ELASTIC DIURNAL MOVEMENTS OF MASSES OF TERTIARY SALT EXTRUDED IN NORTH CENTRAL IRAN

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Abstract

Metal markers were installed along three traverses onto two masses of late Eocene – early Oligocene salt extruded along 2 major faults near Garmsar in Central Iran. Each marker consisted of a 30×30×1 cm steel plate with its four corners securely anchored into the salt by steel bars 50 cm long. An accurate survey method measured the horizontal and vertical distances of particular markers relative to fixed baselines at time intervals between 15 to 60 min. during particular days in 1997. Surface shade temperature was measured at the baseline at the same time intervals. The main results are: 1– Markers moved irregularly between a few centimeters and 7 m each day but their return each evening close to where they began each morning indicates that diurnal strains in the salt were essentially elastic. 2– Horizontal and vertical movements of markers were strongly related to each other and to their distances and heights relative to the baseline. 3– Translating markers movements to salt strains found horizontal strains to relate with their distance from the baseline whereas vertical strains are close to constant regardless of the thickness of salt beneath them. 4– Salt movements measured over hours can be modeled as thermal expansions induced by temperature rise close to those measured. Salt movements measured over longer intervals are modeled by thermal expansions due to temperature rises much smaller than measured. 5– On some days when tidal forces opposed temperature changes, irregular marker movements matched smooth changes in tidal forces at least as well as changes in surface temperature. It is therefore suggested that lunar and solar gravitation affects the movements of extruded salt masses.

Introduction

Assessing the safety of plans to isolate nuclear waste in

salt [1] or extract oil from beneath sheets of allochthonous salt in Golf of Mexico [2] requires a thorough understanding of how natural bodies of salt deform. The hundreds of bodies of salt exposed in Iran are almost unique and are obvious targets for studying salt movements and their causes.

The first field measurements of salt movements were measurements of markers painted on Kuh-e-Namak (Dashti) over 20 years ago [3]. That work reported two

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categories of horizontal movement: first, non-recoverable plastic strains of up to a meter in two days in salt dampened by rain. Secondly elastic strains in which markers on dry salt underwent irregular but essentially diurnal cyclic movement of up to 6 cm and returned each evening close to where they started each morning. More recent measurements [4] found that markers on Kuh-e-Jahani near Firoosabad gravity spreads at up to 6 m/year as a result of extrusion inferred to be at a rate of between 1 and 2 meters per year.

This study was started in 1995 [5] and focuses on elastic diurnal strains of some salt masses extruded along faults near the city of Garmsar in north Central Iran (Figs. 1 and 2). Vertical and horizontal movements of markers, securely anchored in the salt, were measured using a survey method more accurate than methods employed previously. The diurnal movements of markers on salt reported here are two orders of magnitude larger than the horizontal movements reported earlier [3] which raise questions concerning the causes of this difference.

Geological Setting

The stratigraphy and rock types in the study area are characteristic of Central Iran [5]. The salt (Fig. 2) was deposited at the base of the late Eocene – early Oligocene Lower Red Formation which is overlain in turn by limestones and marls of the Qum Formation, Miocene marls and sandstones of Upper Red Formation, Pliocene–Pleistocene clastic deposits of the Hezardareh Formation, and patches of younger alluvium.

Deformed salt is exposed in thick sheets along major regional thrusts and local diapirs extruded along strike slip transfer faults (Fig. 2) where the front of the Alborz Mountains overlooks the plains of the Great Kavir of Central Iran [5]. The salt masses on which the markers were located, rise up to 300 m above the Central Iranian plateau to the south.

Method of Measurements

The two salt masses measured in this study have rugged topographies and high relief (Fig. 2). The location of markers arranged in 3 lines onto the salt was therefore measured accurately using an electronic theodolite (*Wild, 2000S*) located at the ends of 3 baselines located on a flat plane to the south and east (AB, CD and EF on Fig. 2). Horizontal and vertical angles of sight lines to markers on the salt were measured from the ends of the relevant baseline (Figs. 3 and 4). The fixed length, L of each baseline (of about 73 m to 165 m) was measured (±1 cm) using a tape.

Horizontal distances and vertical heights of each marker relative to the baseline were calculated using the formulae listed in Figure 3.

Field observations and aerial photographs suggest strongly that the base of each salt mass approximate the level of the plain on which the baselines were fixed. The elevation measured for each marker is therefore expected to approximate the thickness of salt beneath it.

The following formulae were used to calculate the errors in measurements of the angles subtended between the baselines and sightlines to the markers.

$$\delta_{B_3}{}^2 = \left(\frac{\partial B_3}{\partial B_1}\right)^2 \delta_{B_1}{}^2 + \left(\frac{\partial B_3}{\partial B_2}\right)^2 \delta_{B_2}{}^2$$

$$\delta_{h_1}{}^2 = \left(\frac{\partial h_1}{\partial l}\right)^2 \partial_l{}^2 + \left(\frac{\partial h_1}{\partial B_2}\right)^2 \delta_{B_2}{}^2$$

$$+ \left(\frac{\partial h_1}{\partial a_1}\right)^2 \delta_{a_1}{}^2 + \left(\frac{\partial h_1}{\partial B_3}\right)^2 \delta_{B_3}{}^2$$

$$\delta_d{}^2 = \left(\frac{\partial d}{\partial l}\right)^2 \delta_l{}^2 + \left(\frac{\partial d}{\partial B_1}\right)^2 \delta_{B_1}{}^2$$

$$+ \left(\frac{\partial d}{\partial B_2}\right)^2 \delta_{B_2}{}^2 + \left(\frac{\partial d}{\partial B_3}\right)^2 \delta_{B_3}{}^2$$

The brochure produced by manufacturer of the theodolite (G1 273e, Leica Ltd., Herbrugg), recommends using a standard deviation (in position I + II/2) of 0.5 seconds for horizontal and vertical angels measured by the theodolite from either end of the baseline (Fig. 3). However, a very conservative standard deviation of 2 seconds was used here. The precision in baseline lengths was taken as 2 cm.

Marker 1 was closest to baseline AB being 21.4 m vertically above it and a horizontal distance of about 84 m away. The calculated errors were ±0.4 cm and ±1.7 cm respectively. Marker 4 was furthest from baseline EF being 271 m vertically above it and a horizontal distance of about 1046 m away. The calculated errors were ±4.5 cm and ±16.7 cm respectively.
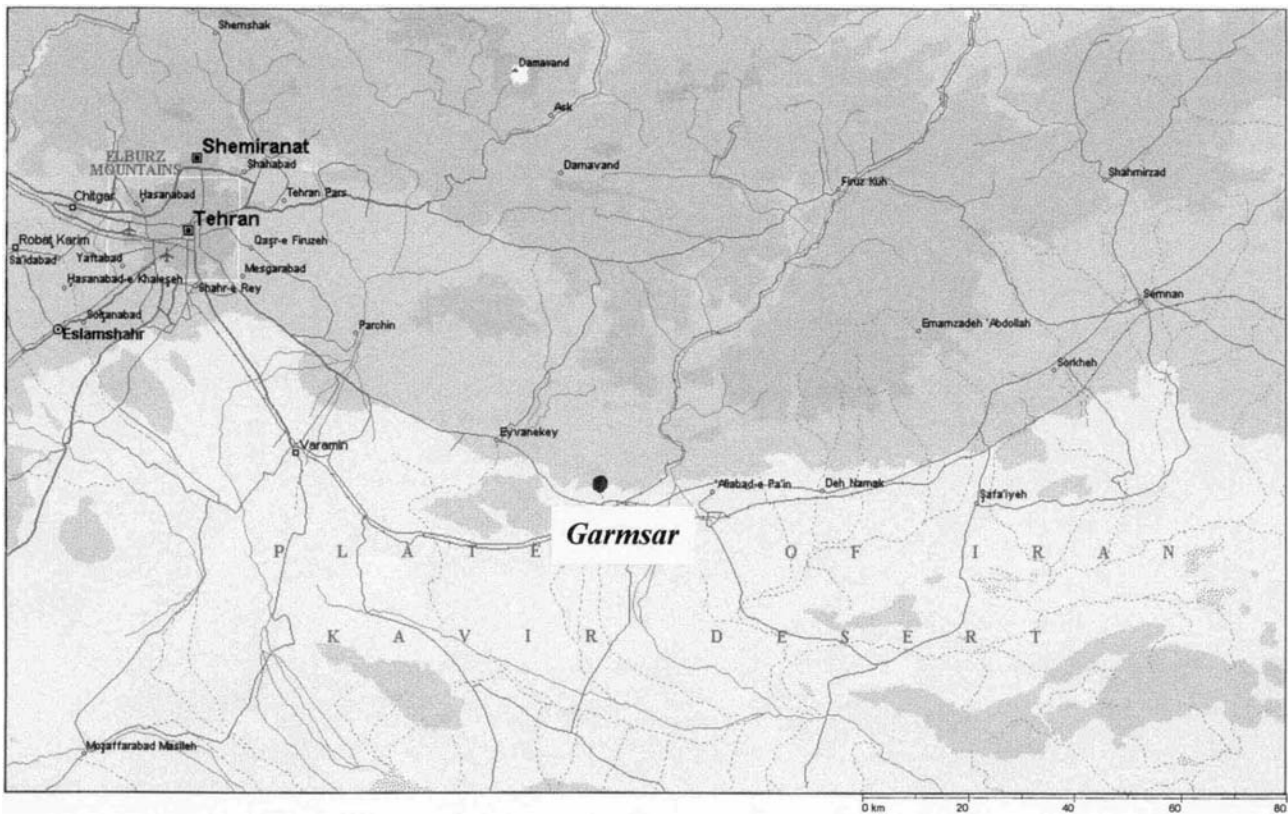
Figure 1. The geographical situation of study area.

Movements of Markers

Horizontal distances and vertical heights between markers and baselines were measured at intervals between 15 to 60 min.

Figure 5 plots changes in position of marker 3 in relation to baseline EF between the hours 7:30 and 16:30 on 3rd January 1997. The upper part of this figure illustrates changes in elevation at intervals of about 15 min. The central part of this figure illustrates changes in horizontal distance and the lower part plots the temperature. As throughout this study, temperatures were measured in the shade on the ground at the relevant baseline. Error bars calculated as described above are shown on Figure 5 but, for the sake of clarity, omitted from other graphs.

Figure 5 indicates that horizontal movements of this marker were irregular in time over a range of 3 m, about 3 times larger than its simultaneous 1 m range of vertical movements without any direct relation with smooth simultaneous changes in temperature over a range of 17°C.

Figure 6 relates the vertical and horizontal movements of five markers relative to baseline AB with surface temperature on 4th January 1997. It is clear there that markers increasing distances onto thicker salt

showed increasing simultaneous vertical and horizontal movements. The graph inserted on Figure 6 illustrates that the horizontal distances of each marker were close to 3 times its vertical height.

Figure 7 records vertical and horizontal movements of marker 4 in relation to baseline EF and surface temperature at this baseline on three different days in 1997, 3rd January, 11th February, and 10th April. These movements differed in both amount and direction on different days and none were simply related to the different temperature changes at the baseline.

Marker Movements as Percentage of Strains of Salt

Of the 6 synchronous movements shown for all 5 markers during 4th January 1997 (Fig. 6), two obvious sets of simultaneous upward and outward movements were chosen for analysis. One set of movements was the largest of the day, that between about 08:30 and 09:30 hours, when the surface temperature at the baseline rose a few degrees Celsius (Fig. 6). These first sets of movements were largely recovered in the following hour. The other, smaller, set of movements was between the first and last reading of the same day, an interval of 9 hours between 07:30 and 16:30 hours, during which the surface temperature at the baseline ended 8°C higher
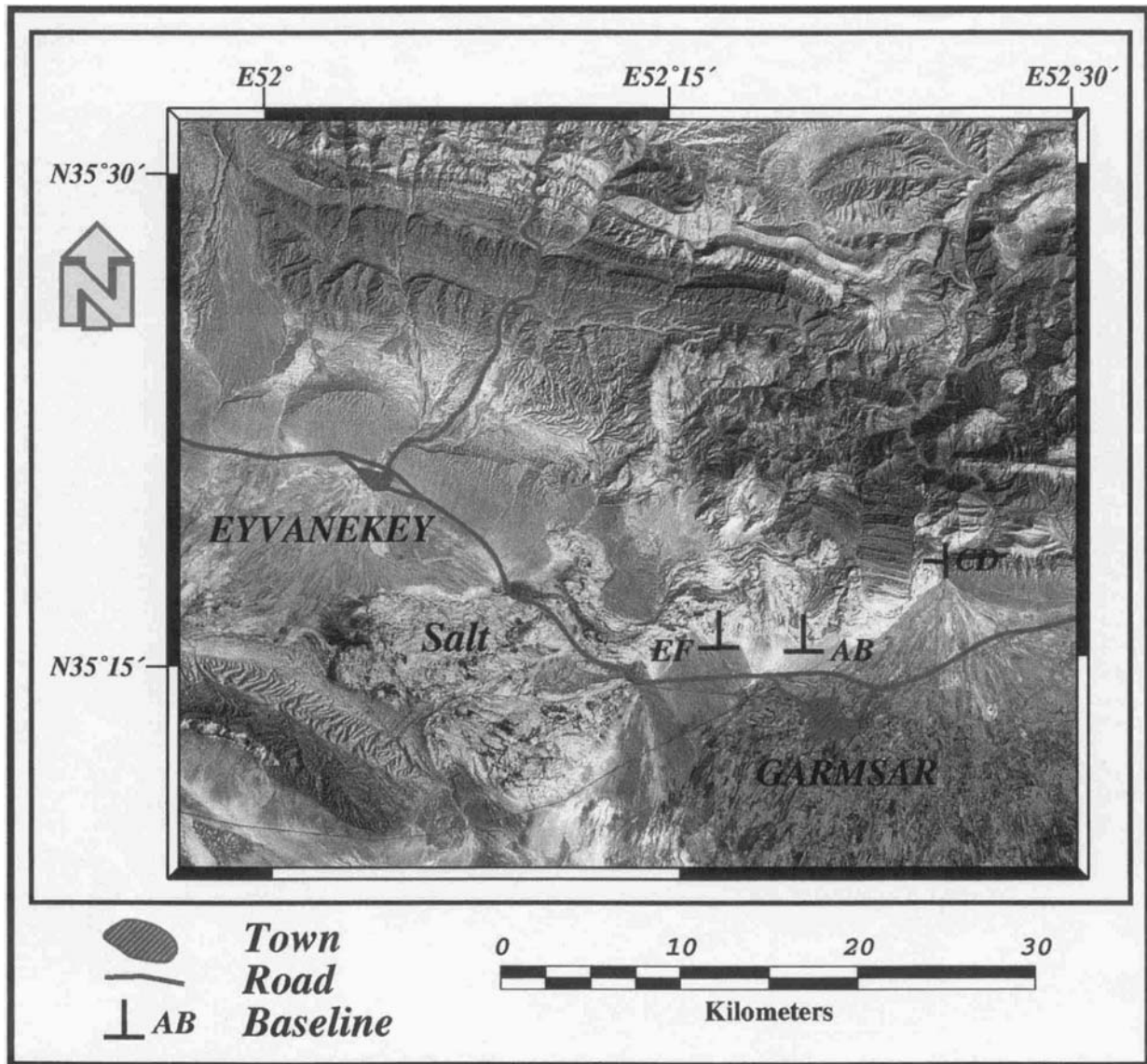
Figure 2. Satellite image of Garmsar area produced from TM data (RGB=741) that shows the dispersion of salt masses by light color and situation of three baselines of AB, CD and EF for measurements.
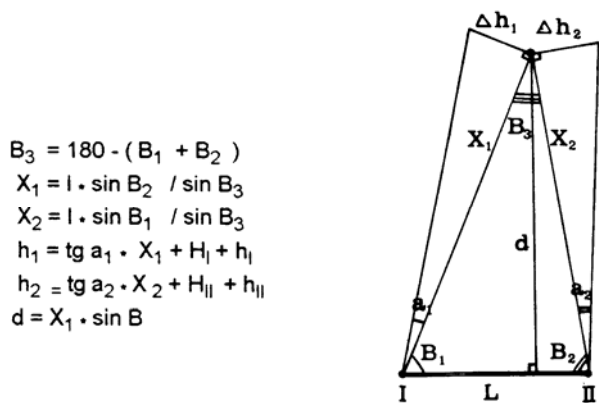

$B_3 = 180 - (B_1 + B_2)$

$X_1 = I \cdot \sin B_2 \ / \sin B_3$

$X_2 = I \cdot \sin B_1 \ / \sin B_3$

$h_1 = \mathrm{tg}\, a_1 \cdot X_1 + H_I + h_I$

$h_2 = \mathrm{tg}\, a_2 \cdot X_2 + H_{II} + h_{II}$

$d = X_1 \cdot \sin B$

Figure 3. Determination of non-accessible horizontal and vertical conditions of marker, L =Length of baseline, B_1 and B_2 = horizontal angles from both sides of baseline to the marker, a_1 and a_2 = vertical angles from both sides of baseline to the marker, H_I and H_{II} = relative elevations of both sides of baseline, h_1 and h_2 = theodolite elevations, d= normal distance of marker to baseline.
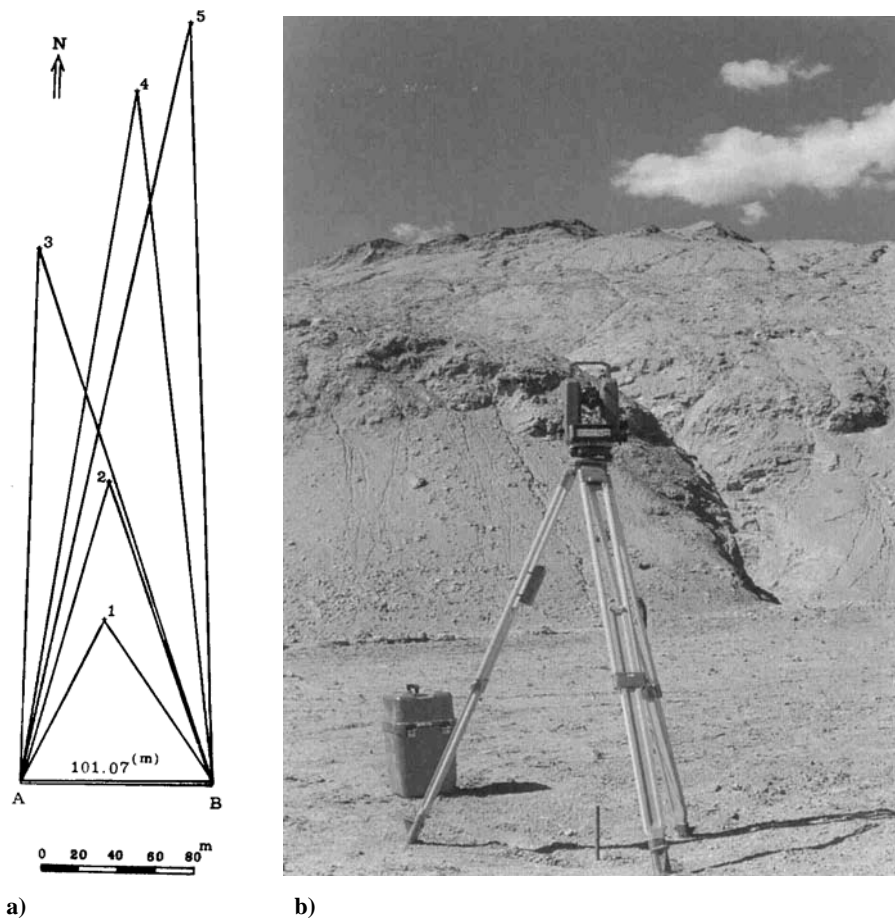
Figure 4. a) Schematic situation of AB baseline and 5 markers on salt masses for measurements. b) Placing of theodolite at point A on AB baseline. The cliff fronting the salt mass is about 30 m from baseline AB.

than its started after changing over a range of 11°C.

Figure 8a illustrates the horizontal and vertical movements of all 5 markers during both time intervals. It can be inferred from Figure 8a that the horizontal movements were a nearly constant 2.2 times greater than the vertical movements of the same marker during both time intervals.

The marker movements plotted in Figure 8a were translated into the percentage strains [(change in length / initial length) * 100%]. Figure 8b shows marker distances plotted against their horizontal movements calculated as % strains of their distance from the baseline during both time intervals (horizontal marker movement measured in cm / initial distance in m). It is clear on Figure 8b that the markers recorded horizontal strains (%HE), increased approximately linearly with their distance from the baseline during both time intervals (and that the %HE between 08:30 and 09:30 hours was about 3 times % HE between 07:30 and 16:30 hours).

Figure 8c shows marker heights plotted against their vertical movements calculated as % strains of the thickness of salt inferred beneath the marker during both time intervals (vertical marker movement measured in cm / initial height in m). The vertical salt strains (%VE) have shown on Figure 8c could be interpreted in two ways. They could either relate linearly to the thickness of the salt beneath them, or be essentially similar regardless of the thickness of the salt beneath them. In the latter case, the mean strain was 0.69% between 08:30 and 09:30 hours and 0.225% between 07:30 and 16:30 hours.

Discussion
Thermal Strains?
Talbot and Roger [3] reported small backward movements of their painted markers when the shadows of clouds passed over the salt they were measuring. They argued that the horizontal diurnal movements they measured were related to complex elastic strains

induced in dry salt by diurnal or shorter temperature changes. Any such thermal strains would be complicated by thermal gradients induced by changes in surface temperatures over different time intervals radiating or conducting into exposed salt masses at different rates.

Dry salt expands about 1 volume % as a result of a temperature rise of 100°C [6]. This implies length changes of 0.33% over a temperature range of 100°C and 0.0033% over a temperature range of 1°C.

To test the likelihood of surface temperature changes being responsible for the salt movements reported here, the two sets of % strains shown on Figures 8b and c were compared with % strains modeled by invoking thermal expansions due to different temperature changes.

At the horizontal strains interpreted from horizontal marker movements increased linearly with distance (Fig. 8b), they were compared with the thermal expansion of a salt mass equal in length to the marker distance subject to a range of temperature changes.
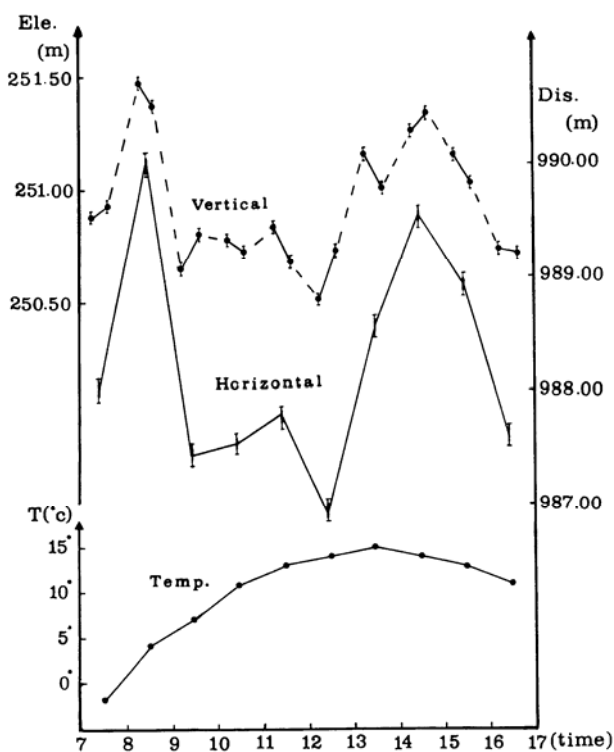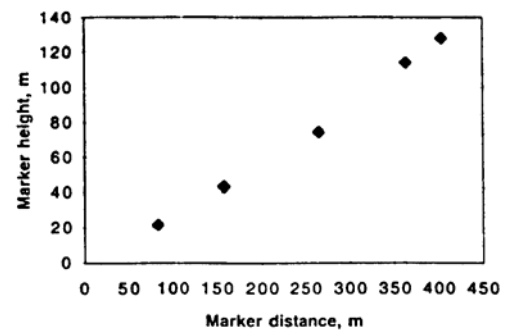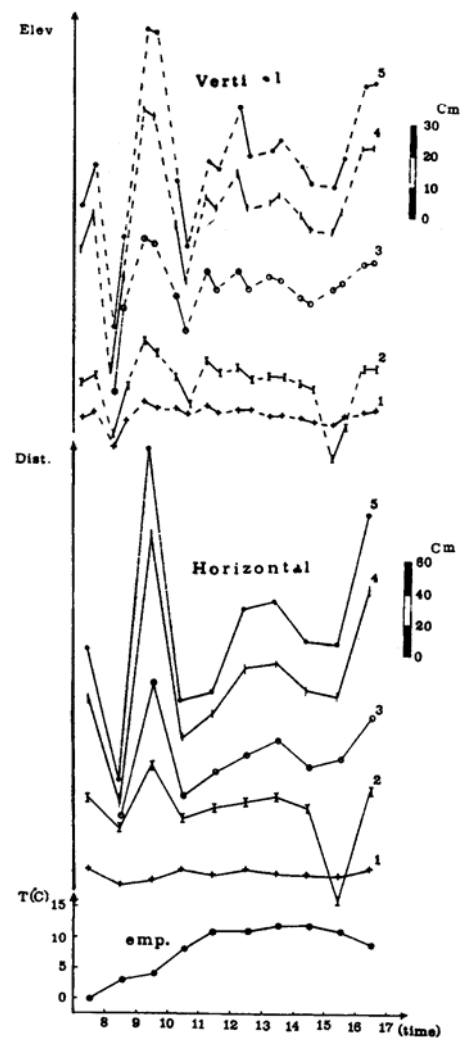

a)

b)

Figure 5. Changes of surface temperature, horizontal and vertical movements at marker number three from EF baseline vs. hour changes in January 3rd 1997. Note measurements were taken at one-hour intervals. Since the measurements could not be conducted simultaneously at the proposed hour from both sides of baseline, it was conducted within about 15 to 20 min interval.

Figure 6. a) Marker distance against marker height of five markers from AB baseline. The relative elevations between the baseline and the markers are respectively about 21.5, 43.5, 74.5, 114 and 128 meters. The horizontal distances of these markers from the baseline are 84, 159, 266, 364 and 403 meters respectively. b) Measurements of vertical and horizontal movements of five markers from AB baseline in January 4th 1997. Since a slide stone obstructed marker number three, the first measurement was not recorded at 7:30 Am.

Figure 9a shows that the strains inferred from horizontal marker movements compare reasonably well with the thermal expansion of a salt mass as a result of a rise in temperature found empirically to have been 3°C between 08:30 and 09:30 hours, and 0.8°C between 07:30 and 16:30 hours. A temperature rise of 3°C is slightly higher than that measured between 08:30 and 09:30 hours but is close to the average hourly rate of increase shown throughout that morning. A temperature rise of only 0.8°C empirically accounts for the smaller strains between 07:30 and 16:30 hours even though the temperature increase over this time interval was an order of magnitude larger.

If the vertical strains interpreted from movements of

the 5 markers over both time intervals (Fig. 8c) are also considered as having increased with height, then they can be modeled as linear thermal expansions of a salt mass as thick as the marker height. In this case, the temperature rise found empirically to match the measured data, "closest" was 8°C between 08:30 and 09:30 hours and 1°C between 07:30 and 16:30 hours. (Fig. 9b) The former is about equal to the relevant measured temperature difference but the latter is about 1/8th.

If, on the other hand, the vertical strains interpreted from movements of the 5 markers during both time intervals (Fig. 9b) are considered to have been essentially constant regardless of their height, then they can be modeled as the thermal expansion of a layer of salt with constant thickness. The linear thermal expansion of salt due to a temperature rise of 3°C is equal to 0.01%. If the 0.694% strain of salt between 08:30 and 09:30 hours was due to a temperature increase of 3°C, the constant thickness of salt expanding over that time interval must have been about 0.694/0.01 (= 69.4 m). Similarly, as the linear thermal expansion of salt due to a temperature rise of about 1°C is equal to 0.0033%, the 0.225% strain between 07:30 and 16:30 hours, the constant thickness over that time interval must have been about 0.225 / 0.033 (= 67.5 m). Notice that both these calculations indicate a similar thickness which is about half the thickness of the salt inferred beneath marker 5.

Thermal expansions modeled as strains of the underlying salt thickness, have to pass through the origin of Figure 9b. The thermal expansions modeled in this way match the measured vertical strains quite well for the time interval between 07:30 and 16:30 but not those measured between 08:30 and 09:30 hours. It is therefore inevitable that the measured vertical strains on Figure 9b are best "modeled" as the thermal expansions of a beam of salt about 70 m thick due to a 3°C rise in temperature between 08:30 and 09:30 hours but only a 1°C rise between 07:30 and 16:30 hours.

The "measured" and "modeled" strains on Figure 9 agree sufficiently well to encourage attributing both sets of movements measured on 4th Jan 1997 to thermal expansion of a 70 m thick beam of elastic salt fixed at one end (that near the theodolite) in response to small surface temperature increases. It have been necessary for small surface temperature changes to penetrate 70 m into the salt to account for the data matches on Figures 9a and 9b. The superficial salt could have acted as an elastic beam 70 m thick fixed at one end if the fractures (joints) apparent in the exposed salt were closed to that depth.

It is not clear why strains induced over 1 h are modeled by thermal expansions over the measured temperature rise and why strains developed in the same salt mass over 9 h are modeled by thermal expansions much smaller than the measured temperature difference.
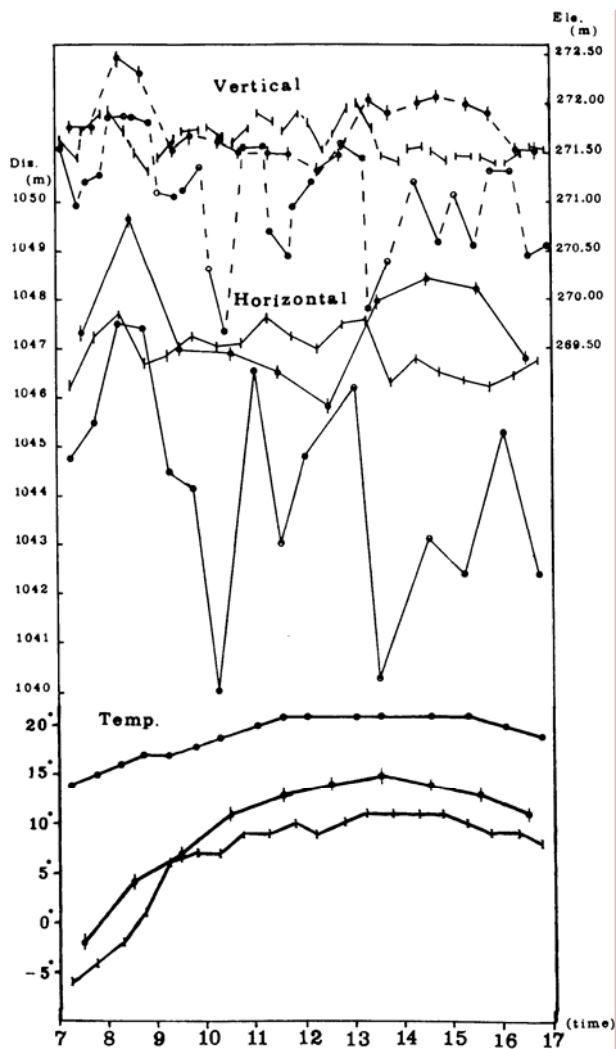

Figure 7. Measurement of horizontal and vertical movements for marker number four from EF baseline in Jan. 3rd 1997 (♦), Feb. 11th 1997 (I) and Apr. 10th 1997 (○).
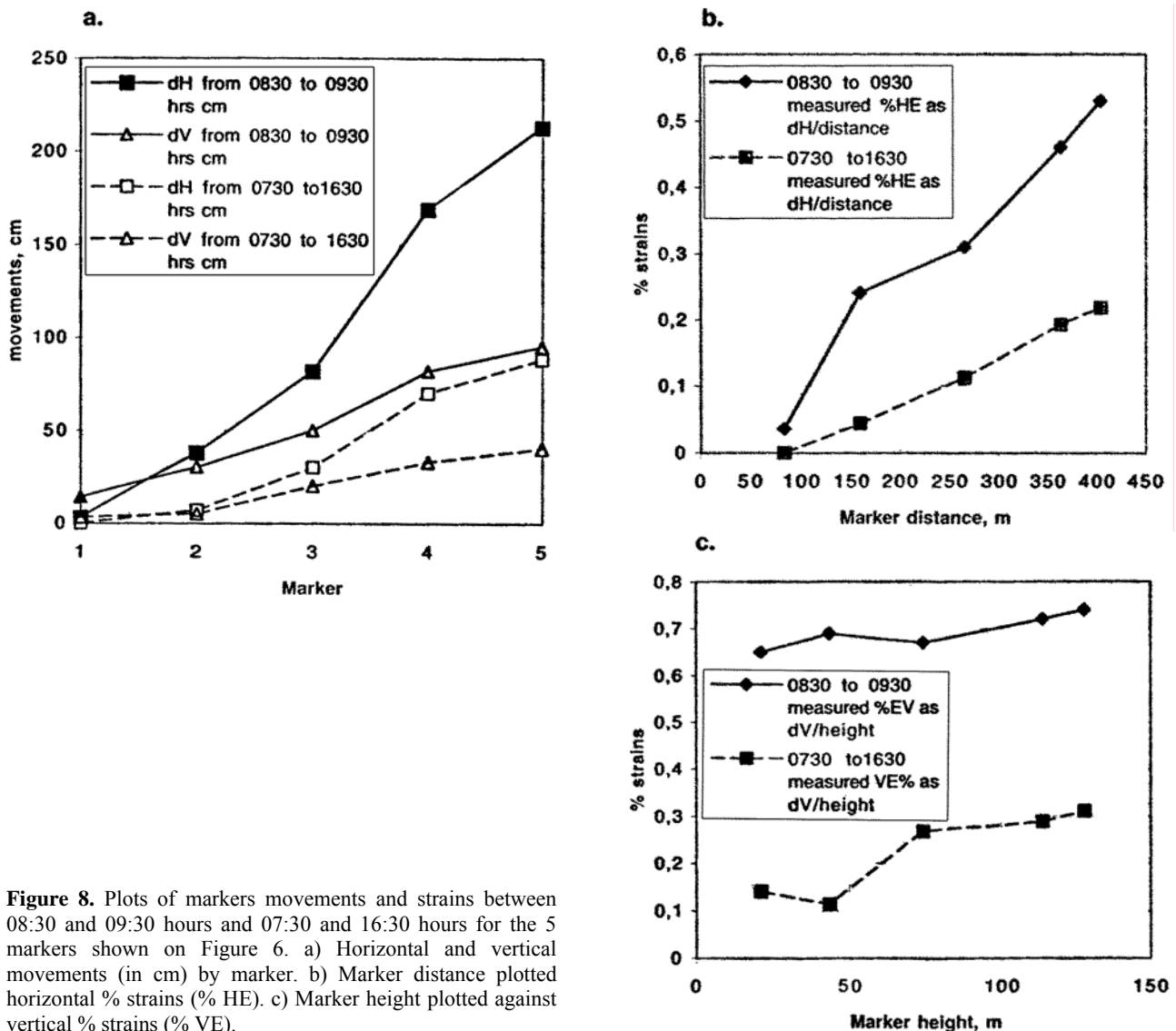
Figure 8. Plots of markers movements and strains between 08:30 and 09:30 hours and 07:30 and 16:30 hours for the 5 markers shown on Figure 6. a) Horizontal and vertical movements (in cm) by marker. b) Marker distance plotted horizontal % strains (% HE). c) Marker height plotted against vertical % strains (% VE).

Tidal Strains?

The horizontal movements reported here are over ranges about two orders of magnitude larger than those reported earlier [3] and like plots in [3], the graphs of vertical and horizontal movements reported here are far more irregular than plots of surface temperature so that any correlation can only be temporary.

Because of the difficulty in modeling salt strains by thermal expansion induced by the temperature rise measured over 9 h, other possible straining forces were sought.

One potential force is lunar and solar gravitational attraction. The differential effects of tidal forces are very obvious on sea level along the shores of deep oceans but are less obvious on solid rocks.

Tidal forces at the appropriate locations during the surveys reported here were determined using "Tidal software" and the resulting smooth curves added to plots like Figures 3, 5, 6 and 7. Changes in tidal forces follow even smoother curves than surface temperatures and, on most records it is difficult to distinguish whether smooth curves in tidal forces or temperature changes best fit the more irregular diurnal marker movements.

As a test, a search was made for records during which the curves of diurnal temperature and Tidal forces were opposed. Figure 10 shows such a plot and it is argued here that, although more irregular, the inward and downward movements of marker 4 relative to baseline EF through most of 3rd January 1997 match the tidal forces at least as well, if not better, than the rise
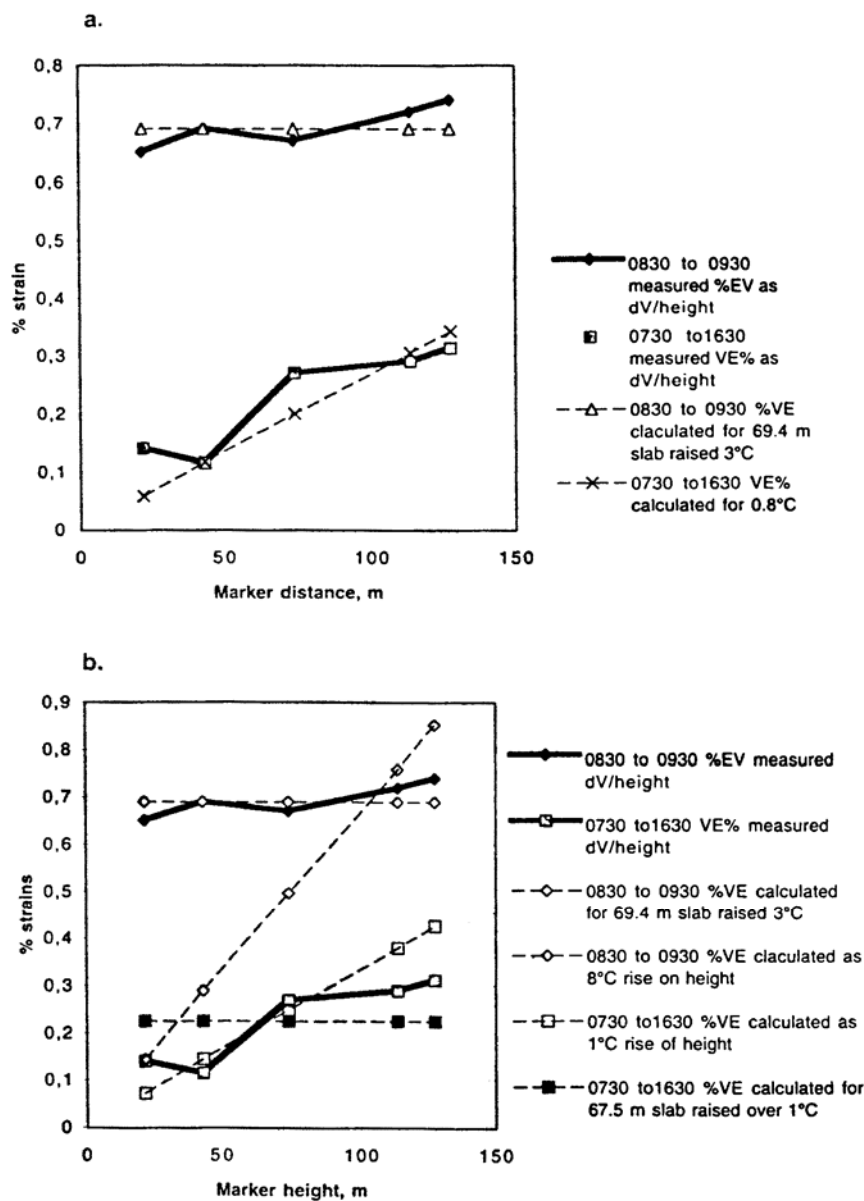
a.

b.

Figure 9. Comparison between measured and modeled strains between 08:30 and 09:30 hours and 07:30 and 16:30 hours for the 5 markers shown on Figure 6. a) Marker distance plotted against measured and modeled horizontal strains. b) Marker height plotted against measured and modeled vertical strains.

and fall of surface temperature. Tidal and thermal forces interfere both positively and negatively with time but the agreement in sign between the tidal forces and salt movements on Figure 10 suggest that tidal forces should be considered as a factor responsible for the movements of exposed salt masses.

Conclusion

Accurate measurements of markers on exposed

masses of extruded salt show them to move between cm and m through irregular diurnal cycles that are recoverable but not identical from day to day. Salt movements over hours can be modeled as thermal expansions induced in a 70 m thick beam of elastic salt fixed at one end by surface temperature changes that are more understandable than salt movements over 9 daylight hours. On some days when changes in tidal forces and temperature were opposed, it is arguable that
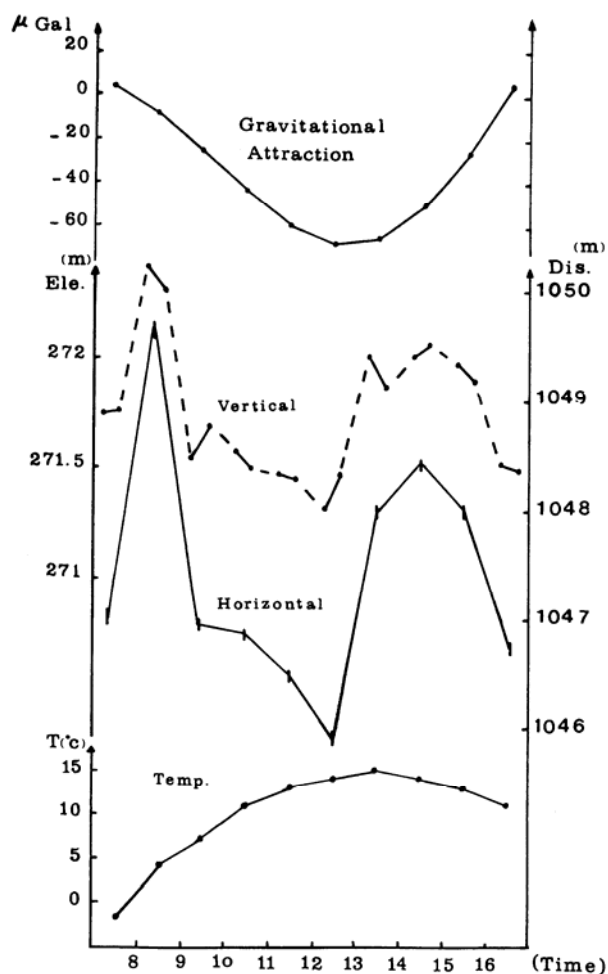
Figure 10. Changes of surface temperature, horizontal and vertical movements and lunar and solar gravitational attractions at marker number four on EF baseline vs. time changes in January 3rd 1997. The lunar and solar gravitational attractions show in microgal and graphs similar to Figure 5.

the directions of salt movements fit the tidal signal better than the thermal signal. Tidal forces should therefore be considered as a factor contributing to movements of exposed salt masses.

Acknowledgements

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