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En Echelon Crack-Arrays in Potash Salt Rock

By

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Summary

There are two types of fracture patterns in the yield pillars of the potash mines of Saskatchewan. The individual members of both patterns are tensile (extension) fractures that propagate parallel with the maximum principal stress trajectory (perpendicular to the minimum principal stress). The difference between the two patterns lies in the arrangement of the member fractures. In the *en echelon tensile crack-array*, the macroscopic fracture consists of individual tensile cracks that are slightly offset from each other. They have only a small overlap and the child crack seems to form randomly on either side of its parent. Consequently, the en echelon tensile crack-array inherits the axial orientation of its members. In contrast, the tensile cracks of an *en echelon shear crack-array*, have a larger overlap and their lateral displacement from each other is biased in one direction. Therefore, the crack-array is no longer axial but inclined 20–25 degrees from the maximum principal stress direction. With increasing stress, the shear crack-array often collapses, forming the *envelope* or *hourglass* structures of the potash mines.

1. Introduction

At room temperature and pressure, salt rocks are the most ductile (deformable without fracture) of all the rock types (e.g. Barr, 1977; Aubertin et al., 1991). The main constituents of potash salt rock, halite (NaCl) and sylvite (KCl), are isometric cubic crystals having several internal slip-systems that can accommodate large plastic strain (ductile intracrystalline strain resulting from the glide and climb of dislocations; Senseny et al., 1992). At room temperature and pressure, however, only two of the slip systems are active (Groves and Kelly, 1963), while the number of independent systems necessary for homogeneous plastic deformation is actually five (Von Mises, 1928). Consequently, salt rocks cannot deform homogeneously in a purely plastic manner. The large permanent strains that accompany salt mining are therefore, in part plastic and in part brittle. Brittle deformation is the outcome of microfracture, the nucleation of cracks (tensile fractures of the microscopic scale) at points of stress concentrations and their propagation along the maximum principal stress trajectory (Carter and Hansen, 1983; Horseman and Passaris, 1984;

Skrotzki, 1984; Skrotzki and Haasen, 1988). In addition to the two salt crystals, the potash rocks of Saskatchewan contain up to eight percent miscellaneous matter, mainly clays. The clays seem to deform in a ductile manner, usually without microfracture. The total permanent strain in potash salt rock therefore comes from several sources: intracrystalline plastic strain, microfracture (brittle strain), ductile strain from grain-boundary sliding, and deformation of the clays.

At the microscopic scale, fracture propagation inside the two salt crystals is controlled by the cubic cleavage system. Fractures at the macroscopic scale of laboratory test specimens and the physical models of mine openings are actually made up of small segments that, at the microscopic scale, either follow cleavage or grain boundaries forming a zig-zag pattern (Fig. 1). Fracture in salt rocks is not limited to the microscopic scale. Vertical tensile fractures that are several meters long are common in the potash mines of Saskatchewan (Fig. 2). The mines operate at a depth of about one kilometre. Considering that the uniaxial compressive strength of the salt rocks is in the 18–25 MPa range and that the extraction rate is around 40 percent, most of the pillars and the abutments are subjected to stresses that are very close to maximum compressive strength. Some of the pillars, called

Fig. 1. Tensile fracture at the microscopic scale is controlled by the cubic cleavage of salt crystals (the 30 mm long, straight fracture) and by grain boundaries (top)

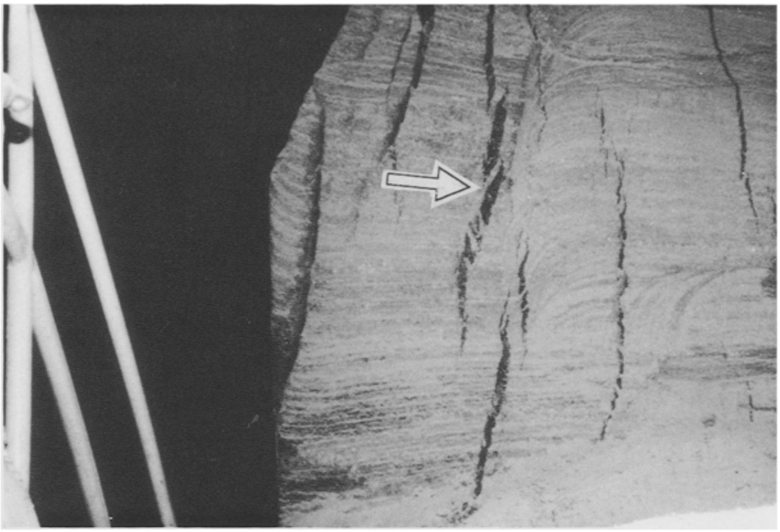

Fig. 2. Looking at a three meter high face of a yield pillar at the Cominco mine in Vanscoy, Saskatchewan. Vertical extension fractures are common features in yield pillars. Even fractures that seem to have propagated as a single fracture are not continuous. The arrow points at a fracture that has at least three separate major segments, each slightly offset from its neighbour. Large tensile fractures seem to grow out of en echelon tensile crack-arrays after the rock bridges separating the individual members of the array are destroyed. Cross-cutting slabs inside the segments mark the position of rock bridges that had already been destroyed

yield pillars, are actually allowed to yield and/or fail entirely. Tensile fractures are particularly common in yield pillars. They range in size from microscopic to room-size (3–5 meters). A large tensile fracture is not a single fracture plane however; it consists of many individual segments that are slightly offset from each other. Pillars that have completely collapsed illustrate the fracture process at a more advanced stage (strain softening phase). These may, in addition to tensile fractures, show some inclined (to the principal stress and the associated tensile fractures) and gently curving structures, which are called in the mines, *envelope* or *hourglass fractures* (Fig. 3). Although the envelopes lie in planes of shear stress, they are not really shear fractures. The fracture surfaces are rough, show no slickensides or any other evidence of shear displacement. Eventually, the blocks of rocks that are bounded by the outer free surface, the inner envelopes and the pervasive tensile fractures, peel off the walls (Fig. 4), slowly narrowing the pillar at mid-height.

The primary goal of this investigation is to examine the role of brittle fracture in the failure process of potash and to reproduce the observed fractures under laboratory conditions. The laboratory investigation followed two lines. First, standard laboratory experiments (uniaxial and triaxial tests) were conducted to describe the evolution of brittle fracture as a function of stress and time by tracking the dilation of the test specimens. Second, physical models using potash salt rock were prepared to follow the evolution of discrete fractures around cavities, again as a function of stress and time. The testing procedures and the laboratory conditions have been described elsewhere (Duncan, 1990; Carter, 1992a).

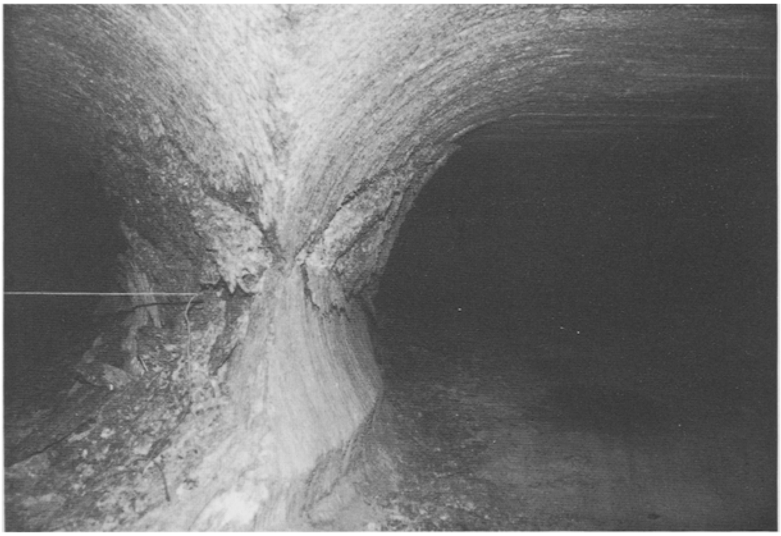

Fig. 3. A heavily stressed pillar at the Rocanville mine of the Potash Corporation of Saskatchewan displaying the hourglass structure. Spalling of this three meter high pillar is accomplished by the separation of blocks of potash along gently curving hourglass and vertical tensile fractures (the latter not shown on this photograph)

The rock for the standard laboratory tests and the physical models was obtained from two potash mines operating in the Saskatoon area of Saskatchewan, the Lanigan mine of the Potash Corporation of Saskatchewan and the Vanscoy mine of Cominco Fertilizers Ltd. Both mines operate in the Patience Lake member of the Prairie Evaporite Formation (Worsely and Fuzesy, 1979).

2. Microfracture in Laboratory Tests

In the standard laboratory experiments (uniaxial or triaxial compression), fracture evolution is rarely observed directly. Many aspects of microfracture and, in particular, its dependence on stress can, however, be inferred from the full set (axial, lateral and volumetric) of stress-strain curves (Fig. 5). In brittle rocks, deformation at low stress is largely elastic and the onset of microfracture (the crack initiation point) is clearly displayed at the point where the initially linear lateral or volumetric strain curve deflects. This would typically occur between 1/3 to 1/2 of the peak stress (strength). In potash, the onset of microfracture is more difficult to identify. The stress-strain curves are not linear at any stress (Lajtai and Duncan, 1988). There is no distinct deflection point either. Nevertheless, in uniaxial compression tests, both the axial and the lateral strain rate seem to accelerate between 10 and 11 MPa. Since tensile crack propagation along the maximum principal stress trajectory does not directly produce axial strain, the extra strain must come from the plastic yielding of the salt crystals. Identifying the start of the brittle mechanism is made difficult by the large ductile strain that may mask the small increase in lateral strain caused

Fig. 4. Section of a 500 mm high block of rock removed from a failed pillar at the Central Canada Potash mine in Colonsay, Saskatchewan. On the left, the block is bound by an hourglass fracture; on the right, by a vertical tensile fracture. There are numerous, small tensile fractures inside the block and a few inclined structures that seem to parallel one or the other bounding surface on the left. The arrow points to an internal inclined en echelon shear crack-array. The sketch at the lower right corner shows the relative position of the block in the pillar

by microfracture. This is certainly the case in Fig. 5. The volumetric strain curve is somewhat more reliable in signalling the entry of microfracture, because the extension due to microfracture and the compression caused by yielding produces an inflection point on the volumetric strain curve. For the uniaxial compression test shown in Fig. 5, this occurs at the relatively high stress of 19 MPa. With continuing microfracture, the strain soon reverses direction (*the strain rate reversal* or *crack damage point*), indicating that at high stress, brittle deformation through microfracture dominates over the ductile strain producing processes. It would appear, that crack initiation in potash occurs at a higher stress than in brittle materials, and can be as high as 75% of strength. It is a fact, however, that the location of the crack initiation and the strain rate reversal points are loading rate dependent (Fig. 6); both decrease with increasing loading rate. The yield point, on the other hand, is much less affected. At high loading rates, potash behaves in a brittle rather than ductile manner. At very slow loading rates, material behaviour becomes more ductile; there may not be microfracture at all. For the slowest rate test shown on Fig. 6, the stress

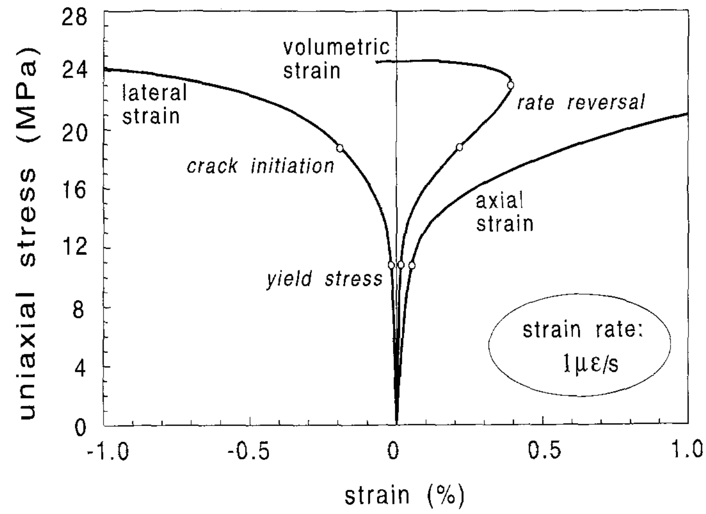

Fig. 5. The stress-strain curves of a uniaxial compression test using potash from the Lanigan mine. The volumetric strain curve displays the three important pre-failure milestones in the deformational history of potash: the yield stress, the crack initiation and the volumetric strain rate reversal

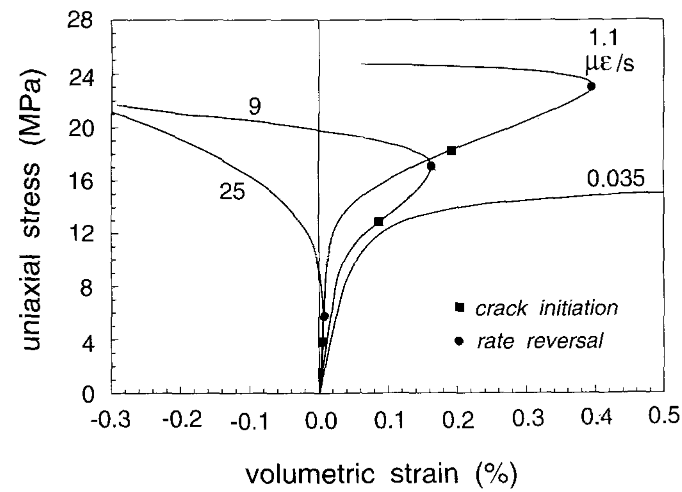

Fig. 6. The crack initiation and the volumetric strain rate reversal stress are strongly dependent on the rate of loading. The labels on the volumetric strain curves identify the average strain rate used in the test. The strain reversal stress drops sharply as the loading rate is increased. The yield stress is less sensitive to the loading rate. As a result, potash behaves like a brittle material when loading is rapid

did not rise above 16 MPa. After three months of testing, the specimen was about 20 percent shorter. It did however have numerous axial cracks as well.

The relationship between the plastic and the dilational brittle lateral strain is noticeable in the creep of potash as well (Fig. 7). In an incremental-load, creep series

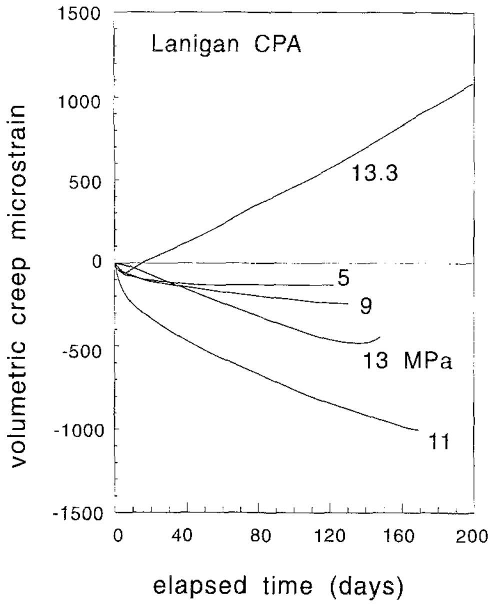

Fig. 7. The interplay between the plastic and the brittle mechanisms of deformation is reflected in this set of volumetric creep strain curves. At relatively low stress (< 12 MPa), only the plastic mechanism is active, i.e. an increase in stress leads to higher compressive volumetric creep strain. This trend is slowly reversed through microfracture. This process is displayed by the 13 MPa creep curve. At high stress (> 13 MPa), brittle deformation dominates over the plastic and the other ductile processes

(Lanigan CPA), the individual volumetric creep strain curves for 5, 7 (not shown for the sake of clarity), 9 and 11 MPa display the expected increase in compressive creep strain with increasing stress. The volumetric creep strain at 13 MPa is compressive only at the beginning; the volumetric strain rate changes to dilation after about 140 days. In another creep test (a different specimen from the Lanigan mine), using the slightly higher load of 13.3 MPa, the rate reversal from compression to dilation, i.e. to microfracturing, occurred much sooner, after only six days. The process of microfracture seems to accelerate above 13 MPa. All specimens loaded above this level, will normally enter into tertiary creep and eventually fail (Duncan and Lajtai, in press).

The stress-strain and the creep curves, produced by standard laboratory tests, are valuable in providing a general description of the deformational process under the relatively homogeneous stress condition of the standard laboratory compression test. Since the creep strain in salt rocks is very sensitive to temperature and humidity changes, the specimens must be properly insulated from the surrounding environment and direct and continuing observation of the fracture process is not practical. Examination of the specimens at the end of the test suggests that during the strain-hardening phase and somewhat beyond it, the fracture of salt rocks involves the propagation of a large number of tensile cracks that normally run parallel to the axially applied maximum principal stress. If the cracks deviate from this course, they do so for microstructural reasons. In salt rocks, the cubic cleavage and the grain boundaries of this polycrystalline medium seem to control the crack path at the microscopic scale (Fig. 1). At the macroscopic scale of the test specimen, the principal stress directions are controlling the propagation direction. The larger tensile fractures of the test specimens are similar to their counterparts in the mines. In detail, the large tensile fracture is made up of a number of shorter segments that are laterally displaced from each other with a small overlap at their tips (Fig. 8). The magnitude of displacement can be quite small (usually a fraction of a millimeter) and its direction appears to be random; it may occur either to the right or to the left of the cracktip. Consequently, this whole system of related, closely spaced cracks, *the en echelon tensile crack-array*, is oriented axially, in the direction of the maximum principal stress.

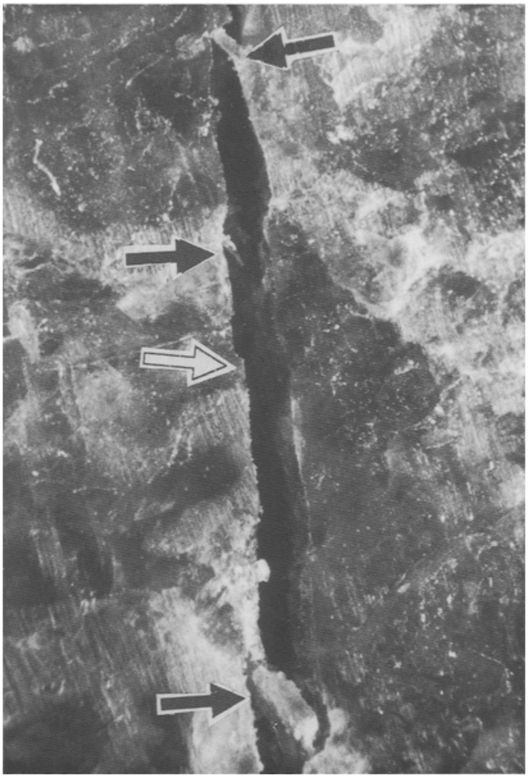

Fig. 8. A 30 mm long axial fracture in a cylindrical Lanigan potash specimen tested in triaxial compression. Note that the present fracture must have evolved through the union of several shorter segments (daughter cracks or step-outs), slightly offset from each other. The three black arrows point to rock bridges that are disintegrating. The white arrow marks a position where only a small jog suggests the position of an earlier step-out

Only in the post-peak, strain-softening phase may one see the appearance of inclined (so-called shear) fractures. Such inclined fractures may not even form in uniaxial compression tests. The specimen may simply disintegrate by the buckling of the slabs of rock created by the propagating tensile fractures. Even a small confining pressure can, however, prevent large-scale buckling. Thus, in triaxial tests, the formation of inclined fractures becomes the norm rather than the exception. The formation of an inclined fracture is a long, complex process. Initially, there is an en echelon arrangement of short, overlapping, tensile cracks. The individual cracks form parallel with the compression direction, but the fracture zone formed by them trends at an angle (20–25 degrees) to the maximum principal stress direction (Fig. 9). Since the zone lies in a plane of shear, the name *en echelon shear crack-array* seems to be appropriate. With further deformation in the strain-softening phase, the shear stress that exists along the inclined trend seems to cause bending, buckling and/or rotation of the rock slabs between the member fractures. Eventually, the whole en echelon array collapses forming a crushed rock zone. In the standard laboratory test, shear displacement normally takes place along the crushed zone. At this point, a shear fracture or fault is formed (Fig. 10).

Fig. 9. The early stages of forming an inclined fracture is shown in this coarser grained, 120 mm high potash specimen coming from the Rocanville mine. Small slabs of rock are bounded by cleavage and form an en echelon shear crack-array. The rock slabs are in the early stages of buckling. Note the steep slope of the fracture array, only 25 degrees with the uniaxial loading direction

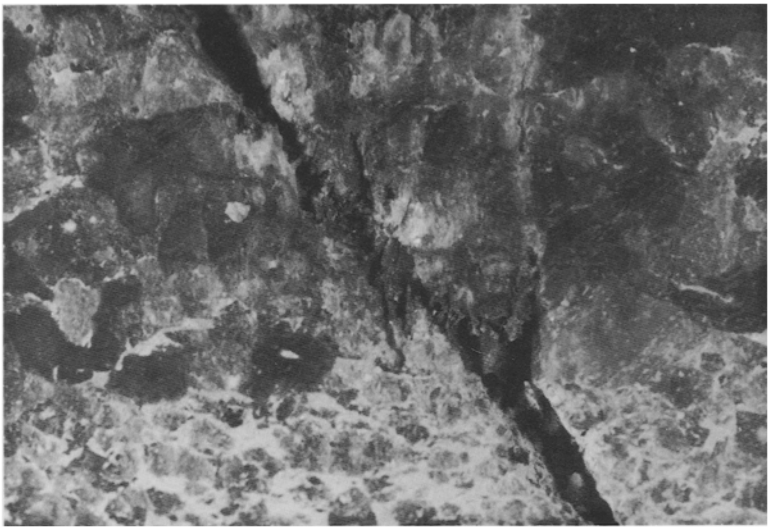

Fig. 10. With continuing deformation during the strain-softening phase, the en echelon arrangement of tensile cracks of Fig. 9 will collapse through the buckling and fracture of the intervening slabs. The structure formed through this process looks like the "shear fracture" in this triaxial specimen of Lanigan potash. The loading direction is vertical. The length of the shear fracture is 50 mm

3. Discrete Fracture in Physical Models

A good environment for growing and simultaneously observing individual fractures is the heterogeneous stress field around cavities. Here, fractures nucleate and extend under a variety of stress conditions. For the uniaxial loading of a physical model that contains a central cylindrical cavity, there are three different stress regions and associated fracture types (Fig. 11):

1. The primary region, where the stress field is tensile. The fracture that nucleates at the perimeter, at the point of the tensile stress concentration, is called the *primary fracture.*
2. The remote region, where the stress field is a combination of a compressive maximum and a tensile minimum principal stress. Fractures that form here are called the *remote fractures.*
3. The compression zone at the two sides of the cavity, where both principal stresses are compressive. The fracture process is called slabbing or spalling, and the individual fractures, *slabbing fractures.*

Fractures in the three regions develop at different uniaxial loads. In uniaxial compression, the usual sequence is from primary through remote to slabbing fracture. Although there are some differences in the detail of the fracture patterns forming in the three regions, the individual fracture is always a tensile fracture that nucleates at a stress concentration point and then extends along the maximum principal stress trajectory.

3.1 *Fracture Patterns in the Physical Models*

Four physical models of cylindrical cavities (Fig. 11) were tested to observe the development of fracture patterns and to collect quantitative data on the total crack length as a function of increasing uniaxial load and elapsed time at constant load.

In a loading experiment, the first fracture is normally the primary, and the last is the slabbing type of fracture. Remote fractures are the most abundant; they form, extend and proliferate over a wide range of stress levels. The high crack density around holes at high stress is usually due to the extension and proliferation of remote fractures.

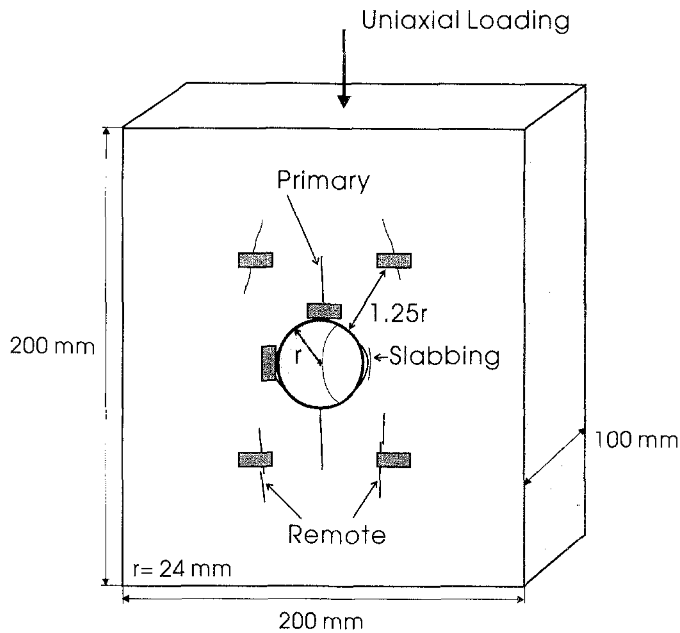

Fig. 11. The typical fracture pattern around a cylindrical cavity in Lanigan potash model that had been loaded by a vertical uniaxial load. Strain gauges (shaded rectangles) were used to signal the nucleation of primary, remote and slabbing fractures

The primary fracture nucleates at the tensile stress concentration of the cavity perimeter at a stress level that is somewhat dependent on the size of the hole (Lajtai et al., 1992). The primary fractures do not travel far in potash; their extent at the collapse of the model as a whole ($\sim$22 MPa) is usually limited to less than 50 mm. Primary fractures are single fractures; they rarely generate off-set cracks.

Remote fractures form a complex pattern. The expected nucleation point for the first remote crack lies at a polar angle of 60 degrees and at a distance of about 60 mm from the centre of the hole (Fig. 11). The elastic stress distribution at this point would give a compressive maximum principal stress and a tensile minimum principal stress. Once nucleated, the individual remote fracture extends with increasing load. It does not propagate as far as the primary fracture, however. In these models, the average remote crack length is about 20 mm which can be compared with the 30–40 mm long primary fracture. Although the extension of an individual remote fracture is soon arrested, the process of fracture propagation continues through the formation of *daughter* or *step-out* fractures. With increasing load, several step-outs may form, giving rise to a slightly overlapping en echelon pattern that trends along the maximum principal stress trajectory. This is then an *en echelon tensile crack-array* (Fig. 12). Whether the step-out nucleates to the right or to the left of the parent crack seems to be arbitrary. In general, there is a balance of left and right step-outs so that the axial trend of propagation is preserved. The rock bridge between the overlapping segments is highly unstable. With increasing load, small microfractures may form in the bridges and the small slabs bounded by them tend to buckle and then break off, eventually destroying the bridge completely. With the bridge destroyed, the two fractures unite to form a single, longer and wider fracture which is still oriented along the maximum principal stress trajectory. In some cases, the earlier position of the rock bridges remains marked by the presence of small broken slabs of rock (Fig. 13). From the nucleation point and with increasing load, the crack-array extends both away from and toward the cavity. Those which propagate toward the cavity, enter into the high compressive stress

Fig. 12. A remote, en echelon tensile crack-array at two times magnification. The rock bridges are still well preserved, although buckling already commenced at the bottom

Fig. 13. Here the union of the members of an 80 mm en echelon tensile crack-array is almost complete. The site of the earlier step-out positions is however marked by the small rotated rock bridges

region, where they may form the shear type of the en echelon pattern (Fig. 14). This is very similar to the *en echelon shear crack-array* observed in the standard laboratory specimen (Fig. 9). The individual fractures are shorter (5–10 mm) than the regular remote fractures and they are more closely spaced with larger lengthwise overlaps. It would appear that the proximity of the free surface of the cavity places a bias on the left or right direction of the step-out. The step-out direction is no longer random; daughter cracks form on one side only, away from the free surface. As a result, the en echelon array no longer follows the trend of the maximum principal stress direction, rather it is distinctly inclined to it.

Slabbing is a high-stress phenomenon. In order to preserve the models for mapping the remote fractures, the models were not loaded high enough to show more than the initial sign of instability at the two points of the compressive stress concentration.

3.2 Stress Dependence

The second purpose of the physical modelling was to obtain some quantitative data on fracture propagation as a function of stress and time. This was accomplished by

Fig. 14. Close to the perimeter of the cavity, the tensile cracks are shorter and the step-out is biased in one direction, away from the free surface. There is also a larger overlap between neighbouring cracks. As a result, a 30 mm long fracture zone formed, trending at an angle to the local principal stress direction

mapping the exposed surface of the models after prescribed load or time increments. The measured data on crack length are presented in the form of *total crack length*, which is a sum of the length of all the mapped fractures. The *total crack length* was plotted against either the uniaxial load or, for the creep tests, against the elapsed time. The fractures do not, of course, form under uniaxial stress conditions. The stress distribution in a fractured medium however is complex; its nature and effect on controlling fracture and the numerical modelling of discrete fracture is beyond the scope of this paper.

The propagation of a primary fracture is stable (Fig. 15). This figure collects extra data from several, earlier tests (Carter, 1992a) as well. The trend of the data shows that with increasing uniaxial load, higher and higher load increments are necessary to extend the primary crack by the same amount. The fitted curve is negative exponential. Primary fracture propagation normally comes to a complete halt before the collapse of the model.

An individual remote fracture propagates in the same stable manner as the primary fracture. It extends to an average length of about 20 mm and then it stalls. This is not, however, the end of fracture propagation. With increasing load a new

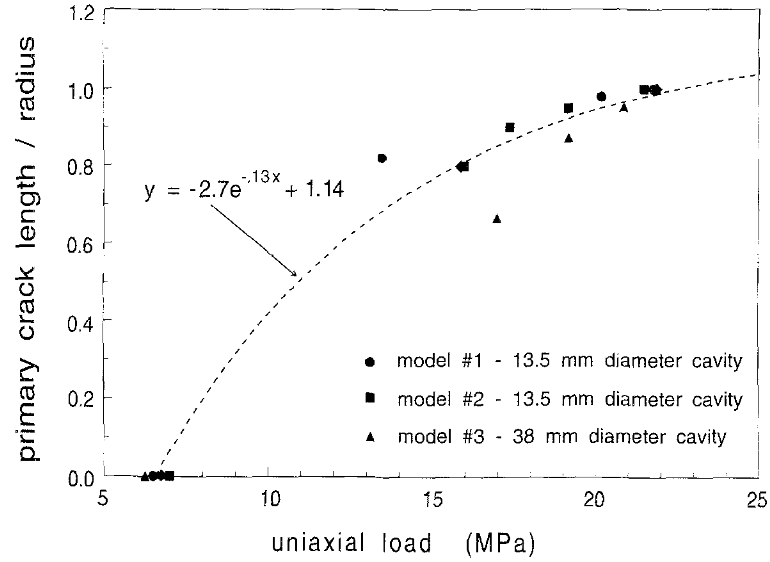

Fig. 15. The propagation of primary fractures as a function of the applied uniaxial compressive load. This figure collects data from three physical model tests that used Vanscoy potash as the prototype material. The trend of the data and the fitted curve suggests that the process is stable. As the crack length increases, greater and greater stress increments are necessary to advance the crack tip by the same distance

fracture, slightly offset from the crack tip, nucleates and then extends in a seemingly stable manner. This process is repeated at other locations as well and with increasing stress, the fractures seem to proliferate rapidly. Although, the individual fractures are seen to extend in a stable manner, the *total crack length* increases in an unstable manner (Fig. 16); smaller and smaller load increments are necessary to increase the *total crack length* by the same amount (Fig. 16, bottom graph). The relationship between *total crack length* and the uniaxial load is now positive exponential. The fitted curve approaches an asymptote at 14 MPa.

3.3 Time Dependence

At constant load, fractures in potash salt rock may nucleate, extend, step-out and multiply with time. In fact, the influence of elapsed time is qualitatively similar to the effect of increasing the uniaxial load. Three creep experiments, using 7, 10 and 13 MPa for the constant load were conducted. The target loads were approached as rapidly as possible with a manual pump. The model loaded to 7 MPa had only a single primary crack. No further cracking was observed over the next 300 hours. The 10 MPa test is shown in Fig. 17. At the beginning of the experiment, there was only one remote fracture and two earlier formed primary cracks. With time, the fracture process evolved to a stage where the whole block was covered by fractures. Nevertheless, the decreasing slope of the *total crack length* vs. time curve (bottom right of Fig. 17) suggests that at this stress, the process of crack extension is stable. The nature of crack extension, whether it is stable or unstable, is however load

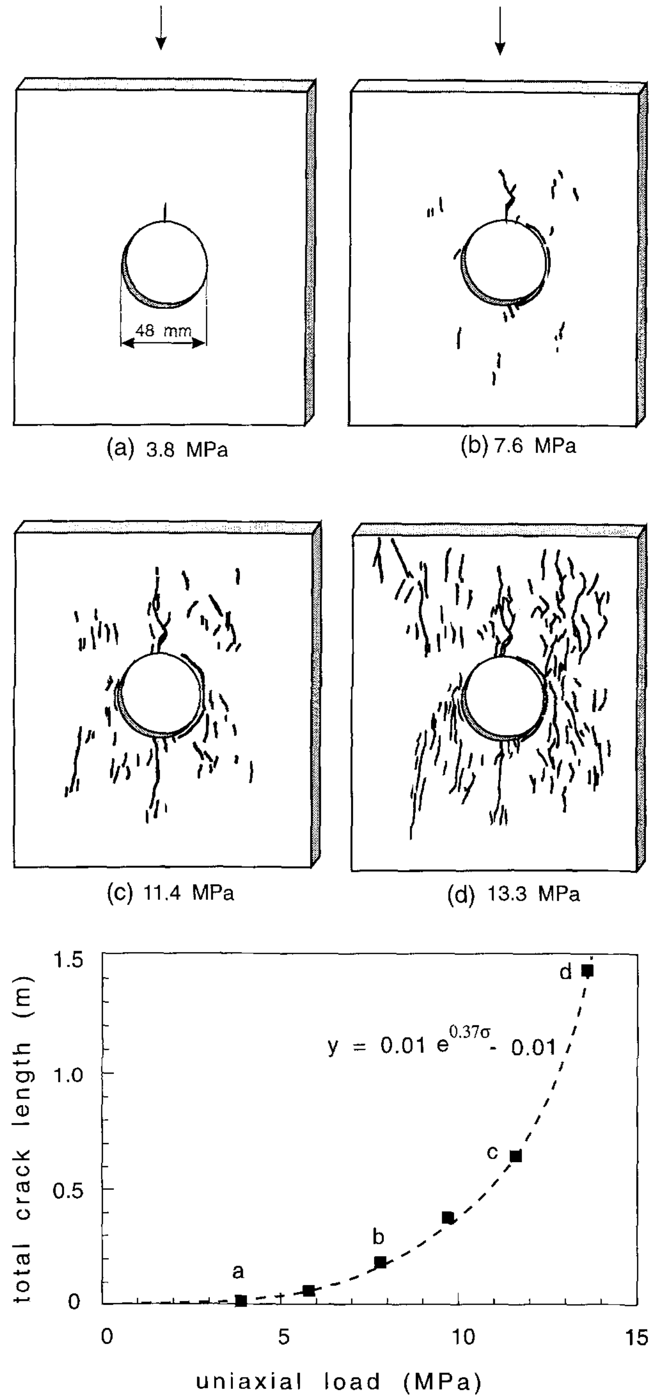

Fig. 16. Maps of the fracture pattern during a uniaxial compression test of a block of potash containing a cylindrical cavity. Fractures are mostly remote to the cavity. The total crack length increases exponentially, suggesting that the process is unstable. The fitted curve has its asymptote at 14 MPa

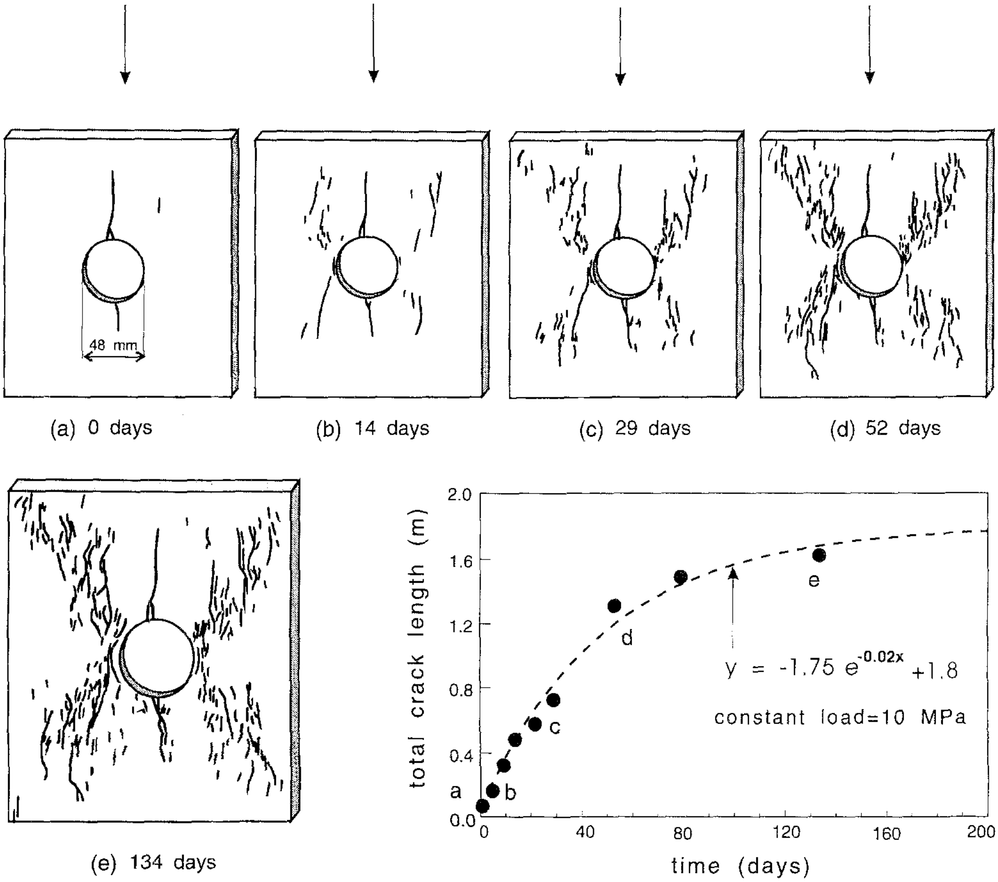

Fig. 17. Maps of the fracture pattern during static loading at 10 MPa, showing that remote fractures grow and proliferate with elapsed time as well as with increasing stress. At 10 MPa, the total crack length increases in a stable manner

dependent. In the last test, using the higher 13 MPa load, the *total crack length* increased in an unstable manner with the model disintegrating after 310 hours.

4. Discussion

In many respects, the observations presented here and the interpretations offered for them are not new. The concept that tensile microcracks may form and then propagate in compressive stress fields has been known since Griffith's time (Griffith, 1924). The process of microfracture-caused dilation was observed, accurately described and interpreted more than 60 years ago (Richart et al., 1928). The hypothesis that shear fractures grow out of en echelon crack systems has been postulated many times before (e.g. Brace, 1964). The role of buckling in the formation of faults in brittle rocks was proposed by Fairhurst and Cook (1966). A few years later, the process was modelled analytically by Peng and Johnson (1972). In the geological context, the concept of en echelon fracture patterns or shear zones has similarly been around for decades (e.g. Ramsay, 1967). The propagation of tensile cracks in single crystals by stepping from one cleavage plane to another has been reported many times (e.g. Kranz, 1983). At the much larger field scale, the formation of daughter cracks at the tip of parent cracks has been described and analyzed by Pollard et al. (1982).

The new element is the concept that en echelon tensile crack systems are fundamental to the formation of both tension and shear fractures. For this potash salt rock, the evidence, that tensile fracture propagation involves the continuing generation of daughter cracks and their union after the destruction of the rock bridge between them, seems to be overwhelming. Evidence comes from all scales of observation, ranging from step-out fractures in a single crystal of halite (Fig. 18) to the large tensile crack-arrays of the yield pillars (Fig. 2). In physical models, the evolution of en echelon tensile crack-arrays have now been observed while modelling with the Saskatoon type potash salt (Lanigan and Vanscoy mines), with Lac

Fig. 18. An en echelon tensile crack-array in a single crystal of halite from the Central Canada Potash mine. The 100 mm wide single crystal has one of its cleavage planes oriented vertically. The three members of the en echelon tensile crack-array follow this cleavage direction. Courtesy of Dr. Alan Coode, Colonsay, Saskatchewan

du Bonnet granite (Cold Spring quarry, Manitoba) and Tyndall limestone (Garson, Manitoba). Despite the fact that granite is purely brittle and about 10 times as strong as the potash salt rock, the en echelon tensile crack-arrays are surprisingly similar (Fig. 19). Even the process by which the rock bridges between the member elements are destroyed is similar. For both rocks, the process involves the formation of additional microcracks and then the buckling of the thin slabs between them. Only in the limestone is the process different. For this rock, the bridge is destroyed by shearing across it, from the end of one crack to the beginning of the other (Fig. 20).

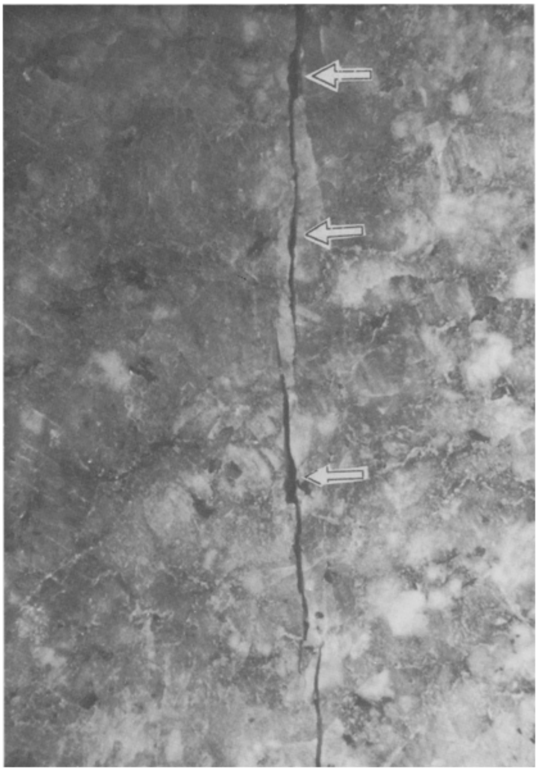

Fig. 19. A 90 mm long en echelon tensile crack-array in Lac du Bonnet Granite. The (remote) fracture was produced in the laboratory while testing a granite block with a central cavity. The photograph now shows only three of the overlapping cracks of the array. Note that the arrows point to small cavities which probably mark the site of additional step-outs. The rock bridges at these sites had already been destroyed

The similarity between the en echelon tensile crack-arrays at the microscopic scale (e.g. Figs. 12 and 13) and the room-size systems of the mine (Fig. 2) is striking despite the difference in size. Because the laboratory experiments suggest that individual members of an array do not seem to increase beyond a certain size ($\sim$20 mm), the growth of the micro arrays into their megascopic equivalents would only be possible through repeating the whole process of array formation and

Fig. 20. A 70 mm long en echelon tensile crack-array in Tyndallstone, a relatively weak limestone. The (remote) fracture was produced in the laboratory while testing a limestone block with a central cavity. Here the rock bridges are destroyed by shearing through them

destruction several times over. The members of a small array unite, forming a longer and wider fracture. The latter may then go through the same process of daughter crack formation to produce the next, larger tensile crack-array.

The process by which en echelon shear crack-arrays form is less clear. The indications are that the formation of a tensile crack-array is encouraged by low confining pressure and, of course, lateral tension. The experimental evidence suggests that as the lateral tension changes into compression, the individual members of the array become shorter and the overlap between them increases. The large overlap between the member tensile fractures that is required to form a shear array could therefore be caused by higher confining pressure, but this may not be sufficient. For a shear en echelon array to form, the displacement of daughter cracks must be biased to one side. In the physical model tests and standard laboratory tests, the presence of a free surface (or discontinuity?) seems to accomplish this. A shear crack-array can, however, be found internally as well (Fig. 21). One can see it associated with other tensile fractures that are not part of the en echelon shear crack-array. This shear crack-array comes from the interior of the rock block shown in Fig. 3. There are several inclined structures in this block running more or less

Fig. 21. An enlargement of the en echelon shear crack-array inside the potash block shown in Fig. 3. The arrows mark the two ends of the 100 mm long en echelon shear crack-array

parallel with the outer, inclined (hour-glass) boundaries of the block. The boundaries follow the so-called envelope curves of a failing yield pillar at the Central Canada Potash mine. The shear crack-array shown in Fig. 21 still has the outline of the en echelon structure. Some of the others have already collapsed and only a narrow crush zone marks the position of the original crack-array. No shear displacement can be seen along any of the shear crack-arrays. This is understandable; the internal fractures do not have the kinematic freedom for sliding.

5. Summary and Conclusions

At room temperature and pressure, the potash salt rock does not have the required number of intracrystalline slip systems to deform homogenously in a purely plastic manner. Large deformations are still possible through the contribution of brittle strain. The latter is caused by microfracture, tensile fractures that propagate along the maximum principal stress trajectory. In uniaxial compression, the process of microfracture is driven by the increasing compressive stress and it is sensitive to the loading rate, and at constant load, to the elapsed time.

Tensile fracture is not restricted to the microscopic scale. In potash salt mines, there are tensile fractures that are several meters long. Field observations, standard laboratory tests and physical modelling suggest that the growth of tensile cracks involves the formation of en echelon tensile crack-arrays. Once nucleated, an individual tensile microcrack does not propagate far. Fracture propagation does not however stop at this point. On increasing load, a child or step-out fracture forms that is slightly offset from the parent crack. The process can be repeated. A microcrack may thus develop into a tensile fracture that is several meters long.

The overlap between elements of an en echelon crack-array seems to depend on confining pressure. Low confining pressure, or lateral tension leads to a small overlap. With increasing confining pressure, the crack elements of the array become shorter and the overlap between them increases. Close to a free surface or a discontinuity, the step-out becomes biased in one direction, away from the discontinuity. When this occurs, the short, overlapping, tensile crack elements form an inclined en echelon shear crack-array. With increasing stress, the shear crack-array may collapse forming a band of crushed rock. When kinematic conditions are favourable, shear displacement may occur along the crushed zone and then, and only then, is a shear fracture or fault formed.

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