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DISSOLUTION AND DEFORMATION OF ROCK SALT, STETTLER AREA, SOUTHEASTERN ALBERTA

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ABSTRACT

Analyses of well-log and seismic data have suggested that about 40 m of rock salt were uniformly deposited within the Upper Devonian Wabamun Group in the Stettler area in southeastern Alberta. Subsequent to deposition, these original rock salts have been leached to the extent that they are now preserved only as isolated to contiguous bodies of irregular shape and variable thickness. Previous studies have concluded that significant dissolution was initiated along the traces of conjugate fault sets, the rectilinear pattern of which has since been obscured by continuing dissolution.

Seismic data suggest that some of the salt-dissolution features in the Stettler area retain a marked linear orientation striking roughly SSW-NNE over a few km at least. In short cross-section (on west-east oriented seismic lines), these structures are manifested as *upward-expanding conical-shaped zones of seismically measurable* subsidence, of the order of 100 ms. These zones of subsidence are characterized by decreasing structural relief above a certain depth, depending mainly on the timing and extent of leaching, gravity stoping and lateral strain within postsalt strata, and by seismic chatter (due to low-amplitude vertical offsets).

The character of these subsidence features is consistent with: (1) the onset of dissolution as a result of reactivated regional faulting and/or fracturing during mid-Late Cretaceous time, providing conduits for unsaturated waters; (2) the plastic or ductile deformation of rock salt (as opposed to brittle deformation); (3) the relatively slow subsidence of the postsalt strata; and (4) accelerated rates of leaching in response to glacial loading and unloading.

INTRODUCTION

Analyses of well-log and seismic data (Anderson et al., 1988; Anderson and Brown, 1992) suggest that about 40 m of rock salt were uniformly deposited within the Upper Devonian Wabamun Group (Famennian Stage) in the Stettler area of southeastern Alberta, encompassing the study area of this paper (Townships 30 to 32, Ranges 20W4 to 22W4). These Wabamun salts are now interbedded within an anhydrite/carbonate sequence. Some time after deposition, these original rock salts were leached to the extent that they are now preserved only as discontinuous remnants of varying thickness and areal extent (Figures 1 to 3). Near the present-day Wabamun subcrop (Figure 3), dissolution is thought to have been initiated by the near-surface exposure of the Wabamun salt but, further to the west, by faulting and/or fracturing.

Previous investigation (Oliver and Cowper, 1983) had suggested that in most of this area the dissolution of these rock salts had been initiated by regional faulting and/or fracturing during the mid-Late Cretaceous. Further study (Anderson and Brown, 1992; Anderson, 1992) has produced strong confirmation of this mechanism and timing of the onset of dissolution (apart from the vicinity of the Wabamun subcrop) and suggested that it was later accentuated by various mechanisms including glacial loading and unloading (Anderson and Brown, 1992; Anderson, 1992). Leaching, once initiated, appears very often to be a self-sustaining process, whereby fractures created by the collapse of overlying strata provide conduits for unsaturated waters thereby facilitating further dissolution (Anderson and Brown, 1991, 1992).

In this paper we examine some seismic data acquired over an area of dissolution subsidence in order to gain some insight into the type of deformation that can occur as a result of salt removal by dissolution. In order to do this, we first give a brief summary of some of the relevant previous work related to the properties of rock salt, particularly its mechanical behaviour. We then suggest a schematic scenario for the dissolution of rock salt and the ensuing deformation and subsidence.

ROCK SALT PROPERTIES

Rock salts exhibit unique physical properties and mechanical behaviour. In situ, they are remarkably soluble, relatively impermeable and nonporous, almost incompressible, highly ductile, and rather easily deformed by creep. The plastic behaviour of rock salt is demonstrated by salt glaciers, or namakiers, and by flow patterns observed in salt domes (Talbot and Jarvis, 1984; Richter-Bernburg, 1987).

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According to Carter and Hansen (1983), the elastic and plastic strains produced during loading are generally less than 0.01 and are not particularly significant when compared to the long-term creep of rock salt. In the presence of unsaturated water, solution-precipitation creep can occur within the low-temperature, low-pressure regime (Urai et al., 1986). Strain rates for in-situ deformation of salt vary by over eight orders of magnitude, from 10^{-8} s^{-1} to 10^{-16} s^{-1} (Jackson and Talbot, 1986), the more rapid rates being those of borehole and mine closures, the lower rates being typical of diapiric growth.

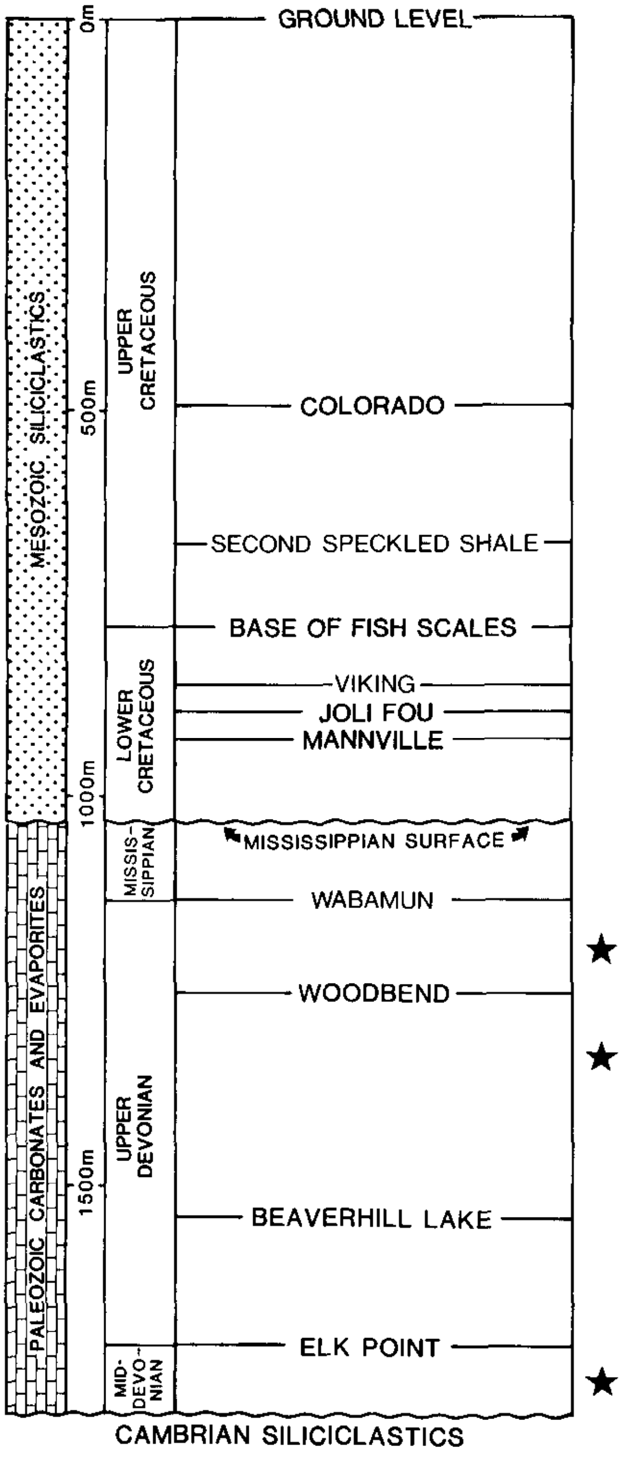

Fig. 1. Generalized stratigraphic column of southeastern Alberta (modified after Hopkins, 1987). The named horizons are group tops, except that four formations of the Colorado Group are also labelled (Joli Fou to Second Specks). Stars denote Devonian salt units that may have undergone dissolution in the Stettler area.

The solubility of halite is one to three orders of magnitude higher than the solubility of either anhydrite or limestone under normal groundwater conditions. The dissolution of rock salt, in the presence of unsaturated water, is essentially instantaneous relative to the time scale of the relevant transport mechanisms (molecular diffusion, free convection and forced convection). The rate of solid rock salt removal is therefore controlled by the diffusive and/or convective flux of sodium and chloride ions away from a halite-bearing formation (Davies, 1989).

Salt is characterized by its ability to deform either in a ductile (plastic) or brittle manner, depending on the temperature, stress state and deformation rate. At temperatures expected for the salt-dissolution subsidence process, the primary creep (or ductile-deformation) mechanisms for rock salt are glide and solution precipitation (Urai et al., 1986). If intercrystalline water penetrates the subsiding salt mass, deformation by solution-precipitation creep is capable of producing strain rates that are orders of magnitude higher than are possible in relatively dry salt at the same stress states (Davies, 1989). Thus, in a zone of ongoing dissolution, relatively rapid creep of adjacent salts back into the dissolution cavity could conceivably help to prevent the formation of huge cavities and subsequent catastrophic collapse, and instead contribute to more gradual subsidence whose horizontal extent would increase upwards as dissolution proceeded through time.

The dissolution of rock salts in the subsurface can create pore space, differential stresses, creep and ultimately subsidence. There are two basic types of subsidence: (1) very slow subsidence characterized by predominantly ductile deformation; and (2) relatively rapid subsidence characterized by predominantly brittle deformation (Ege, 1979; Davies, 1989). These two types of subsidence represent the end members of a continuous range of subsidence processes. Ductile deformation typically generates an upward-expanding zone of subsidence (Figure 4), whereas brittle deformation is characterized by an inverted-cone-shaped vertically migrating collapse cavity or chimney (Figure 5).

THE SEISMIC DATA

In order to gain some insight into the type of deformation that can occur as a result of salt dissolution, we examine some seismic data acquired over an area of dissolution subsidence in the study area (Townships 30 to 32, Ranges 20W4 to 22W4). The time-structural anomaly on the interpreted seismic line of Figure 6a is principally due to the dissolution of Wabamun rock salt. We have interpreted 40 m of salt to be present to the east and west of traces 39 and 145 respectively and little, if any, residual rock salt in the vicinity of trace 89.

In general terms, the collapse feature of Figure 6b can be described as a zone of measurable subsidence that is expanding upward and is roughly cone-shaped in the plane of the section (perpendicular to strike). These features are characteristic of ductile deformation of salt and gradual related subsidence. The curved nature of the zone of subsidence on the seismic line is partially a consequence of the acoustic velocity function within the subsurface. This acoustic velocity tends to increase more or less continuously with depth, as demonstrated by Anderson (1992). Seismic "chatter" is observed within the zone of subsidence suggesting that there are numerous low-amplitude vertical-throw faults present within the zone of subsidence. Note that the zone of subsidence, as drafted, is intended to encompass only those regions of seismically measurable subsidence. Minor subsidence has probably occurred outside this zone and in response to both lateral creep and dissolution.

Figure 7 shows another seismic line parallel to the line of Figure 6. This is one of a suite of west-east parallel lines (Anderson, 1992) about 6 km long, covering roughly 5 km in a SSW-NNE (strike) direction and establishing the linear nature of this collapse feature in this strike direction. One may also observe that the relief along the Colorado (Figure 1) and post-Colorado horizons, less than 20 ms, is significantly less than on most underlying post-Wabamun units (Figures 6, 7). We interpret these relationships as support for the proposition that the dissolution of Wabamun rock salt in the Stettler area was initiated during late Colorado time (mid-Late Cretaceous) by regional faulting and/or fracturing (Figure 8), at a time when the depth of burial of the rock salt was of the order of 850 m.

In Figure 6, the shallowest correlatable reflections on the example seismic line are still slightly low (time-structurally) within the zone of measurable subsidence, supporting the idea of a late-Pleistocene/Holocene phase of dissolution. Alternatively, it is possible that this relief is a result of

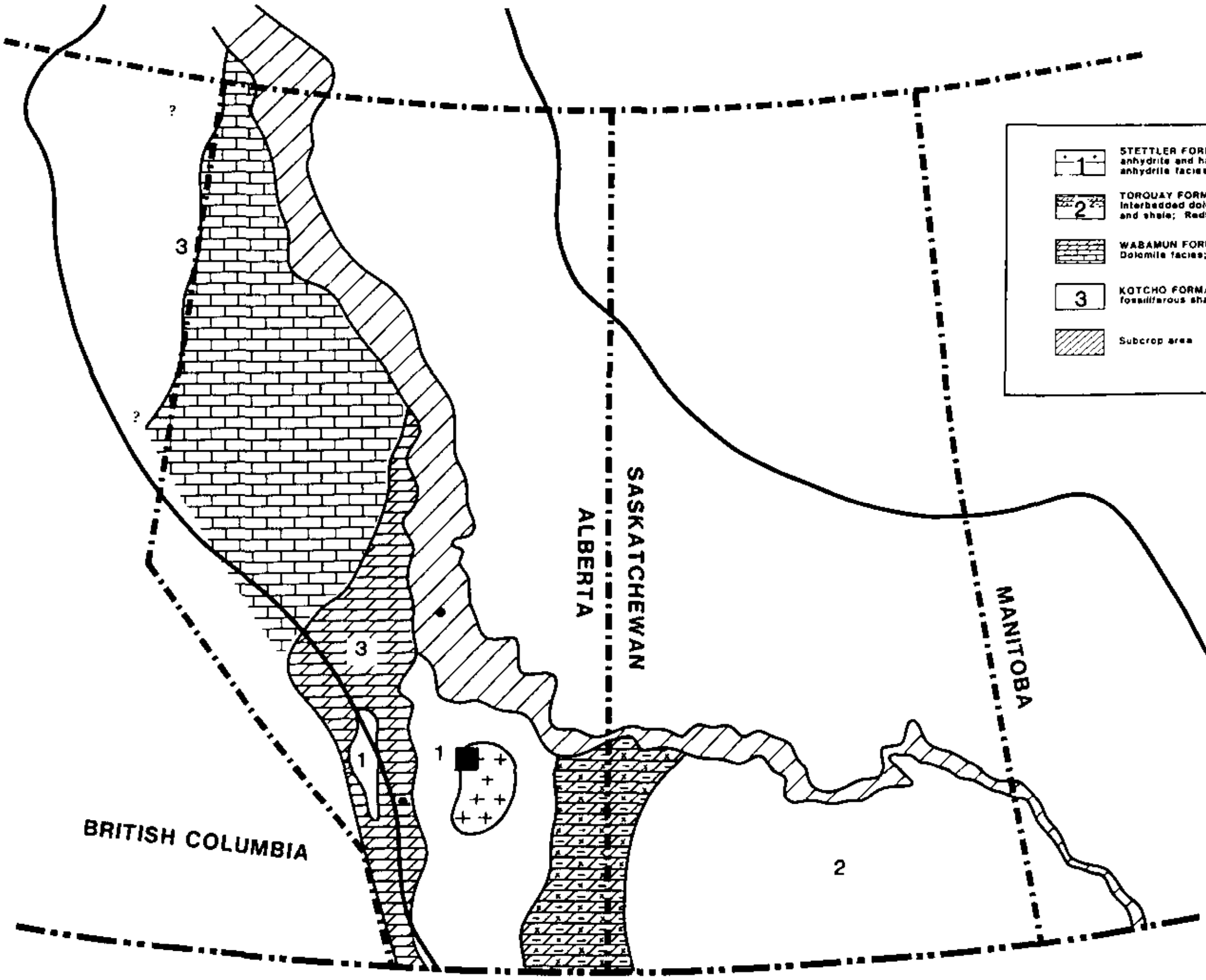

Fig. 2. Distribution of the Stettler Formation (Wabamun Group) and its equivalents in the interior plains of western Canada (modified after Belyea, 1964, and Meijer Drees, 1986). The study area (T.30 to 32, R.20W4 to 22W4) is indicated by the small square near the northwest extremity of the kidney-shaped halite-anhydrite area.

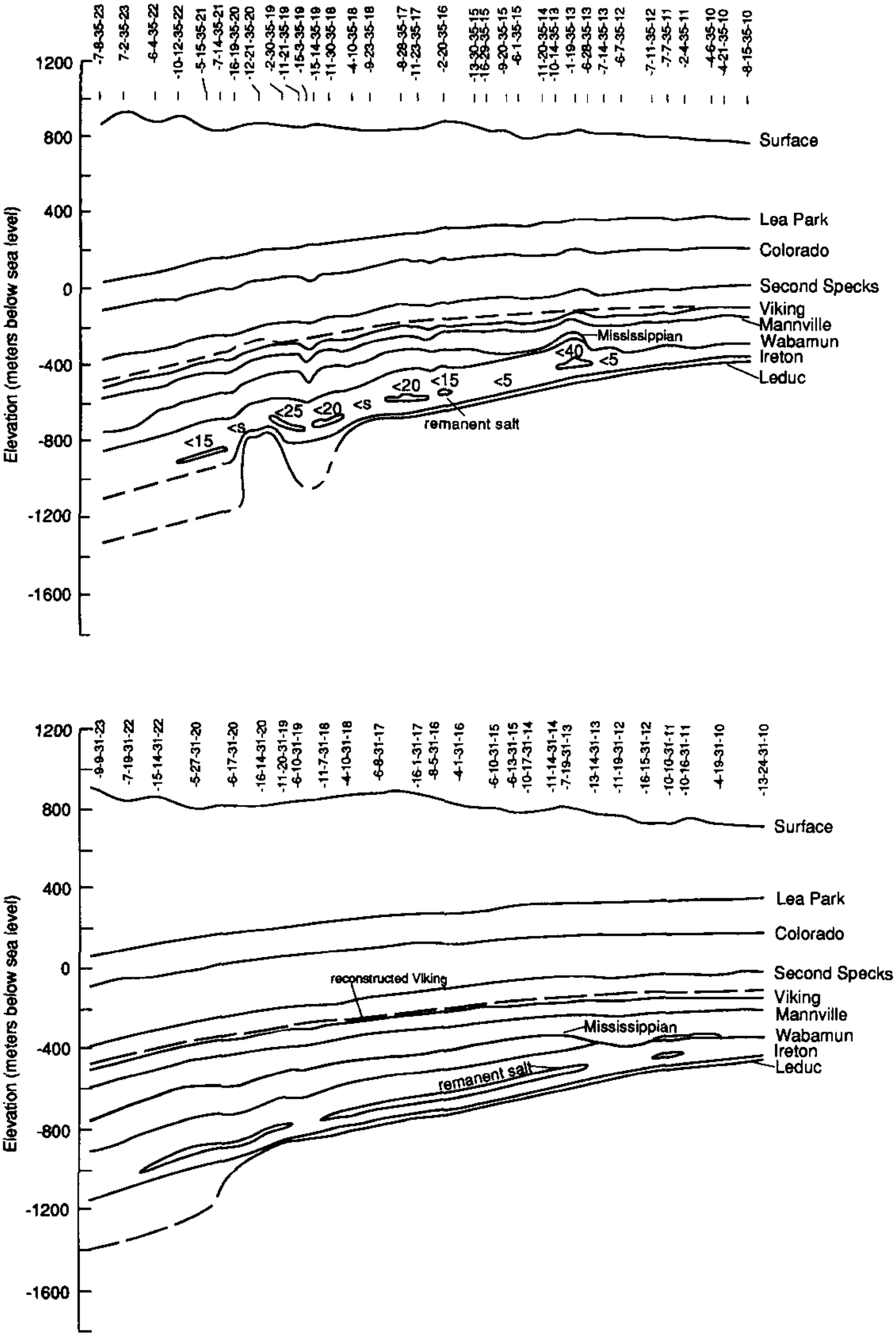

Fig. 3. West-to-east geologic cross-sections illustrating the discontinuous nature of the Wabamun Group rock salts in southeastern Alberta. As is indicated, these rock salts attain a maximum net thickness of the order of 40 m. Both present-day and reconstructed profiles for the Viking horizon (Figure 1) are displayed. Ideally, the reconstructed profile represents the structural relief which would be observed if dissolution of the salt had not continued after Viking time.

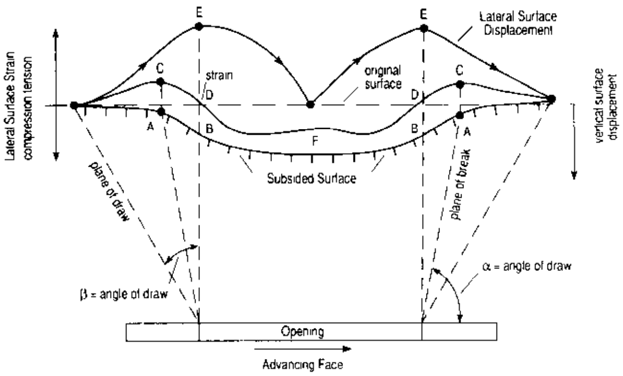

Fig. 4. Idealized representation of trough subsidence (Ege, 1979). Deformation of this type can result from the (predominantly) ductile deformation of residual rock salt and the slow subsidence of the overburden. Such features are characterized by an upward-expanding conical-shaped zone of subsidence.

ice-loaded compaction of the "compensation" sediments that originally infilled the collapse subsidence.

DISCUSSION

The above interpretation of the incorporated seismic data supports earlier suggestions that the dissolution of the Wabamun rock salt in the Stettler area was initiated by regional faulting and/or fracturing in mid-Late Cretaceous time. The fault/fracture planes provided conduits between the evaporitic beds (at a depth of about 850 m) and adjacent aquifers, thereby initiating leaching and subsidence. The shape of the zone of measurable subsidence suggests that the rock salts in the vicinity of the fault/fracture planes deformed plastically (i.e., flowed towards the zone of dissolution even as the main edge of the rock salt moved away). Partially as a consequence of the plasticity of rock salt, dissolution is apparently a self-sustaining process, whereby fractures

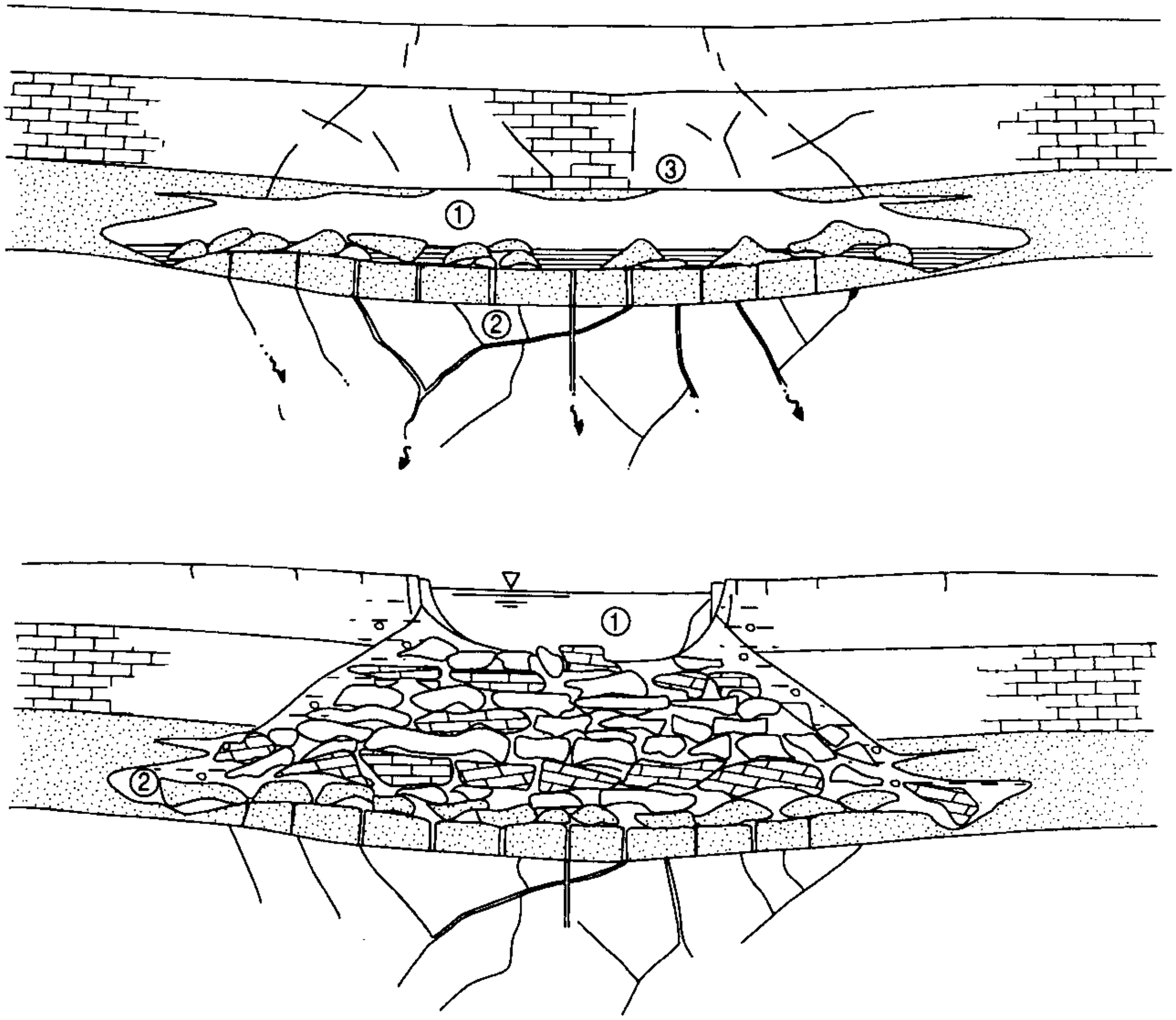

Fig. 5. Schematic illustration of the upward propagation of a subsidence chimney (modified after Nieto et al., 1985). The vertical migration of the cavity can cease (pending additional dissolution) if sufficient gravity stoping occurs and/or if the collapse cavity becomes effectively bridged in the subsurface.

created by the collapse of overlying strata provide conduits for unsaturated waters, facilitating further dissolution. These processes have resulted in removal of vast volumes of rock salt from many parts of the Western Canada Sedimentary Basin (Edmunds, 1980; Meijer Drees, 1986), complete in many areas and incomplete in others where salt bodies of various shapes and sizes remain here and there (e.g., Figure 2). On the basis of work cited above, we believe that the rate of this dissolution would have been controlled by the rate at which the saturated brines were transported out of the system. As the main edge of the rock salt (edge of the zone of measurable subsidence) migrated away from the fault/fracture conduit, the rates of dissolution and subsidence would have slowed.

In more geologically oriented studies of Wabamun salt dissolution (Anderson et al., 1988; Anderson and Brown, 1992) the marked correlation between the present-day drainage patterns (rivers, lakes, sloughs) and the locations of the edges or, more accurately, the near-zero contours of salt remnants is pointed out. This relationship may be indicative of an accelerated late-Pleistocene/Holocene phase of dissolution. We suggest that this latest phase of accelerated leaching could have been caused by: (1) glacial loading and a resultant increase in temperature and differential pressure; (2) glacial unloading and potential influx of fresh water; and (3) the potential reversal in regional hydrologic environment from centrifugal flow to centripetal flow as a consequence of sediment rebound in response to deglaciation (Figure 8).

Conclusions

The seismic data presented above suggest that some of the salt-dissolution features in the study area retain a marked linear orientation, striking in the SSW-NNE direction. In the short cross-sections shown (west-east oriented seismic lines),

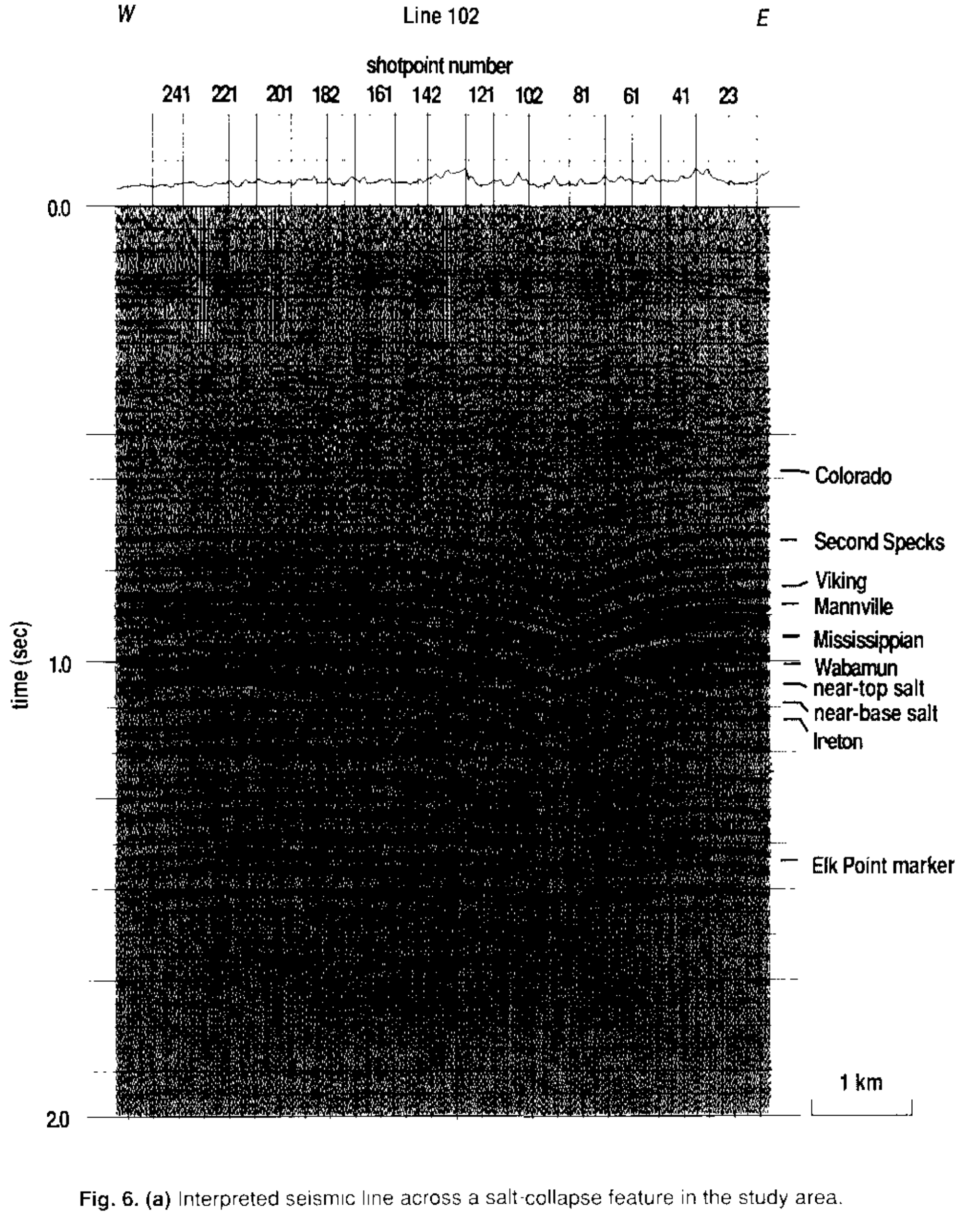

Fig. 6. (a) Interpreted seismic line across a salt-collapse feature in the study area.

this structure is manifested as an upward-expanding zone of seismically measurable subsidence. This zone of subsidence is characterized by a decrease in the amplitude of structural relief at shallower depths (depending mainly on the timing and extent of the leaching, gravity stoping and lateral strain within postsalt strata) and seismic chatter (due to small-amplitude vertical offsets).

The character of these subsidence features is consistent with: (1) the onset of dissolution as a result of reactivated regional faulting and/or fracturing during mid-Late Cretaceous time; (2) the plastic deformation of rock salt (as opposed to brittle deformation thereof); (3) the relatively slow subsidence of the postsalt strata; and (4) accelerated rates of leaching in response to glacial loading and unloading.

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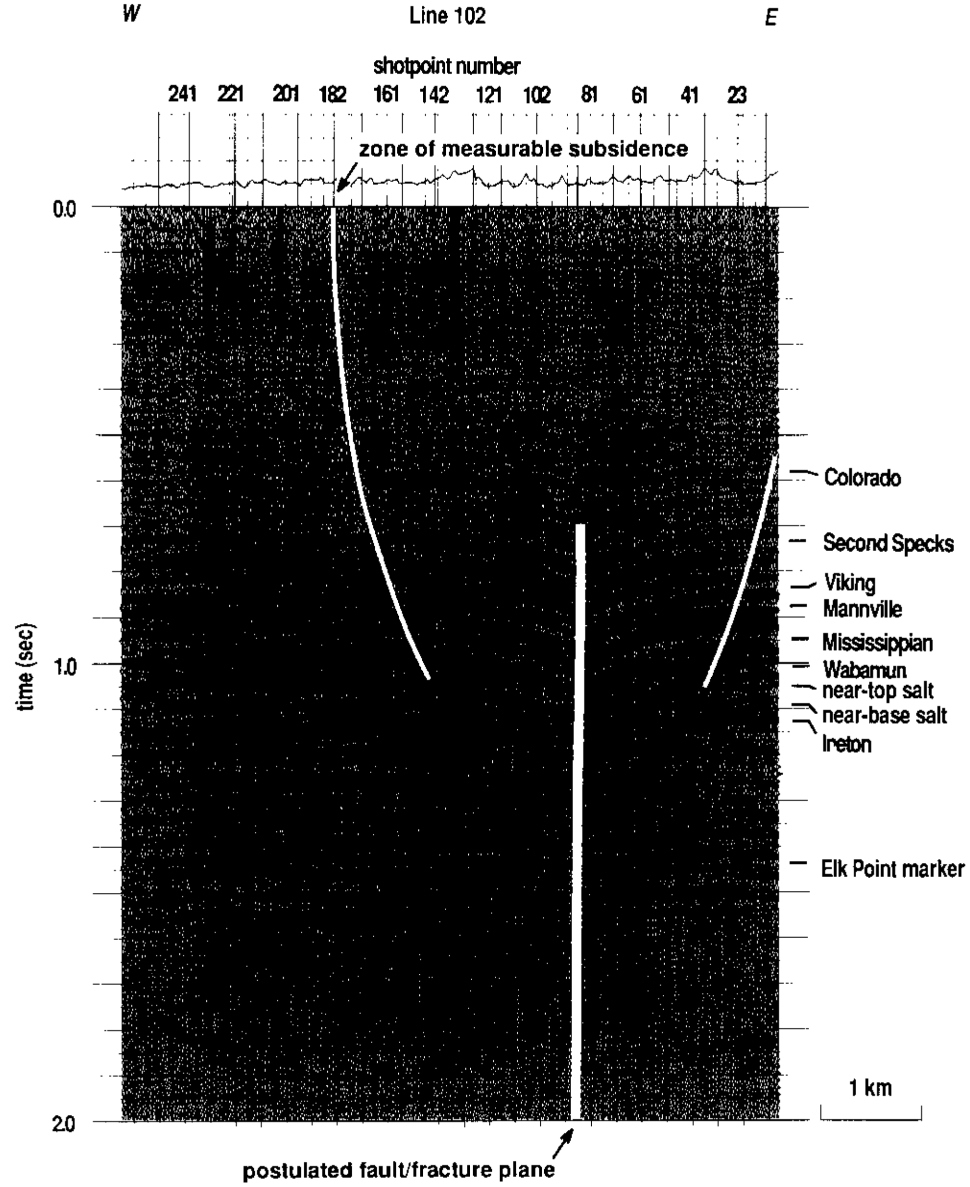

Fig. 6. (b) The hypothesized fault and/or fracture plane and the envisioned upward-expanding zone of subsidence are superposed on the interpreted seismic line of (a). As noted in the text, minor subsidence has probably occurred outside this zone, in response to both lateral creep and dissolution.

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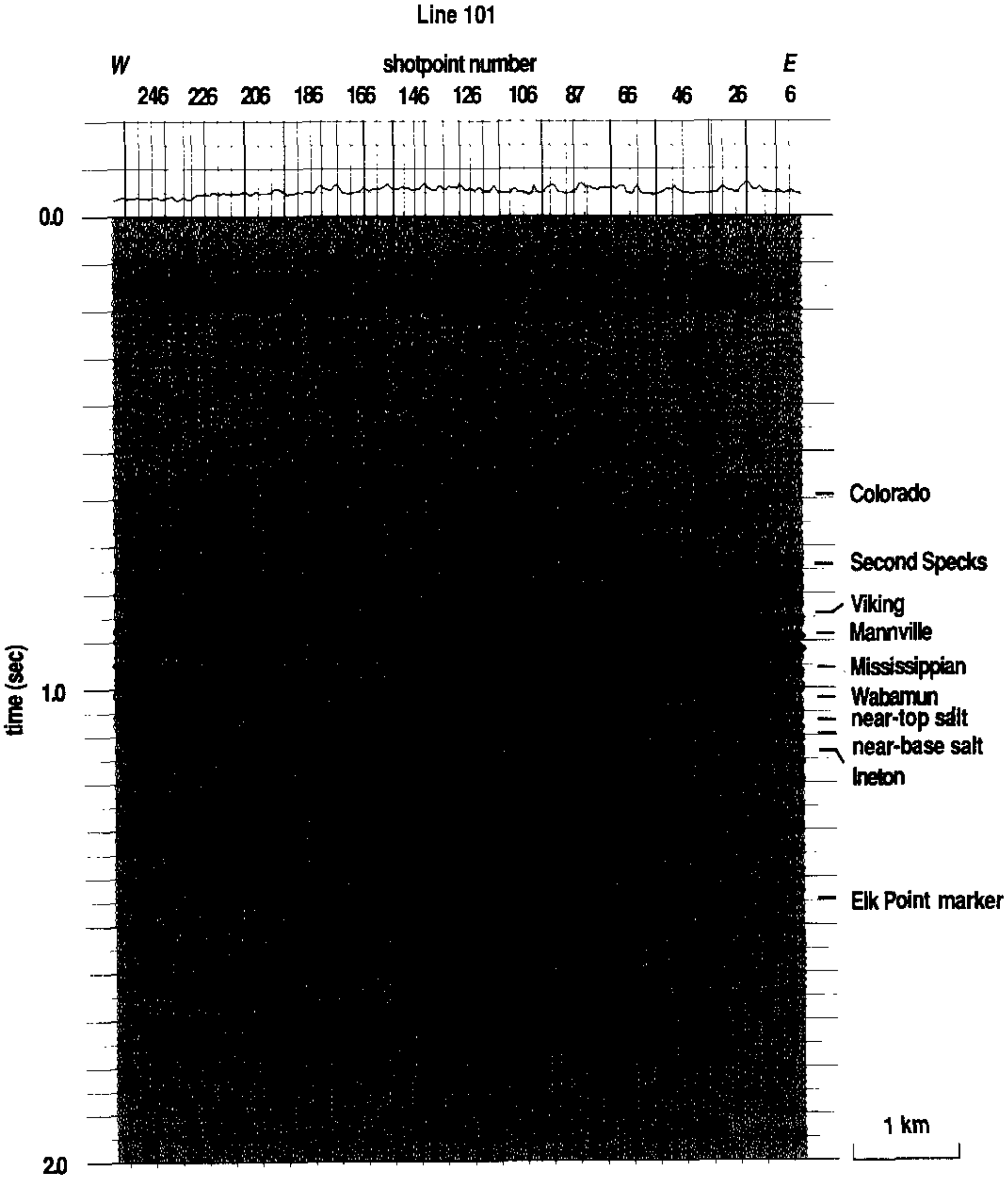
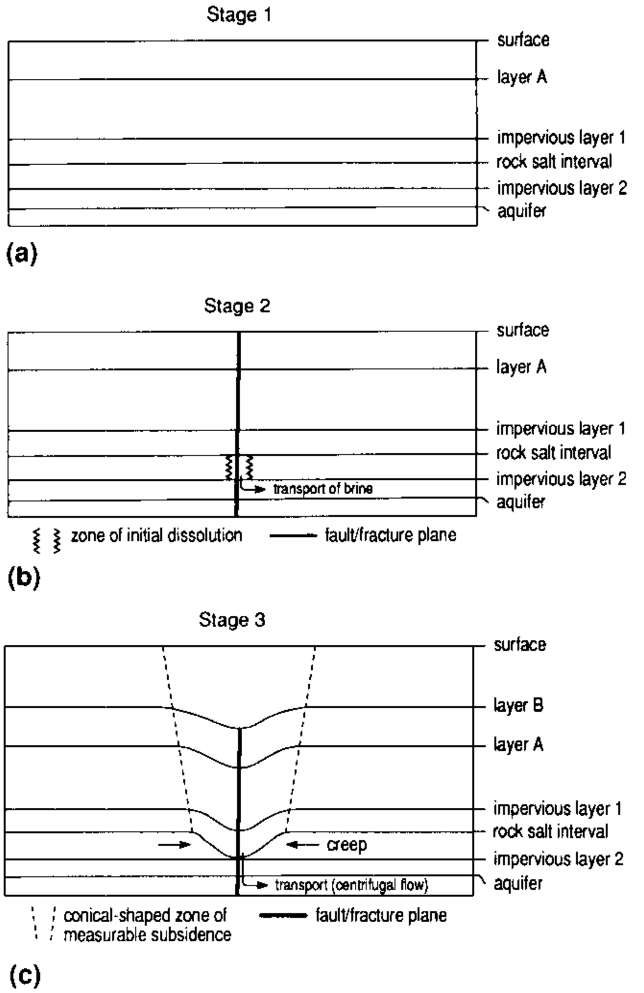


Fig. 7. West-east seismic section located about 0.8 km north of the section of Figure 6.



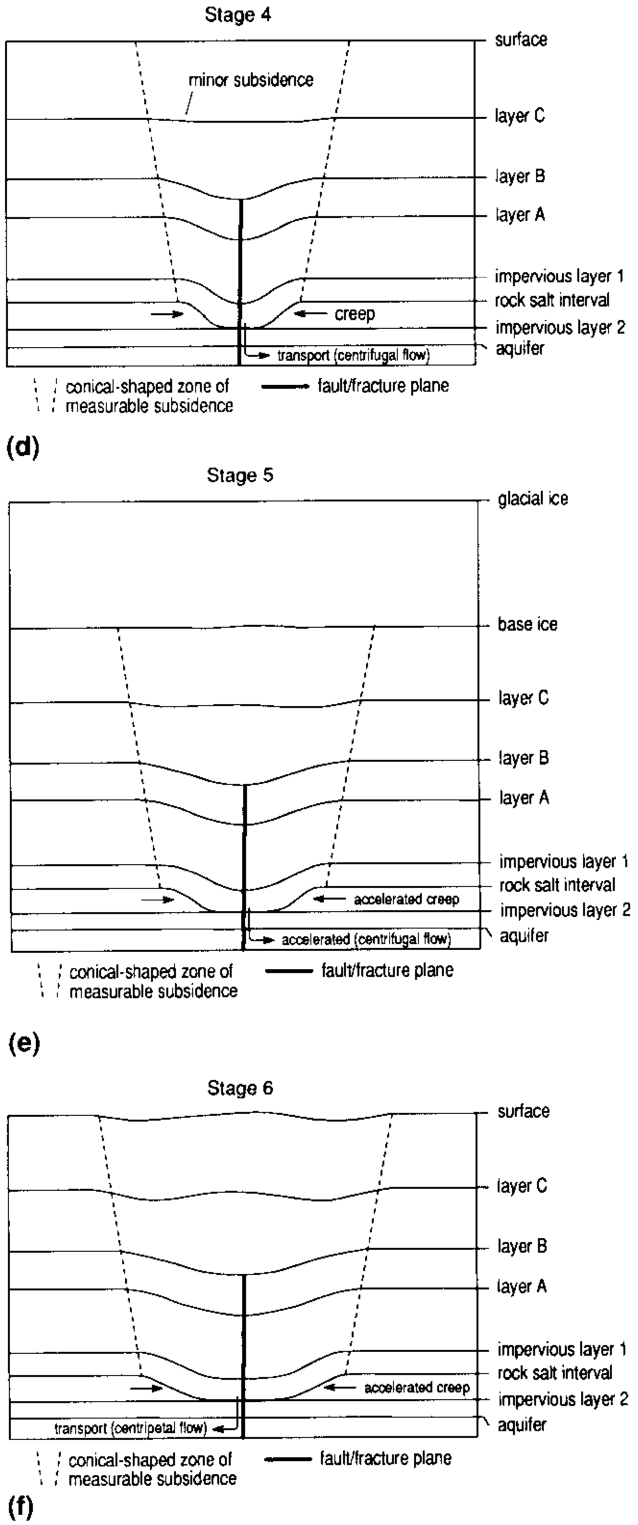


Fig. 8. Schematic illustration of the dissolution of rock salt and resulting subsidence in response to regional faulting and/or fracturing and glacial loading and unloading. **(a)** Analogous to early-Late Cretaceous time in the Stettler area; the rock salt is shown to be uniformly deposited and relatively undisturbed. At this time there is no effective communication between the rock salt and the underlying aquifer. **(b)** Analogous to mid-Late Cretaceous; regional faulting and/or fracturing has occurred. A conduit between the rock salt and the underlying aquifer has been created and the transport of brine waters by free and forced convection has been initiated. The initial rate of dissolution is relatively rapid. **(c)** Analogous to mid-Late Cretaceous; the postsalt strata are shown to have subsided in response to the dissolution of rock salt. The collapse feature is manifested as an upward-expanding conical-shaped zone of subsidence which suggests that the rock salt is creeping towards the zones of active dissolution, even as the main salt-edge (edge of zone of measurable subsidence) is regressing. Solution-precipitation creep is envisioned as the dominant mechanism; the rate of movement is probably accentuated by the presence of the dissolving brines. **(d)** Analogous to upper-Late Cretaceous and Tertiary; the zone of measurable subsidence has migrated a significant distance from the fault/fracture plane. Hence, the rate of dissolution (effectively controlled by the transport rate of dissolved salt) is relatively low. As a result, the regressive migration of the zone of subsidence and the creep of the residual rock salt have slowed considerably. **(e)** Analogous to Pleistocene; the study area is overlain by several kilometres of glacial ice. This additional load is envisioned as having increased both the temperature of the rock salt and the rate of centripetal flow (basin-to-margin flow). These changes increase both the rate at which the rock salt creeps (increased temperature and stress differential) and the transport rate. As a result, dissolution and subsidence rates are relatively high. **(f)** Analogous to Holocene; the glacial ice has retreated. Rapid removal of this load is envisioned as having changed the hydrologic environment in the area from centripetal flow to centrifugal flow (margin-to-basin flow). As a consequence of the sudden influx of relatively fresh waters (some of glacial origin), dissolution and subsidence rates remain relatively high. In this schematic model, the permeability (and flow rate) within the fault/fracture plane is envisioned as having increased due to rebound-induced reactivation.