10 cm over a distance of 250 m.

References and Notes

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3. F. Gera, *Geol. Soc. Am. Bull.* **83**, 3551 (1972).
4. W. C. Gussow, *Nature (London)* **210**, 518 (1966); *Mem. Am. Assoc. Pet. Geol.* *8* (1968), p. 16.
5. Plans to continue monitoring our markers through to February 1978 had to be abandoned because of illness. Political disturbances ruled out our visiting the salt glacier in the 1978–1979 rainy season.
6. *Geographical Handbook: Persia BR525* (British Naval Intelligence, London, 1945).
7. For every reading, a linear sighting target was maneuvered until it was vertical in the line of sight. The distance between the target and the paint marker was then measured with a tape. Numerous repetitions of some of the readings in different weather conditions allowed us to estimate our accuracy, which is indicated in the fig-

ures by error bars. Heat haze was not an obvious problem, even over our longest sightings (350 m) on the hottest days, perhaps because a gentle breeze was usually blowing.
8. C. J. Talbot, *J. Struct. Geol.* **1**, 5 (1979).
9. On both occasions the surface of the salt glacier dried thoroughly, the colors paled, and white salt was reprecipitated along the grain boundaries on most exposed surfaces. On humid or wet days, the salt moved silently. When the salt was dry, clicks and cracks could be heard 50 m away from the cliff on which the median sight was painted. As the salt was dryng, such noises could be heard only when the markers moved upstream (and the salt was generally in tension). When the salt surface was thoroughly dry, the noises were loud and numerous (ten per minute) during all significant movements. Fragments of salt (< 1 cm^3) fell during particularly large downstream movements (when most of the salt was in compression). Polygonal or rectilinear fractures perpendicular to the vertical or horizontal surfaces of the salt closed as the sun shone on the salt near them and reopened in the evening. Strain gauges bonded across such cracks when they closed recorded strains of several hundred microstrains in directions which changed in response to the position of the sun.
10. By recording temperatures immediately behind increasing thicknesses of dry halite in the sun, we found that the highest temperatures of the day occurred near 1300 hours on the surface of the salt, near 1500 hours at a depth of 10 cm, and at about 1545 hours at a depth of 20 cm. Just as the daily thermal peak was delayed with depth in the salt, so the thermal peak decreased in value with depth (for example, 44°C at the surface, 25°C at 10 cm, and 20°C at 20 cm, but on different days).
11. S. P. Clark, Jr., *Geol. Soc. Am. Mem.* 97 (1966), p. 75.
12. The slope of the top surface of the salt (α) rarely exceeds 14°, and the thickness (h) is unlikely to be much greater than 50 m. If we use these values and 2.18 g/cm^3 for the density of the salt (ρ) and 982 cm/sec^2 for the gravitational acceleration (g) in the relationship $\tau = \rho gh \sin \alpha$, we find that τ, the shear stress at the bottom of the salt glacier, rarely exceeds 2.5 bars.
13. H. Odé, *Geol. Soc. Am. Spec. Pap.* 88 (1968), p. 543; L. Varo and E. K. S. Passaris, paper presented at the Rock Engineering Symposium, Newcastle University, Newcastle upon Tyne, 1977.
14. We thank the Iranian Geological Survey for providing logistic support and Sir Peter Kent for advice. Financial support was provided by the Royal Society, the Carnegie Trust for the Universities of Scotland, Dundee University, and E. R. Rogers.

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Sounding the Stratosphere and Mesosphere by Infrared Limb Scanning from Space

Abstract. *Inversion of the measurements obtained by the infrared limb scanner on the Nimbus 6 satellite has demonstrated that the stratospheric and mesospheric temperatures and ozone concentrations may be obtained remotely from space with accuracy and precision comparable to in situ methods. Such global data have many applications in middle atmospheric research and operational temperature sounding.*

The possibility of natural or anthropogenic perturbation of the stratosphere and mesosphere (the middle atmosphere, 15 to 80 km) and especially reduction of the O_3 concentrations have caused considerable concern in recent years (*1*). This concern over O_3 arises from the threat of increased ultraviolet radiation reaching the earth. Such stratospheric changes could also affect the climate.

In order to provide input parameters for computer models to evaluate these changes and to look for the predicted effects, observations of temperature and trace gas concentrations are required over the globe; this suggests that satellite observations are needed. To be useful, these observations should be accurate, precise, and capable of resolving variations less than a scale height deep.

Most satellite determinations of middle atmosphere temperature structure (for example, results obtained with the selective chopper radiometer and pressure modulated radiometer) and the vertical O_3 distribution (backscatter ultraviolet instruments) thus far have been obtained from measurements made by downward-viewing radiometers and spectrometers (*2*). Nadir determinations are characterized by low vertical resolution (because the upwelling radiation comes from effective layers 12 to 20 km deep), the need for more than one sensor to cover a wide range of altitudes, and the inability to measure the vertical distribution of any stratospheric trace gas, except daytime O_3 above 30 km, which requires still another sensor.

Gille (*3*) pointed out that measurements of infrared radiation emitted by the atmosphere, obtained while the satellite was scanning the earth's horizon or limb, could be inverted to yield day and night vertical distributions of stratospheric and mesospheric temperatures and trace gas concentrations. The advantages of infrared limb scanning include (*4*) the capability for better vertical resolution (layers approximately 4 km deep) and the capacity to sound for temperatures or trace gases with a single instrument over a wide range of altitudes. The opacity of clouds in the lower atmosphere limits coverage to the upper troposphere and above.

This report presents results from the limb radiance inversion radiometer (LRIR), the first satellite-borne limb scanner. They show that retrievals of temperatures and O_3 concentrations in the stratosphere and mesosphere are not only in good agreement with in situ rocket measurements but also that the quantitative accuracy and precision of limb scanning are comparable to those of in situ rocket measurements.

The LRIR was fabricated by the Honeywell Electro-Optical Center in Lexington, Massachusetts. It was launched on 12 June 1975 and provided high-quality data for its planned 7-month lifetime. Instrumental details are given elsewhere (*5*). The fields of view at the horizon (4000 km distant) are 2 km high by 20 km wide. A high signal-to-noise ratio was obtained by cooling mercury-cadmium telluride detectors to 63 K with a two-stage (CH_4-NH_3) solid cryogenic cooler. Radiometer channels were selected in the bands having strongest atmospheric emission, including two covering the 15-μm bands of CO_2 for temperature determination, and one in the 9.6-μm bands of O_3. In-flight calibration was effected by having the radiometer "view" cold space and an internal 320 K blackbody every 32 seconds.

Gille and House (*4*) have described the physical basis of determining temperature as a function of pressure through the use of two regions of the 15-μm CO_2 bands having different opacities. The temperature solution is then used with the measured O_3 channel radiance to determine the O_3 distribution (*6*).

Examples of typical temperatures and O_3 concentrations are shown by the solid lines in Figs. 1a and 2a, respectively. In situ rocket comparison measurements are shown by the symbols. The altitude coverage is from 15 to 65 km, with vertical resolution adequate to resolve the 6-km temperature structure seen by the rocket (~ 50 km). There is good overall agreement between the temperature determination and the rocket measurement (Fig. 1a), and among all O_3 measurements except near the maximum, where the two rocket techniques show significant differences (Fig. 2a).

In order to assess the LRIR results, their accuracy and precision must be established. The precision, or repeatability, may be determined readily by calculating the standard deviation (σ) of a group of 12 to 16 sequential inversions, at a time and location for which atmospheric variations over the 300 to 400 km covered are minimal. The averages of several determinations are shown by dashed lines in Figs. 1b and 2b. These values result from an "end-to-end" evaluation, which includes the effects of atmospheric variations and data transmission, as well as instrument noise and data processing. For both temperature and O_3 concentration, the repeatability of the LRIR results is similar to (or perhaps slightly better than) that of rocket observations (*7, 8*).