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Fold trains in a glacier of salt in southern Iran

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Abstract—A substantial glacier of rock salt flows downslope north eastwards from the salt dome at Kuh-e-Namak (Dashti), and this work describes and attempts to rationalise the deformation structures within it. The crystalline halite in both the salt dome and the glacier consists of layers of different colours, grain size and relatively insoluble mineral content. The colour bands develop folds which, together with tectonic slides, thin and multiply the colour bands in successive zones down the length of the glacier.

The folds occur as trains in which the individual components increase in maturity as they move downstream. The folds characteristically mature over short distances and become isoclinal between successive fold generation zones so that refolding is rarely obvious. All the folds seen can be attributed to changes in the boundary conditions of the glacier—either of a general or local nature. Some folds can be explained in terms of either a former increase in volume or the current wasting of the salt sheet—but most obviously relate to irregularities in the bedrock channel negotiated by the salt during its downslope flow. Expressed in these terms most folds form where the salt glacier decelerates, and become inconspicuous where it accelerates.

The relative volume of the glacier slowed by each bedrock irregularity impeding its flow decreases systematically down its length. This is thought to be due to a general decrease in competence of the rock salt down the length of the glacier as a result of a decrease in the grain size of the halite and the relative increase in the proportion of insoluble minerals due to the loss of halite by solution. The downstream decrease in grain size is similar to the process of mylonitisation in other rocks, and tends to be concentrated in particular parts of each fold generation zone.

A foliation is defined to differing degrees in various parts of the glacier by shape fabrics in one or more of the glacier's three components: porphyroclastic remnants of the coarse grained transparent halite characteristic of the salt dome, a fine grained halite groundmass, and the entrained insoluble minerals. The clear halite porphyroclasts appear least susceptible to strain but their presence controls whether or not the colour bands fold near irregularities in the bedrock channel.

Similarities between the structures in the salt glacier and those developed in various other rocks are obvious.

INTRODUCTION

In southern Iran, Hormuz (Infracambrian) salt rises in many tens of diapirs through a thickness of 8–10 km of folded Phanerozoic sediments making up the Zagros Mountains. Many such diapirs had reached the surface by Triassic times (Ala 1974) and others reached the surface during the Mio-Pliocene Zagros folding, when movements of old established salt structures were accelerated or reactivated and new structures may have been generated. Some diapirs which have not yet reached the surface may still be rising. Many of the salt structures which breach the surface are probably still active for they form topographic domes standing proud of their surroundings despite a low but significant annual rainfall. Some of these topographic domes, consisting mainly of crystalline halite, feed extrusive sheets of halite. These flow downslope over the surface and are known as salt glaciers (Lees 1927, 1931, Harrison 1931, Gussow 1968, O'Brien 1957, Gera 1972, Kent 1958, 1970).

Such salt galciers represent a paradox to rock mechanics, for polycrystalline halite is thought to be plastic so that, to flow, it requires loads or temperatures which are too high to be likely at the surface. It has therefore been argued, on both theoretical and experimental grounds, that the salt glaciers are now stationary and represent "wasting remnants of catastrophically fast (and hot) flows in the past" (Gussow 1966, 1968, Gera 1972). On the other hand, field workers have argued that at least some of the glaciers may still be active (Lees 1931, Kent 1966, 1970). Recent measurements suggest that the salt glacier which forms the basis of this study still flows at a rate approaching half a metre a day when it is sufficiently wet during the few weeks of the annual rainy season (Talbot & Rogers, in prep.). During the dry season the salt glacier merely shrinks as it dries and then expands and contracts on a smaller scale in response to surface temperatures. Fissures are few and, unlike so many of the crevasses in ice, rarely gape open.

This work describes the deformation structures and fabric within the glacier flowing down the northeast flank of Kuh-e-Namak (Mountain of Salt) at Dashti, 28°17'S, 51°43'E (Fig. 1). A much smaller glacier exists at the southwest end of the same salt dome but it is doubtful if this is still flowing. In the northeast glacier the multicoloured layers of salt, the folds in them, and the associated foliations and tectonic slides are analogous to the structures in many orogens, thrust sheets, landslides, submarine slumps, ice glaciers and, possibly, lava flows. The salt rises from below before flowing downhill and so provides a closer analogy to lavas and nappes than glaciers of ice fed by accumulations of snow falling from above.

The diapiric salt mass of Kuh-e-Namak pierces an anticlinal ridge of Phanerozoic sediments (Roohi &

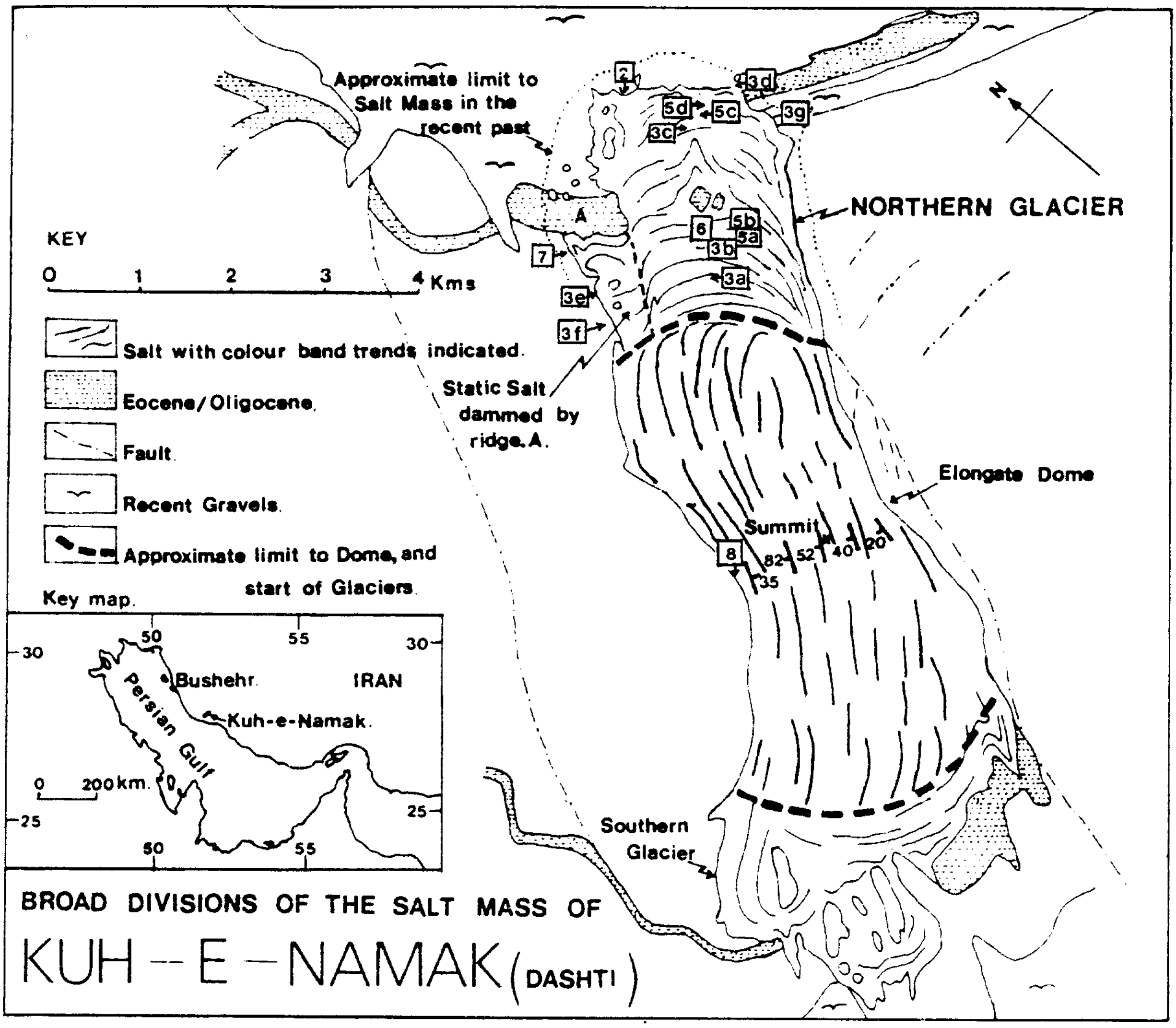

Fig. 1. Map of the salt body at Kuh-e-Namak (Dashti). Two glaciers of salt flow to the northeast and southwest from the ends of an elongate salt plug piercing an anticlinal ridge. Numbers in squares represent the locations from which the following figures were viewed; these are traced from photographs unless otherwise stated.

McQuillan 1976) and is elongate NE–SW in plan across the trend of the NW–SE trending anticlinal ridge and along a normal fault with a 1000–1500 m displacement. The diapir supports an extensive topographic dome of halite which reaches 1500 m above sea level, hundreds of metres higher than the surrounding country rocks. The two glaciers extend 2–3 km from both ends of the elongate dome down the dip slopes of the regional anticline to the plains of outwash gravels close to sea level (Figs. 1 and 9).

All the salt mass is proud of its immediate surroundings so that the present drainage is off the salt. The entrained insoluble material therefore consists almost entirely of Hormuz sedimentary debris brought up from depth. This englacial debris, magenta, brown or black in colour, surfaces in various zones along the salt mass from the summit of the dome to the snout of the northeast glacier. Glacial moraine and isolated bodies of salt in front and beside the salt imply that the glacier has been larger in the past than it is now and indicate that the glacier is wasting at present.

THE COLOUR BANDING

Everywhere the crystalline halite sequence is exposed it displays a layering defined by different grain sizes and by different colours which depend on the nature and proportions of the insoluble components present in each layer.

The salt dome

To reach the surface, the original Hormuz bedded sequence must have migrated several kilometres horizontally and then risen perhaps ten or so kilometres up the diapir. The salt exposed at the surface of the dome already has a long deformation history therefore. However, it is considered likely that the colour bands are vestiges of the original bedding. The halite exposed on the topographic dome is characteristically clean and coarsely crystalline (e. g. 3 cm dia) and individual grains are transparent. The colours of the rock mass are muted (white, pink, honey, pale green and grey) and layers of the same colour are characteristically metres to tens of metres thick. Zones of pure recrystallised halite (e. g. in the strain shadows of entrained Hormuz limestone blocks) are transparent and commonly show cubic intergrowths up to 5 cm on each side. The layers of different colours usually dip steeply to the NW and strike NE–SW along the long axis of the elliptical plan of the dome. A slight grain shape fabric defines a foliation parallel with the steep colour bands. Unlike most other salt plugs, therefore, the overall symmetry of the internal fabric at Kuh-e-Namak is approximately monoclinic rather than concentric about a steep axis.

The precipitous northeast and southwest flanks of the dome are interpreted here to mark the transition from the topographic salt dome overlying the diapiric body to the glaciers overlying country rock (Fig. 1). Such steep slopes are perhaps analogous to the way in which a drop in the water level marks where still ponded water overflows into an open channel.

Various progressive changes which continue down the length of the northeast glacier start in the flanks of the dome. Thus the colours start to intensify as the proportion of insoluble components increase downstream because of the solution of halite. The halite also starts to lose its clarity while beginning its decrease in grain size.

The northern glacier

Wherever the base or sides of the glacier are unobscured, the colour bands in the salt are conformable to the sides and bottom of the bedrock channel in which the salt flows. On the scale of the complete glacier the colour bands tend to define listric surfaces which are convex downstream and downwards as in many glaciers of ice (e. g. Hambrey 1977). On a more local scale the glacier is found to have internal deformation structures which in most cases relate to irregularities in the bedrock channel. These irregularities take two main forms: (1) longitudinal troughs aligned along the direction in which the glacier flows; and (2) scarp and dip ridges of country rock which cross the direction of flow. The scarp and dip ridges tend to impede the flow of the salt and the structures within the glacier which are associated with these ridges form the main subject of this work. However, the salt structures associated with the longitudinal troughs in its channel warrant a brief description here.

The glacier has overridden and infilled several stream gulleys incised in bedded fluvio-glacial deposits which accumulated in front of the advancing salt sheet. In the snout the colour bands at the base of the salt sheet can be seen to conform closely to the outlines of such buried channels and this local downbulging appears to dissipate vertically upwards through the glacier (Fig. 2). These local fluctuations in the orientation of the colour banding can be traced upstream from the snout, in some cases for up to 500 m (Fig. 1), to the foot of Kent's cuesta, the only group of exposures of bedrock in this glacier (Kent 1970, plate III). Minor longitudinal synforms and antiforms are locally discernable in the colour bands in various other parts of the glacier and these are assumed to overlie gaps or humps in scarp and dip ridges of bedrock beneath. Such synforms and antiforms are continuous individual features rather than fold trains and will not be considered further in this work.

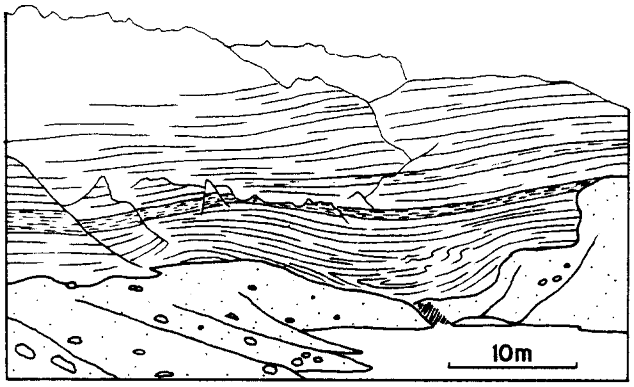

Fig. 2. A view looking upstream at part of the snout of the northern salt glacier. The colour bands near the base of the salt conform to the shape of a stream gulley eroded in the (dotted) fluvio-glacial deposits and since overridden by the salt. The accommodation folds dissipate upwards in the salt.

Most other folds in the salt are sub-similar in style (Hudleston 1977). However, towards the snout of the glacier, where the colour-contrasts in the salt sequence intensify, single layers of comparatively clean salt develop disharmonic ptygmatic folds with an almost concentric style. In any particular colour combination the paler, cleaner salt layers act in a more competent manner than the contiguous darker, dirtier layers. Those folds which were seen to come closest to a ptygmatic concentric style affected a 1 cm thick layer of clean, clear, translucent salt surrounded by dirty black salt not far from the snout. These had a wavelength averaging about 7 cm. The viscosity contrast implied by these single-layer folds was calculated using Hudleston's (1973) modification of Biot's relationship between the dominant wavelength, the thickness of the folded single layer, and the contrast in effective viscosities between the layer and its surroundings. They imply a viscosity contrast of 8 to 14 depending on the amount of shortening assumed to have taken place. This value probably represents the highest contrast in effective viscosities likely to exist in the materials which make up the salt glacier at any one location. Down the length of the glacier dirty layers decrease in competence as the dirt in them is concentrated, while any surviving clean layers remain competent. As a result, contrasts in effective viscosities between the various layers within the glacier tend to increase downstream. However, even in the snout, the effective viscosity contrasts remain generally low, and although they must play some part in generating folds it will be suggested that changes in the boundary conditions of the glacier are more significant.

THE FOLIATION

The general conformity of the coloured layers to the lower and lateral boundaries of the salt in both the dome and the glacier suggests that the colour banding, inherited from a primary sedimentary banding, is now a flow banding parallel to the particle movement paths in most places. Such an interpretation is confirmed in the dome and large areas of the glacier where a foliation parallels the colour layers. This foliation is defined by the orientation of grain shape fabrics in one or more of three components: halite porphyroclasts; their fine grained groundmass of halite; and elongate fragments of insoluble minerals, commonly gypsum and spectacular haematite. The three dimensional nature of the grain shape fabric was not mapped systematically but linear fabrics appear to be rare and flattened fabrics seem to be more common than others. The halite decreases in grain size down the length of the glacier in a process which looks very similar to mylonitisation in other rocks. The coarse grains of transparent halite of the dome decrease in grain size by the dynamic recrystallisation of subgrains around the margins of the individual large grains (White 1976). As they recrystallise the smaller subgrains contribute to the ever increasing volume of fine grained translucent groundmass at the expense of the large clear grains.

Large volumes of the glacier have an isotropic fabric and, approaching zones of high strain, the fine grained matrix is liable to develop a shape fabric where the porphyroclasts still remain subcircular in section. In localised zones of high strain even the porphyroclasts become generally elliptical in exposed sections before abruptly separating to smaller subcircular clasts on reaching particular mechanical limits to their degree of strain. It is difficult to escape the conclusion that the mylonitisation associated with the flow of the glacier involves one or more diffusion processes despite the fact that such flow occurs at surface temperatures and pressures and is contrary to theoretical expectations (Verall *et al.* 1975). As the glacier only appears to flow when it is sufficiently damp the obvious inference is that the addition of fresh water considerably hastens diffusion in rock salt (e.g. Varo & Passaris 1977).

FOLD TRAINS

Fold trains have developed in several parts of the salt glacier and representative examples will be described to illustrate their various aspects before generalisations are attempted in a discussion. The fold trains are called such here because in particular groups of folds, successive examples downstream seem to represent different stages

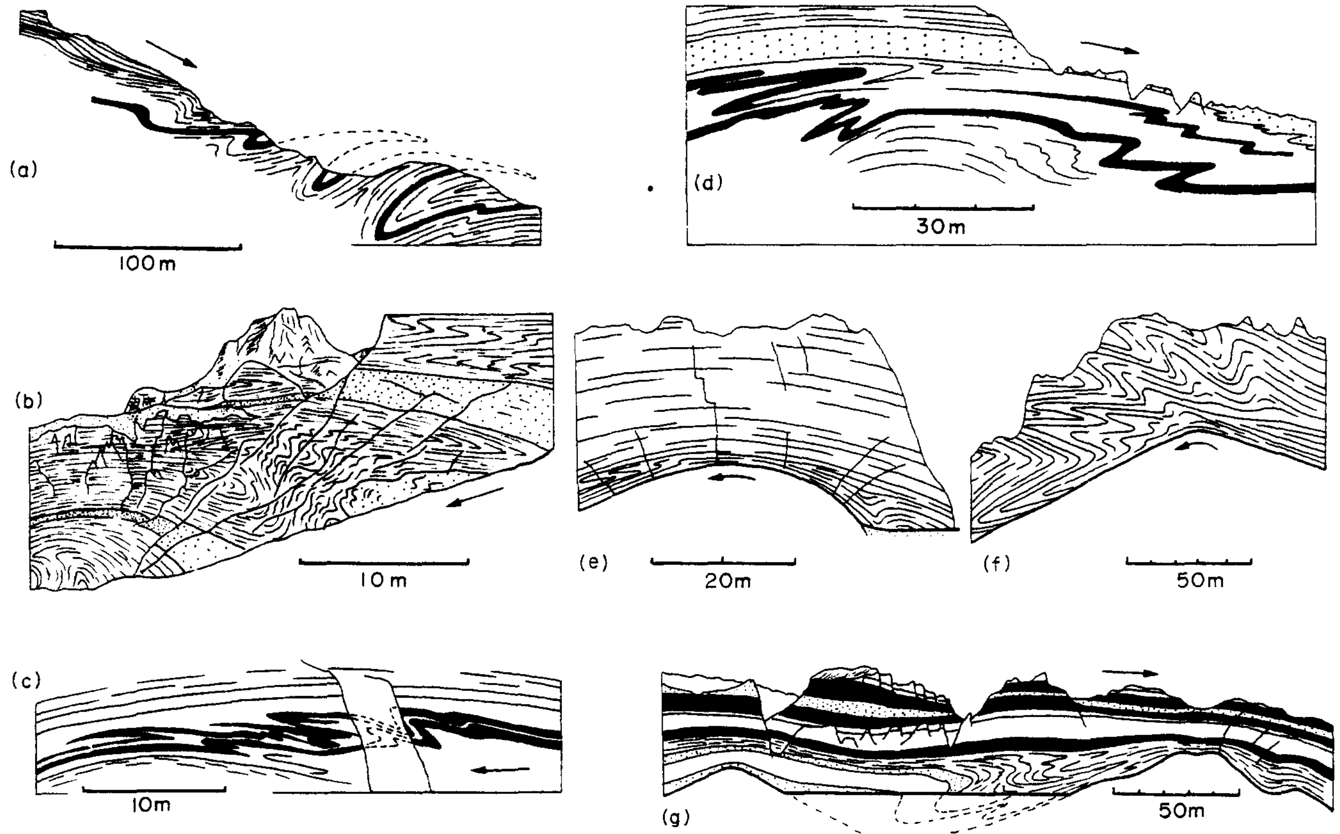

Fig. 3. (a) A reconstruction from photographs and field sketches of the highest fold train developed in the salt glacier. All the salt shown is much the same colour and an arbitrary layer has been blackened to emphasise the fold style. An arrow in this and subsequent diagrams indicates the glacier flow direction. (b) The major nappe-like folds forming the lower end of the first (highest) fold train in the glacier. The dotted layer(s) represent pale green salt. (c) A fold train in two layers of clean honey-coloured salt (shown as black) upstream of an upward bulge in the salt in the lower reaches of the glacier. (d) Field sketch of folds developed in two cream coloured salt layers (black) both up and downstream of a hump in the colour bands. (e) Folds at the base of the glacier both up and downstream of a ridge of bedrock. Here, on the western flank of the glacier, the salt is a uniform pale pink in colour. Fissures radiate upwards from the base of the salt. (f) A field sketch of folds developed in uniform pale salt flowing over a bedrock ridge high on the western margin of the salt glacier. (g) Folds in the lower parts of the glacier between two ridges of bedrock on the eastern flank of the glacier, just short of the snount. Black — dirty black salt; dotted — magenta coloured dirty salt; clear — white and honey coloured clean salt.

along particular morphological trends. Thus the upstream folds in each train are expected to mature in time to forms similar to those seen downstream in the same train. The glacier seems to flow into and through zones in which folds generate; immature folds are assumed to develop at the upstream end of each zone as individual folds and then move downstream and mature as they do so.

The downstream end of each fold train will be taken to lie where the axial planes curve through the horizontal to dip downstream, because at about this stage they become isoclinal and more or less inconspicuous.

The earliest folds in the salt glacier develop at various heights down the flanks of the topographic salt dome, short distances downstream of where the foliation and colour banding curl to parallel the surface slope (Fig. 3a). The highest fold arises as a result of a gentle steepening of a short thick limb about an axial surface which dips very gently upstream (about 8°). This asymmetry, seen in the first fold, persists downslope where successive folds exposed at the surface increase in amplitude and tightness about curved axial surfaces which progressively steepen.

Folds like those in Fig. 3(a) appear to pile up on the backs of folds like those shown in Fig. 3(b) as part of the same major fold train characteristic of the upper part of the glacier. On the scale of the complete glacier such major folds (cf. nappes) are noncylindrical and their axial surfaces are listric with a concave upwards aspect upstream of where they pass through the horizontal. The orientations of the major fold axes are locally variable but are generally across the glacier in its central portion and turn to parallel its sides at the margins. Like folds with much the same style developed on a much smaller scale in quartzo-felspathic mylonites the fold axes range from perpendicular to parallel to the bulk movement direction in the general plane of flow (Carreras *et al.* 1977). The folds in the salt glacier could also be described as large scale examples of the sheath-like folds described by Quinquis *et al.* (1978) in metapelites which have suffered either subduction or obduction in a blue schist facies metamorphism.

Figure 3(c) illustrates a small-scale disharmonic fold train typical of the fold trains seen near the snout of the glacier. In this example two layers of clean honey-coloured salt, 50 and 55 cm thick at their upstream end, develop disharmonic asymmetric folds about axial surfaces which are inclined upstream. These folds form upstream of a gentle antiform which has an axis perpendicular to the general direction in which the glacier flows, and is defined by the gentle upward sweep of the unfolded colour bands above and below the zone of disharmonic structures (Fig. 3c). At the crest of this general antiform the original two thick honey-coloured salt layers have been thinned and repeated by folds and a lag slide, and are represented by four honey-coloured layers which range in individual thickness from 3 to 10 cm. Upstream of the first fold perhaps 20–30% of the outcrop of the honey-coloured layers consists of more or less circular (2 cm dia) porphyroclastic remnants of the clear crystalline halite seen in the salt dome. Where the folds are almost isoclinal and have developed a lag on the upstream limb of the gentle antiform, the porphyroclasts in the honey-coloured salt have much the same surface area but are elliptical, with the ratios of their principal axes being about 1.4 – 2.0, and elongate along the trace of the lag and the axial surface of the fold. On the crest of the upward bulge the individual elliptical porphyroclasts appear to separate abruptly to form more numerous porphyroclasts which are essentially circular and only about 0.5 – 1 cm in diameter.

Most of the features seen in the fold train shown on Fig. 3(c) are considered characteristic of the majority of fold trains in the glacier. In each successive fold train down the length of the glacier the colour bands involved are not only further thinned and multiplied but the porphyroclasts also undergo a further decrease in grain size in association with asymmetric folds and tectonic slides. Most fold trains start to develop some distance upstream of a gentle antiform in the colour bands which crosses the direction in which the salt flows. The folds have curved axial surfaces and intensify and often develop slides immediately upstream of this local upward bulge of the glacier. They become isoclinal on its crest and become more or less indistinguishable downstream of the bulge. The gentle antiforms in the glacier can be seen to overlie scarp and dip ridges in the bedrock where this is exposed in and around the glacier. The obvious folds within the salt are not being refolded by the broad antiforms, instead they are being generated in the salt upstream of ridges of bedrock which locally retard the flow of the glacier.

The axial surfaces of the upstream folds in Fig. 3(d) bend up over an assumed underlying bedrock obstruction and folds are absent where the thinned layers are horizontal. However, downstream of the hump outlined by the fold envelope, another, independent, set of folds exists in which the axial surfaces fan about a focus at the lower end of the hump.

Comparison of the scale of the folds seen in the higher parts of the glacier (Figs. 3a & b) with those seen in the lower parts (Figs. 3c & d) illustrate the general decrease in the scale of the folds associated with each obstruction the glacier encounters along its length. This decrease in size occurs together with a tendency for the folds in each successive train to be increasingly restricted to smaller and deeper volumes of the salt. Figure 3(e) emphasises this point by showing folds affecting only the lower levels of the otherwise uniform salt both up and downstream of a ridge of bedrock covered by the northwest flank of the glacier near its snout.

On the eastern flank, near to the snout of the glacier, the salt flows over some ridges of bedrock without folding (Fig. 3g). It is not clear whether the fold illustrated in Fig. 3(g) developed downstream of one obstruction or upstream of the next, or whether the fold dates from a time when the whole of the glacier flowed over both ridges. It appears that the lower third of the glacier flows up and over the first ridge (on the left in Fig. 3g) without folding. However, it folded and is now more or less ponded behind the next, larger ridge — while the upper two thirds of the glacier flows over both potential barriers without developing any folds. A few basal layers aggregating only a few metres in thickness are the only representatives of the lower third of the glacier to cross the second ridge (to the right in Fig. 3g).

Fractures radiating upwards through the glacier from the bedrock ridges are illustrated in both Figs. 3(e) and (g). Such fractures probably originate during a dry season when the glacier deforms as an elastic solid in response to temperature changes. After a rainy season (when the photographs were taken from which most of these figures were traced), such fractures not only curl downstream on a large scale when traced up through the salt but also segment into short sections separated by discrete planes of sub-horizontal differential flow. The large scale curls of these fractures and the shape of many of the folds indicate that the upper parts of the salt profile generally flow faster than the lower parts. However, the small scale displacements of the steep fractures, the tectonic slides and many of the folds demonstrate that the flow profile is quite complex in detail as a result of both penetrative and non-penetrative strain.

Figure 3(f) illustrates the folding developed in uniform clean pale salt flowing over a limestone ridge high on the northwest flank of the glacier. This case appears typical of those few fold trains developed downstream of obstructions to flow, in that the axial surfaces, foliations and colour bands all pass through the horizontal in steep zones just downstream of the bedrock ridge. When traced up through the salt, these zones probably indicate where the top surface of the glacier was horizontal before it was dissected by erosion.

SOME DETAILS OF THE STRUCTURES

Various details of the deformation within the salt glacier are worth considering before a description of some examples of refolding is integrated with a discussion of the generation and loss of the folds.

In between most zones in which folds are generated, the foliation and colour banding in the salt appear more or less parallel and planar. In a few such areas however, isoclinal or nearly isoclinal folds are obvious in the colour banding and the foliation is axial planar to these folds (Fig. 4a). Construction of dip isogons demonstrates that such folds are similar in style on a large scale because they are combinations of other classes of fold styles developed in different colour layers on smaller scales (Ramsay 1967, p.432).

The fold trains so far described are made up of folds of more or less constant scale, albeit of progressively increasing maturity. Combinations of folds with multiple wavelengths are common in the lower levels of the upper half of the glacier. The minor folds have much the same style as the major folds and their doubly curving axial surfaces tend to fan about the axial surfaces of the major folds. Examples are shown in Fig. 5(a) where the amplitudes of the minor folds can be seen to increase up through the glacier and where the minor folds locally assume the nature of a very coarse crenulation cleavage with intensely attenuated limbs. Slides tend to develop in many of the attenuated limbs of the large scale crenulation cleavage, and the first signs of misfit of the colour bands across the 'cleavage' seem to develop at shallower levels in successive examples downstream (Fig. 5b).

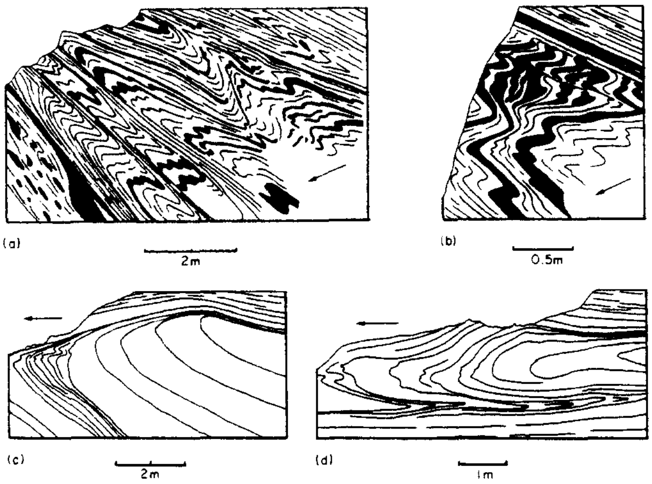

Fig. 5. (a) Minor folds defining an asymmetric anticlinorium with a very coarse crenulation cleavage deep in the middle reaches of the glacier. Black represents white recrystallised salt. A tectonic mélange is shown on the left (downstream) margin. (b) A few hundred metres downstream of 5(a) several thrusts can be seen to generate over a short distance. In this view the highest thrust generates out of sight to the right (i.e. upstream), the second highest becomes a thrust when traced right to left and the lower potential thrust zones become thrusts out of sight (downstream) to the left. (c) Extreme thinning of the upper limb of a major fold just behind the snout. (d) Thinning of both limbs of the same fold seen in Fig. 5(c) slightly further west (see Hudleston 1977).

Thinning can affect the upper (Fig. 5c) or lower limbs (Fig. 5d) of individual folds and the identification of individual tectonic slides as thrusts or lags appears to be impossible on the basis of local structural geometry. Only because the general direction of downhill flow of the glacier is known can the examples of each shown in Figs. 4(b) and (c) be distinguished.

The shapes of porphyroclasts of clear halite in a transluscent matrix of fine grained halite is apparent on parts of Fig. 4(c). The long axes of these generally elliptical porphyroclasts can be seen to define a foliation which fans about the trace of the axial surfaces of a fold in which the lower limb has been thinned. Close inspection of such examples in the field discloses that the fine grained groundmass has a stronger shape fabric with much the same orientation. Figure 6(a) shows the shape and orientation of such porphyroclasts in an immature asymmetric minor fold couple developed on the upper limb of the fold shown in Fig. 4(c). The manner in which these porphyroclasts record the strains they suffer gives an intriguing if partial (i.e. two dimensional, macroscopic) insight into how the glacier deforms internally.

Three types of strain regime can be differentiated on Fig. 6(a) by mapping the degree of ellipticity (Fig. 6b), relative size (Fig. 6c) and orientation (Fig. 6d), of the

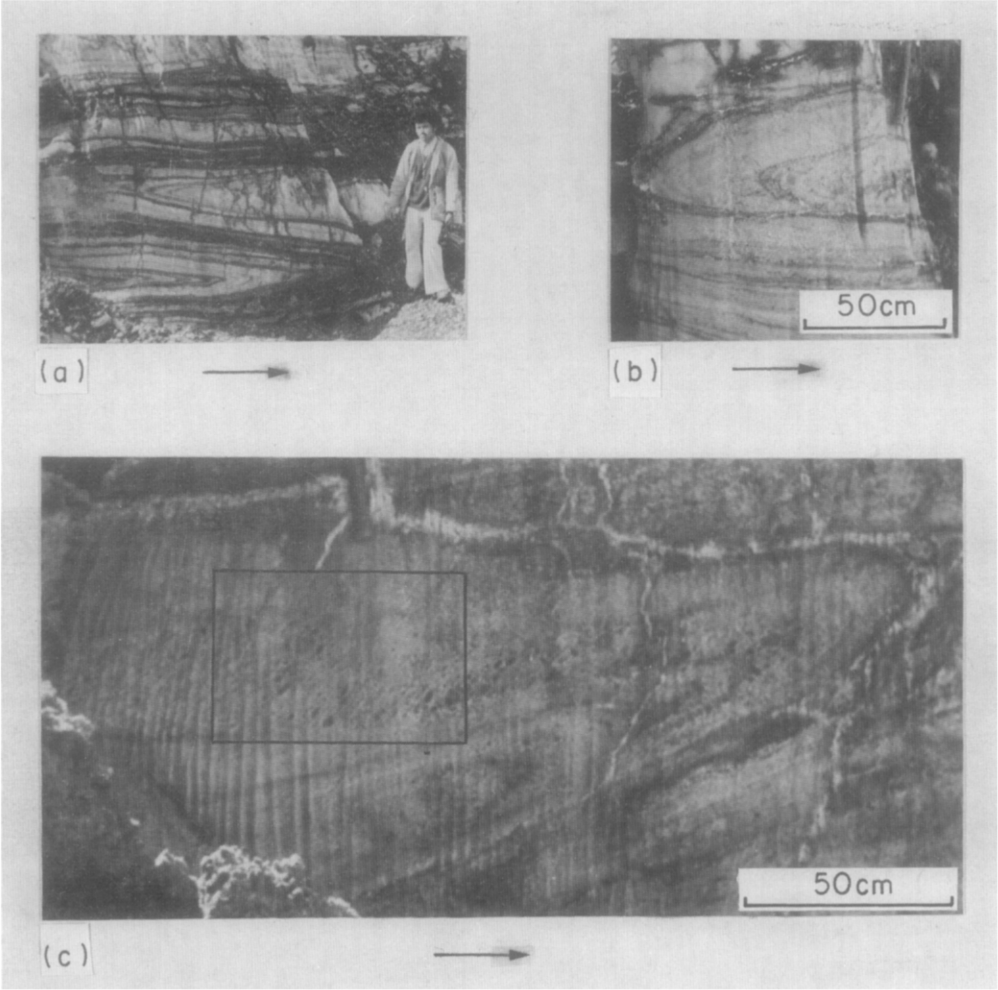

Fig. 4. (a) Isoclinal folds repeating one of the bands of magenta coloured salt which is several metres thick in Fig. 3(g) (in which the location of this photograph is indicated). (b) A lag slide developed on the lower limb of a fold exposed in a pinnacle high on the eastern side of the glacier. Notice the porphyroclasts of halite defining a shape fabric. (c) A thrust developed in the lower limb of an asymmetric fold near the centre of the glacier. The area outlined was analysed for Fig. 6.

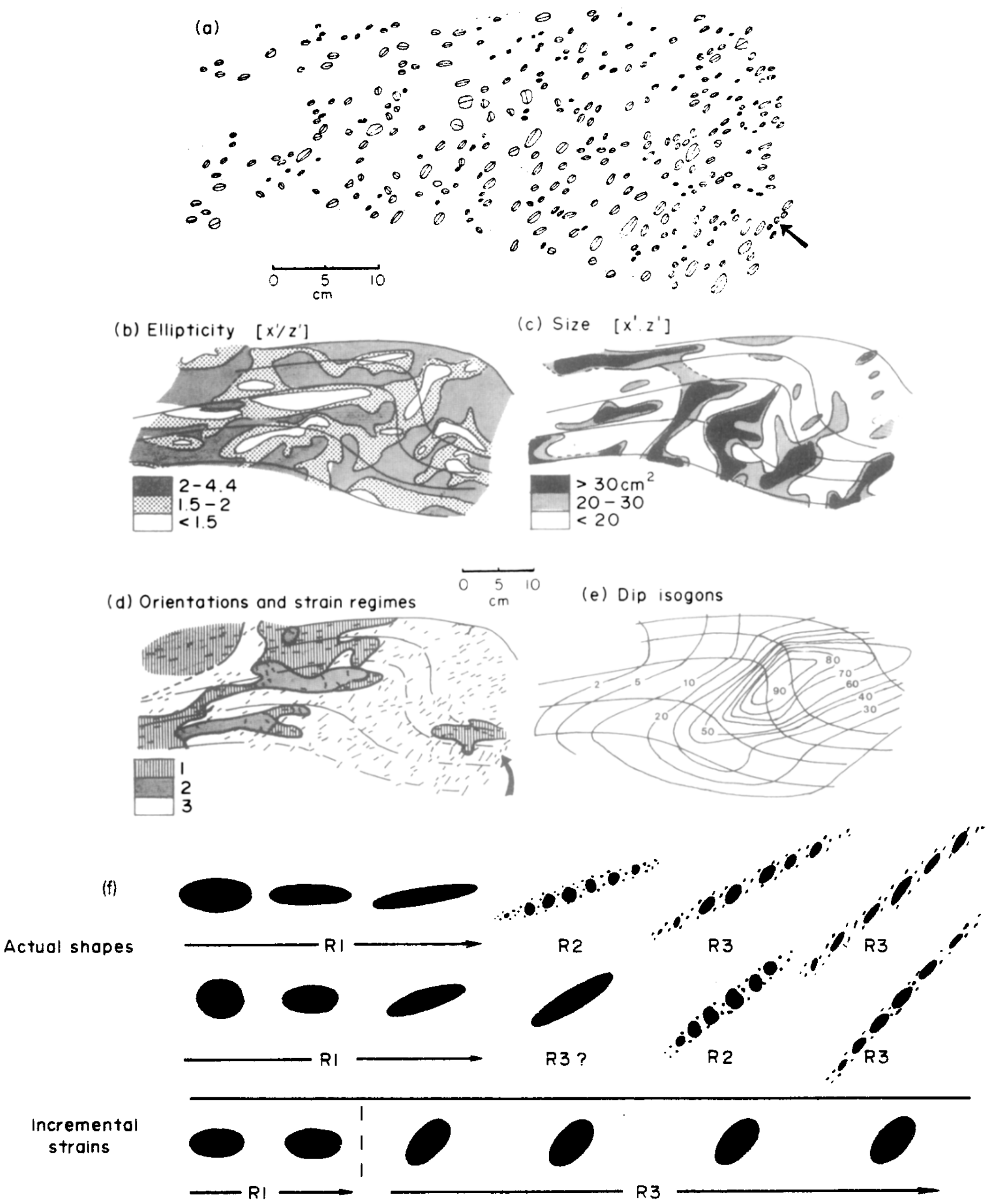

Fig. 6. (a) A tracing of the porphyroclasts exposed in the small immature fold outlined in Fig. 4(c). (b) Contours of the degree of ellipticity of the porphyroclasts in Fig. 6(a). The values shown were measured on a version of Fig. 4(d) 55 cm long. (c) Contours of the 'size' of the porphyroclasts in Fig. 6(a) The values contoured are the product of the longer axis multiplied by the shorter axis for each exposed porphyroclast of halite and relate to their actual dimensions in the field. (d) The long axes of the porphyroclasts in Fig. 6(a) and the three types of strain regime described in the text. (e) Isogons of dip (in degrees) measured relative to the orientation of the colour bands on the left hand edge of the diagram. (f) The shapes (top two rows) of two representative porphyroclasts as they suffer the strain increments indicated in the bottom row and which separate at limiting ellipticities. R1→3 indicate the strain regime such shapes would be classified under in Fig. 6d.

halite porphyroclasts; the three regimes being outlined in Fig. 6(d). Away from where the minor fold is most strongly developed, the long axes of the elliptical grains, together with contours of their degree of ellipticity and contours of their size, tend to parallel the colour bands (regimes of type 1 in Fig. 6d). Where the fold is most obvious all these features tend to parallel either the traces of the axial surfaces of the minor folds or dip isogons (regimes of type 3 in Fig. 6d). The pattern of dip isogons is centred on the steep, shared limb and not the axial surface of the coupled folds (Fig. 6e). In transitional zones (regimes of type 2 in Fig. 6d) the porphyroclasts tend to have low ellipticities and have 'long' axes which differ in orientation from those typical of the other regions; however, rather than being intermediate in orientation, they lie at a large angle to the orientations of those in both the other types of regimes. Regimes of type 2 occur on or near one of the boundaries between regimes of types 1 and 3 in a zone where the dip isogons indicate that the colour bands have been rotated between 1 and 20° from orientations where they have been undisturbed by the minor fold. The boundaries between all the various regimes are irregular but tend to parallel either the colour banding or the traces of the axial surfaces in different places (Fig. 6d).

Figure 6 illustrates a situation in which a local strain fabric, associated with a minor fold, has been superimposed on an earlier and more general strain fabric which is parallel to the colour banding in the limb of the more mature major fold (Fig. 4c). When one homogeneous strain is added to another with a different orientation one might expect such porphyroclasts to record smooth transitional increments of rotation while they steadily increase in ellipticity; such a record is missing. This seems to be because there is a limit to the degree of ellipticity the clear halite porphyroclasts can reach before abruptly separating or recrystallising to smaller 'clasts' which are sub-circular in section. Three particular grains with low ellipticities are indicated in Fig. 6(a) (bottom right, arrowed). These three individual grains were almost certainly derived by the fracturing or dynamic recrystallisation of a single larger grain with an axial ratio approaching 5:1. As well as this obvious abrupt decrease in grain size such imbricate daughter grains are also each probably cores to mantles of much smaller subgrains. The process of breakdown of the large grains to smaller grains occurs in regimes of both types 1 and 3 in Fig. 6 and seems general throughout the glacier wherever the porphyroclasts suffer any significant change of shape. This process means that the porphyroclasts can only record a comparatively short range of increments of the total strain history suffered by the rock mass in which they are found. The limiting ellipticity at which separation or breakdown occurs seems to differ from place to place and appears to depend on the amount of rotation compared to the rate of change of shape of the porphyroclasts in particular areas. In the case illustrated in Fig. 6, the extreme ellipticities in regimes of types 1 and 3, where comparatively little rotation occurs, exceed 4:1. In the margins of domains of type 1, where the larger grains have started to rotate towards the trace of the axial surface of the minor fold, the ellipticities of the porphyroclasts seen in outcrop rarely exceed 3:1.

The manner in which the larger grains separate to smaller daughter grains shortens the long axes of the parent grains considerably more than it does their short axes. Indeed, many of what are interpreted as daughter grains have long axes almost perpendicular to the long axis of the likely single parent grains (cf. Nicholas & Poirier 1976, pp.287 and 294) and such a relationship explains the characteristics of the macroscopic grains in regimes of type 2 (cf. Figs. 6a, d and f). In the process of rotating from the orientations typical of a regime of type 1 to those in a regime of type 3 it is inevitable that large grains separate to smaller sub-circular grains of regime type 2. The new sub-circular daughter grains lose all memory of regime 1 and can only record subsequently imposed increments of strain — and these have the orientation characteristic of regimes of type 3. Such a continual seeding of the deforming rock with sub-circular 'unstrained' grains could be considered as a form of large scale annealing by dynamic recrystallisation. This means that, rather than the smoothly progressive rotation of an old shape fabric, rock salt with an adequate proportion of porphyroclasts abruptly acquires fabrics with new orientations soon after suffering increments of strain with different orientations (Fig. 6f). The colour bands themselves are not lost in this annealing process. Instead they fold where the sub-circular daughter grains within them strain with an orientation different from that of their parent grains and define an easily recognised new foliation which crosses the colour bands and is parallel to the axial surfaces of the folds as they form.

DISCUSSION

Wynne-Edwards (1963) and Hudleston (1977) have suggested that marker bands in flowing fluids or rheids only develop folds where or when the flow lines or particle movement paths cross the bands. The transition from situations in which the flow lines parallel the marker bands to those in which the flow lines start to cross the marker bands is attributed by these authors to changes in the direction or velocity of flow of the material due to changes in the boundary conditions. Observations on the salt glacier agree with this picture — but add another component to the conditions necessary for the generation of folds in this manner, namely the presence of a significant volume of macroscopic porphyroclasts in the salt. All the exposed fold trains in the salt glacier at Kuh-e-Namak can be attributed to either visible or reasonably assumed local or general changes in boundary conditions.

At the moment, the salt glacier appears to be in retreat and it has probably been wasting for some time. Some of the structures described here undoubtedly relate to this currently active general change in the boundary conditions — and many more may do so in unidentified ways. One possible example has been mentioned, where folds indicate that the whole of the salt glacier used to flow over a bedrock ridge whereas only the upper two-thirds do so now (Fig. 3g). Another example involves the damming of part of the glacier entirely. As the glacier

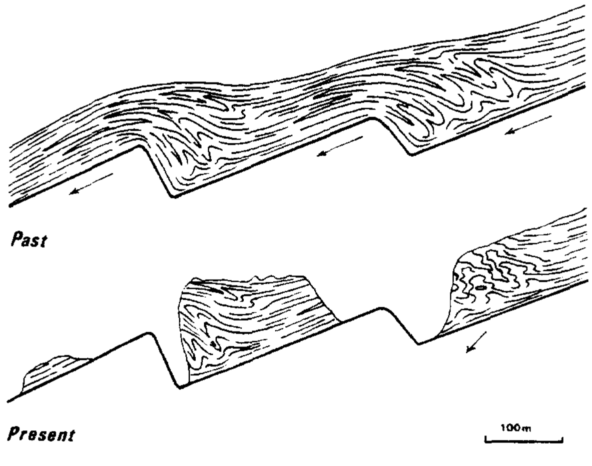

Fig. 7. A diagramatic representation of the wasting of part of the glacier dammed behind ridge A on Fig. 1. The folds indicating that the salt used to flow over both obstructions shown were refolded in the upstream salt mass when it started to flow around the obstruction (towards the viewer).

wasted, part of it eventually became incapable of surmounting a particular ridge of bedrock (ridge A in Fig. 1). Isolated remnants of salt downstream of this smoothed and furrowed ridge of limestone indicate that the salt used to flow over and beyond it. Now, however, a large area of the salt glacier is dammed behind this ridge and the active portion of the glacier flows past it in an impressive 100 m wide shear zone characterised by the only folds with vertical axial surfaces and vertical axes exposed in the glacier (Fig. 1). The dammed salt has not been entirely static however. Parts of it have flowed northwards around the obstruction, and the flow lines established since the dramatic change in boundary conditions has led to refolding of the steep axial surfaces associated with the former flow regime (which surmounted the ridge) about sub-horizontal axial surfaces (Fig. 7). This refolding is very reminiscent of the backfolding in many nappes (e.g. Chadwick 1975 p.53), but in the salt glacier the potential dam was always present and became increasingly effective as the moving mass wasted. The barrier to flow did not rise into place beneath the flowing salt as has been suggested for the massifs inducing back folds in nappes in other metamorphic rocks.

Refolding also occurs in the margins of the salt dome feeding the glacier (Fig. 8). The major folds shown in Fig. 8 probably relate to the rise of the salt up the diapir. The later, smaller folds (bottom right in Fig. 8) indicate gravity-driven flow of the salt over towards, and then down free faces which have different slopes in the middle distance and foreground. Many similar examples of trains of minor folds are seen in the colour bands behind what can only be recently developed free faces near the snout of the salt glacier. Such minor fold trains are the only folds which have been recognised as relating to changes in the top, or side, free boundaries of the salt body.

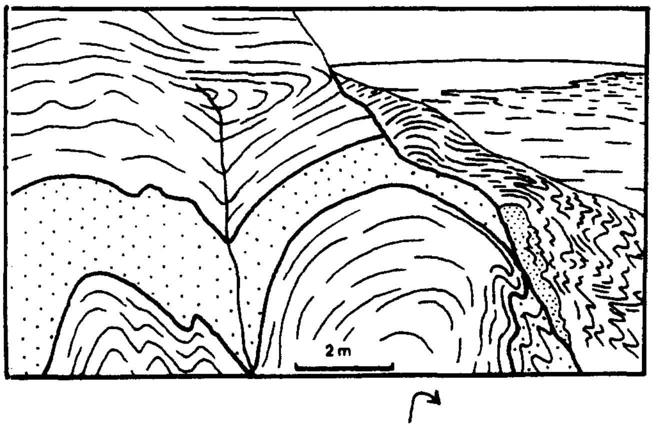

Fig. 8. Part of the western margin of the salt dome. The major folds, associated with the rise of the salt up the diapir, are refolded at bottom right by small scale folds due to gravity driven flow down the free surface of the topographic salt dome. Dotted — pale pink in white salt.

The vast majority of the folds, slides and foliations in the salt body studied appear to relate to irregularities in the bottom and, to a lesser extent, the lateral boundary conditions it meets in its general downslope flow. Such local changes in the bottom boundary conditions are fed back and up through the salt to control the shape of the top boundary to an extent which depends on the local state of the rock salt in the glacier. In the upper reaches of the glacier the whole salt pile folds near obstructions — presumably because the clean coarse grained salt there results in a relatively competent body. Downstream, the glacier decreases in grain size and becomes richer in insoluble minerals and presumably becomes less competent. As this process continues the folding becomes increasingly restricted to disharmonic folding of competent horizons near the base of the glacier. Eventually, near the snout, no folds develop in the glacier as it flows over various major obstructions to flow (right hand side of Fig. 3g).

Figure 9 illustrates cartoons of what are considered the characteristic major features of folds developed in the salt glacier as it flows downslope over bedrock irregularities with different geometries. Variations in individual examples of such fold trains obviously depend on the local material properties of the glacier, its thickness and velocity, and the height and shape of the obstruction. Nonetheless, consideration of the cartoons (Figs. 9a & b) allows a crude approximation of the shape of the rock channel down the complete length of the glacier by downward extrapolation of the exposed structures (Fig. 9c). No independent check on the thickness of the glacier has been possible but the interpretation shown correlates with the bedrock morphology visible at the margins.

Wynne-Edwards (1963) suggested that variations in the rate of movement of flowing fluids would encourage the flow lines to cross any marker bands and so lead to internal folds. One of the characteristics of the salt glacier is that it only flows when sufficiently wet (Talbot & Rogers, in prep.) and this is only likely for, at most, a few weeks each year. Penetrative flow of the salt glacier is therefore episodic and many of the folds within it might be expected to relate to this effect. It is possible, even probable, that one or more individual folds in each train develop during particular episodes of flow — but no other aspect of the folding can be attributed here to the episodic nature of the flow. This is not to say that changes in velocity are not associated with the generation of folds, they are.

The slowing and thickening of a fluid body moving beneath a free surface results in a divergence of its internal flow lines. It is significant that the flow surfaces in the salt glacier, indicated by the foliation, diverge from one another wherever folds form, and converge where these folds become isoclinal and inconspicuous (Fig. 9). It is noticeable that folds form where the glacier slows and not where it accelerates. This is consistent with other fluids which commonly develop instabilities of flow where they decelerate but not where they accelerate. The flow lines indicate that the salt slows just upstream of most partially obstructing ridges of bedrock (Fig. 9a), but in a few cases it slows downstream of them (Fig. 9b). This difference is attributed here to different flow geometries in relation to the slope. Where the

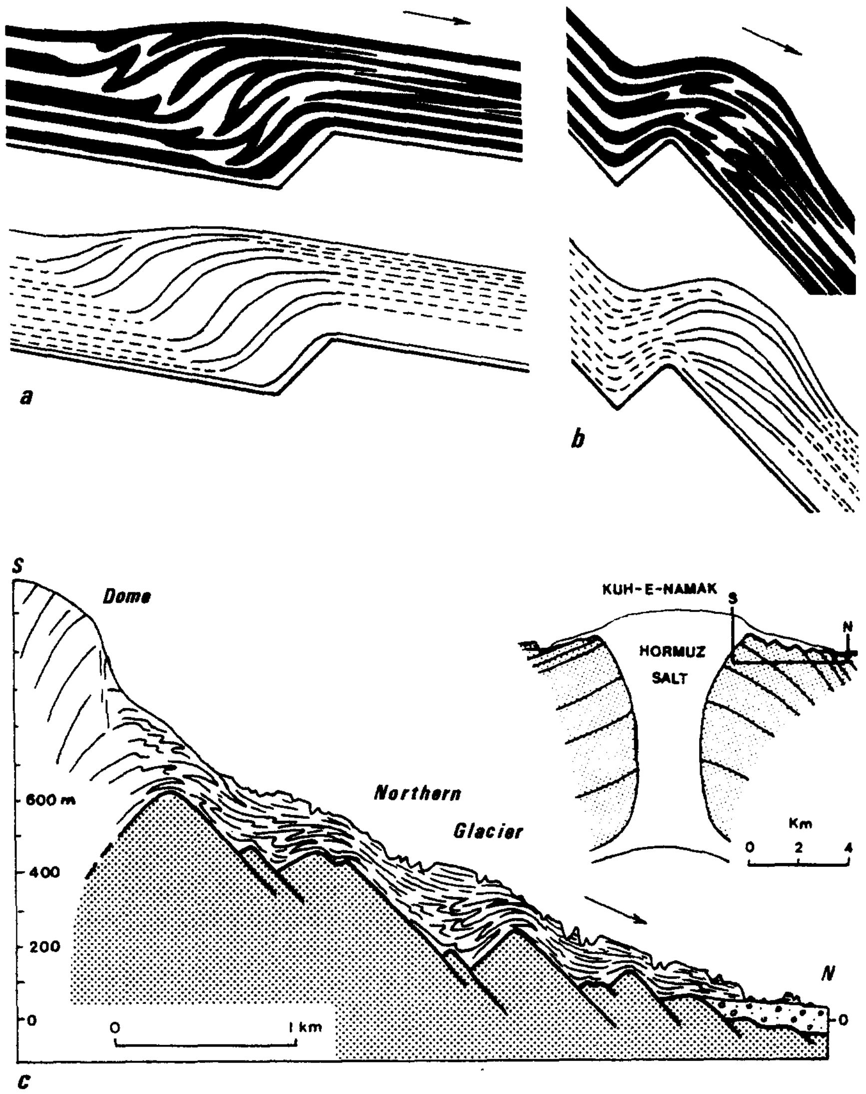

Fig. 9. Cartoons of fold trains in the salt glacier associated with steplike irregularities in the bedrock channel. (a) Top: colour bands in a fold train developed upstream of a step. Bottom: foliation at the same location, dashed where it parallels the colour banding, unbroken where it is axial planar to the folds. (b) A fold train developed downstream of the step. Notice that in both (a) and (b) the folds form where the foliation diverges, and become isoclinal where the foliation converges. (c) A cartoon section down the complete length of the glacier.

glacier slows upstream of such obstacles, it surmounts them by slowing, thickening and changing its direction of flow. In yet other cases the glacier thickens between successive ridges of bedrock and the consequent slowing and inducement of folds occurs downstream of particular ridges (e.g. Fig. 3g).

These changes in the pattern of flow are obviously due to the different boundary conditions encountered by the salt as it flows past irregularities in its channel. As suggested by Wynne-Edwards (1963) and Hudleston (1977) such changes result in folds where the foliation diverges and crosses the colour bands. However, folds do not develop everywhere the flow paths diverge. In the lowest reaches of the salt glacier the colour bands still diverge near obstructing bedrock ridges even though they do not fold. Just where the flow lines in the salt glacier diverge because of particular obstructions depends on the local geometry — but whether or not folds are generated in these locations depends on another factor. The general downstream decrease in competence of the salt succession can account for the diminishing volumes of salt slowed near successive obstructing ridges. Nonetheless, it hardly accounts for the complete absence of folds in the glacier near the obstructing ridges just short of the snout for the flow lines still diverge (right hand side of Fig. 3g). The manner in which the halite porphyroclasts deform in a vertical down-glacier section provides an explanation for the formation of folds where the flow lines diverge along most of the length of the glacier but not where they diverge near the snout.

In stretches of the glacier where the boundary conditions remain constant as the salt flows downslope the shape of the porphyroclasts record more or less irrotational strains, generally a flattening. The long axes of successive generations or porphyrocasts remain parallel to each other and to the colour banding. Where the glacier slows on encountering new basal boundary conditions the porphyroclasts tend to undergo external rotation while changing shape with internal rotation. The rate at which individual porphyroclasts rotate towards the orientation representative of the strain regime they have just entered depends on the rate at which they are translating compared with their rate of straining. However, their shape as they enter the new strain regime is also important. A highly elongate elliptical grain will rotate only slowly compared with a less elliptical grain. A circular grain need not rotate at all, it will immediately record the orientation of the newly imposed increments of strain undisguised by any record of any proceeding strain history.

A body of porphyroclastic rock salt entering a regime of strain with a new orientation at a uniform rate will probably contain porphyroclasts of halite with a wide range of more or less elliptical sections. Each macroscopic grain will start to rotate towards the new orientation at a rate dependent on its shape. The least elliptical grains will rotate fastest and their long axes will soon parallel the orientation of the local increments of strain. The most elliptical grains entering the new regime, those rotating most slowly, are closest to separating into subcircular daughter grains even without the rotational component which will probably accelerate such breakdown. Each new set of sub-circular daughter grains will immediately start recording strains with the new orientation. In a comparatively short distance therefore all the macroscopic grains will be recording strains with the newly imposed orientation.

The continual episodic annealing of the macroscopic porphyroclasts of halite within the salt glacier means that the foliation is continually being regenerated. The foliation traces the quite simple flow paths of the salt but its regenerative aspect is not obvious until the colour bands start to fold about it. Nonetheless, it is important to appreciate that the foliation is being continually renewed wherever a significant proportion of porphyroclasts make up the rock mass. Where the flow of the glacier is down a smooth channel the foliation regenerates parallel to the colour layers which therefore effectively mark the flow planes. Where the glacier is slowed by irregularities in its channel the foliation is still regenerated parallel to the flow planes but these are now oblique to the colour banding. The shape of the colour bands reflects the sum of the strains of their component grains. Obliquely imposed elongation therefore results in local thickenings of the colour bands, and these thickenings propagate upwards as folds towards the free surface of the glacier, to an extent dependent on the competence of the materials involved. Where the flow planes converge, the folds become isoclinal and the colour bands in the limbs once more become parallel to the foliation and the flow lines.

An obvious explanation for the absence of folds near the snout, even where the flow lines diverge, is that the few macroscopic porphyroclasts which have survived this far downstream comprise an insufficient proportion of the rock to result in the regeneration of a new foliation oblique to the colour bands. With so few porphyroclasts the old foliation in the fine grained groundmass appears to be capable of rotating into new orientations so smoothly that it remains parallel to the colour bands.

Foliations in ice appear to define planes of simple shear so that the long axes of strain ellipses on a large scale only parallel the foliation after immense strains (Hambrey 1977). In contrast, the porphyroclasts which locally define the foliation in the rock salt of the glacier appear to define the XY principal planes of strain ellipsoids which record only the last few increments of strain suffered by the rock as a whole. The foliation is therefore continually being regenerated in porphyroclastic rock salt. The way in which new foliations generate in ice is obscure (Hambrey & Milnes 1977 p.681). It is perhaps significant that new foliations often emerge from beneath the chaotic blocks of ice falls and it is possible that the ice is annealing in such falls so that beyond them it can only record subsequently imposed increments of strain.

A large number of irregularities in the flow channel of the salt glacier is indicated by the numerous fold generation zones developed in the salt. If glaciers of ice do not have such internal structures this could be for one or two reasons: either that old foliations in ice are able to rotate smoothly without missing increments of rotation; or because the bedrock channels of ice glaciers have been smoothed by erosion. Smooth glacial channels are to be expected on a planet which has recently suffered a prolonged period of episodic glaciation, ice sheets and glaciers advancing over previous unglaciated scenery might develop more internal structures than those we see now.

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