Plastic deformation and dissolution of rock salt: A case history

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ABSTRACT

Analyses of well log and seismic data suggest that about 40 m of rock salt were uniformly deposited within the Famennian-age Wabamun Group in the Stettler study area, 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. Investigation suggests that in the immediate study area, the dissolution of these rock salts was initiated by regional faulting and/or fracturing during the mid-Late Cretaceous, and accentuated thereafter by various mechanisms including glacial loading and unloading. Leaching, once initiated, appears to have been self-perpetuating; a process whereby fractures, created by the collapse of overlying strata, provide a conduit for unsaturated waters, thereby facilitating further dissolution.

Seismic data suggests that some of the salt-dissolution features in the Stettler study area retain a marked linear orientation (SSW-NNE). In short cross-section (on west-east oriented seismic lines), these structures are manifested as upward-expanding conical-shaped zones of "measurable" subsidence. These zones of subsidence are characterized by decreasing structural relief at shallower depths (due principally to the timing of the leaching, stoping and lateral strain within post-salt 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 regional faulting and/or fracturing during mid-Late Cretaceous time; 2) the plastic deformation of rock salt; 3) the relatively slow subsidence of the post-salt strata; and 4) accelerated rates of leaching in response to glacial loading and unloading.

INTRODUCTION

Rock salts exhibit unique physical properties and mechanical behaviour. Insitu, they are remarkably soluable, relatively impermeable and non-porous, almost incompressible, highly ductile, and rather easily deformed by creep (Figure 1). In the presence of unsaturated waters, the dissolution of rock salt is essentially instantaneous relative to the time-scale of the transport mechanisms (molecular diffusion, free convection and forced convection). The plastic behaviour of rock salt is demonstrated by salt glaciers and by flowage patterns observed in salt domes (Talbot and Jarvis, 1984; Richter-Bernburg, 1987).

The dissolution of rock salts in the subsurface can create pore space, differential stresses, creep and ultimately subsidence. There are two basic types (end members) of subsidence: (1) very slow subsidence characterized by the ductile deformation of rock salt; and (2) relatively rapid subsidence characterized by the brittle deformation of rock salt (Figures 2 and 3). Ductile deformation is typified by upward-expanding zones of subsidence; in contrast, brittle deformation by a vertically propagating cavity or collapse chimney. Particularly in this later case, measurable surface subsidence may not occur; pending further dissolution, the cavity may be effectively bridged and/or infilled as a consequence of stoping.

The seismic data suggest that the linear salt-collapse features in the Stettler study area (T30-T32, R20-R22W4M) can exhibit, in short cross-section, an upward-expanding zone of measurable subsidence. This zone of subsidence is characterized by a decrease in the amplitude of structural relief at shallower depths (primarily as a result of the timing of the leaching, stoping and lateral strain within post-salt strata), and seismic chatter (due to small-amplitude vertical offsets). The character of these collapse features is consistent with the plastic deformation of rock salt and the relatively slow subsidence of the post-salt strata.

ROCK SALT MECHANICS

The natural creep limits - limits of elastic behaviour - of rock salts are extraordinarily small compared to most other rocks and difficult to determine in the laboratory. Indeed most researchers think that rock salt does not have a yield point; they conclude that over time, rock salt will eventually exhibit plastic deformation (ie. creep).

The total strain of rock salt is given by:

$$e = e_e + e_p + e_t + e_s + e_a$$

where e_e is the elastic strain upon loading, e_p is the plastic strain produced during loading, e_t is the transient or primary creep strain, e_s is the secondary or steady state creep strain and e_a is the accelerating or tertiary creep strain. According to Carter and Hansen (1983), e_e and e_p are generally less than one percent (<1%) and are not particularly significant with respect to the long-term creep of rock salt. These authors also state that the accelerating creep strain e_a is generally observed at stresses above one-half of the short-term breaking strength in unconfined creep tests and in low-temperature, low-temperature triaxial creep tests. Under these conditions, microfracturing leads to macroscopic failure by faulting (Glide mechanism; Figure 1).

Transient creep e_t (LT creep mechanism; Figure 1) is non-recoverable and deccelerating. This type of creep stems from the constraints placed on dislocation glide at low temperatures, where diffusion rates are low and dislocations cannot surmount obstacles to glide and climb by cross-slip. Each increment of strain makes further motion more difficult (strain hardening) and thus the creep rate decreases continuously with time.

According to Carter and Hansen (1983), steady state creep e_s encompasses Solution Precipitation creep, HT creep, Cobble creep and N-H creep (Figure 1). HT creep can be thought of as non-decelerating LT creep. With respect to the former mechanism, vacancy diffusion in the higher temperature regime is thought to allow for climb by dislocation intersection processes. In the same temperature regime, but at very low stresses, stress-induced bulk vacancy diffusion (Nabarro-Herring creep) or grain-boundary diffusion are thought to occur.

In the presence of water, Solution Precipitation creep (Figure 1) can occur within the low-temperature, low-pressure regime. This mechanism is described by Urai et al. (1986) as solution transfer creep; a dynamic recrystallization process. The presence of even trace amounts of brine has a marked effect on the deformation of rock salt in laboratory tests (Figure 1). Tests on dry dilated salt show more-or-less conventional dislocation creep behaviour (Glide); brine-bearing samples, in contrast, show a marked weakening at low strain rates (low differential stress). According to Urai et al. (1986) this is associated with dynamic recrystallization and a change of deformation mechanism to Solution Precipitation creep. These authors surmise that trace amounts of brine are present in rock salt in-situ, and that the presence of such fluid accounts for the observed discrepency between typical laboratory and in-situ observations. Rock salt under typical laboratory conditions (dry) deforms as an elasto-plastic; rock salt in-situ deforms as a plastic. Indeed the salt glaciers in Iran flow under gravitational stresses alone.

According to Jackson and Talbot (1986), the strain rates for the in-situ deformation of rock salt vary by over 8 orders of magnitude from $10^{-8}s^{-1}$ to $10^{-16}s^{-1}$. The most rapid rates are those of borehole closure during accelerating creep ($10^{-8}s^{-1}$), mine closures and steady state borehole closures ($10^{-9}s^{-1}$ to $10^{-11}s^{-1}$) and namakiers (salt glaciers; $10^{-8}s^{-1}$ to $10^{-11}s^{-1}$). The rates of diapiric extrusion assisted by folding ($10^{-13}s^{-1}$) and the rates for the most active phase of gravity driven diapiric growth are significantly lower ($10^{-8}s^{-1}$ to $10^{-11}s^{-1}$). These rates are significantly lower than the strain rates at which laboratory specimens are typically tested ($>10^{-7}s^{-1}$).

DISSOLUTION AND MASS TRANSPORT OF HALITE

The solubility of halite (359 g NaCl/l H_2O at 25 ^{0}C) varies somewhat (depending upon temperature, pressure, and the concentrations of other solutes), but it is one to three orders of magnitude higher than the solubilities of anhydrite and limestone under normal groundwater conditions. The dissolution of rock salt is essentially instantaneous relative to the time scale of the transport process in the presence of unsaturated water; the rate of solid rock salt removal is therefor controlled by the convective and/or diffusive flux of sodium and chloride ions away from a halite-bearing formation. Transport mechanisms include molecular diffusion, free convection and forced convection.

Mass transport by diffusion is a very slow process. Davies (1989) cites the following example: in the situation where a halite unit is separated from an underlying fresh-water aquifer by a 10 m thick aquiclude having a *De* value of 10^{-11} m^2/s, the regional halite removal rate is on the order of 5 microns per year. In most natural situations, the water in the aquifer has higher initial salinities and the *De* values of the aquiclude are most likely a few orders of magnitude lower. Therefore, in most situations, halite removal rates controlled by diffusion are much less than one micron per year.

According to Davies (1989), mass transport by free convection (driven by gravity acting on an inverted fluid density gradient), is much faster than transport by diffusion alone. Davies cites as an example, a situation where a 1-m wide fracture zone with a hydraulic conductivity of 10^{-4} cm/s transects the aquiclude described in the previous paragraph. The localized halite removal rate for this scenario is on the order of a few centimeters per year, which is orders of magnitude higher than the removal rate for diffusion alone.

Once salt-rich brine passes from a fracture zone into an underlying aquifer, the mode of mass transport is altered significantly. Forced convection through the aquifer, driven by a regional head gradient, becomes the primary transport mechanism. However, if the vertical component of the external head gradient is small, the vertical component of flow may still be primarily driven by buoyancy (Davies, 1989).

BRITTLE VERSUS DUCTILE SUBSIDENCE

Salt is characterized by its ability to deform either in a ductile (plastic) or brittle manner, depending on temperature, stress state, and deformation rate. At temperatures expected for the salt dissolution-subsidence process, the primary ductile deformation mechanisms for rock salt are dislocation glide (Glide creep) at moderate differential stresses and moderate deformation rates, and Solution Precipitation creep at low differential stresses and low deformation rates (Figure 1). If intercrystalline water penetrates the subsiding salt mass, deformation by intergranular liquid diffusion (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).

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 (Figures 2 and 3). These two types of subsidence represent the ends of a continuous range of subsidence processes. As is illustrated in Figures 2 and 3, ductile deformation typically generates an upward-expanding zone of subsidence; brittle deformation in contrast is characterized by inverted cone-shaped, vertically-migrating collapse cavity (chimney). Whether or not measurable subsidence is expressed at the surface depends upon several factors including the timing of the dissolution, the areal extent and volume of the leached rock salt, the depth to the rock salt, and the response of the overburden. For example subsidence may not be exhibited within those sediments deposited after dissolution and collapse has ceased. In a second scenario, as a result of either stoping or bridging, the vertical migration of measurable subsidence could effectively cease, pending additional dissolution. Particularly in the former case, structural relief could be induced in the subsurface as a result of the compaction of the "compensation" sediments (Oliver and Cowper, 1983).

EXAMPLE SEISMIC DATA

The rock salts of the Wabamun Group (Upper Devonian) in the Stettler study area (T30-T32, R20-R22W4M) of southern Alberta are interbedded within an anhydrite/carbonate sequence and have been leached to the point that they are now preserved only as discontinuous remnants of variable thickness and areal extent (Figures 4, 5, 6 and 7). Several authors including Anderson (1992), Anderson and Brown (1991, 1992) and Anderson et al. (1988) suggest that the dissolution of these rock salts, in the immediate study area, was initiated by regional faulting/fracturing during the mid-Late Cretaceous, and accentuated thereafter by various mechanisms including glacial loading and unloading. They have also reported that leaching is often self-perpetuating; a process whereby fractures, created by the collapse of overlying strata, provide a conduit for unsaturated waters, thereby facilitating further dissolution.

In support of these hypothesis, Anderson (1992) presents the interpreted seismic line shown as Figure 8. According to this author, the time-structural anomaly on these data is principally due to the dissolution of Wabamun rock salt. It is suggested that 40 m of rock salt are present to the east and west of traces 39 and 145 respectively, and that there is little, if any, remnant rock salt in the vicinity of trace 89.

In general terms, the collapse feature highlighted on Figure 9, can be described as an upward-expanding conical-shaped zone of measurable subsidence; a feature characteristic of the ductile deformation of salt and gradual related subsidence. Seismic "chatter" is observed within the zone of subsidence suggesting that numerous low-amplitude vertical displacements are 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 occured outside of this zone and in response to both lateral creep and dissolution.

Anderson (1992) also discusses the absence of significant relief (less than 20 ms) along the Colorado and post-Colorado levels, and the linear nature of this collapse feature (as evidenced on a suite of parallel seismic lines). These relationships are cited as support for the thesis that the dissolution of Wabamun rock salt in the Stettler study area was initiated during upper Colorado time (mid-Late Cretaceous) by regional faulting and/or fracturing (Figure 10). During the mid-Late Cretaceous, the depth to the rock salt was on the order of 850 m.

In a geologically-oriented study of Wabamun salt-dissolution, Anderson and Brown (1988, 1992) note the marked correlation between the locations of lakes, rivers and the present day near-zero edges of remnant salt. This apparent relationship is presented in support of an accelerated late-Pleistocene/Holocene phase(s) of dissolution. These authors suggest that this latest phase(s) 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 de-glaciation (Figure 10).

In Figures 8 and 9, the shallowest, correlatable reflections on the example seismic line are time-structurally low within the zone of measurable subsidence, supporting the thesis of late-Pleistocene/Holocene phase(s) of dissolution. Alternatively, it is possible that this relief is due to the glacial-induced compaction of "compensation" sediments.

SUMMARY

On the basis of the interpretation of the incorporated seismic data, it is suggested that the dissolution of the Wabamun rock salt in the study 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; leaching and subsidence were thereby initiated.

The shape of the zone of measurable subsidence suggests that the rock salts in the vicinity of the fault/fracture planes deformed plastically (ie. 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 appears to have been self-perpetuating; a process whereby fractures, created by the collapse of overlying strata, provide a conduit for unsaturated waters, thereby facilitating further dissolution. The rate of dissolution is thought to 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 are thought to have slowed.

The most recent (post-Pleistocene) episode(s) of relatively rapid leaching appears to have been triggered by glacial loading and/or unloading. It is suggested that this latest phase(s) of accelerated leaching could have been caused by: 1) glacial loading and the resultant increase in both temperature and stress differential; 2) glacial unloading and potential influx of fresh-water; and 3) the possible reversal in regional hydrologic environment from centrifugal-flow to centripetal flow as a consequence of sediment rebound in response to de-glaciation.

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FIGURES

Figure 1. Deformation mechanism map for halite indicating the stress/temperature environments of the seven classifications of creep reviewed in the text (Urai et al., 1986).

Figure 2. 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 measurable subsidence.

Figure 3. Schematic illustration of the upwards propagation of a subsidence chimney (Davies, 1989). The vertical migration of the cavity can cease (pending additional dissolution) if sufficient stoping occurs and/or if the collapse cavity beomes effectively bridged in the subsurface.

Figure 4: Stratigraphic chart of the Paleozoic in the south-central mountains, northern mountains and southern plains areas of Alberta (modified after AGAT Laboratories, 1988).

Figure 5: Stratigraphic chart of the Mesozoic in the south-central mountains, northern mountains and southern plains areas of Alberta (modified after AGAT Laboratories, 1988).

Figure 6: Distribution of the Stettler Formation (Wabamun Group) and its equivalents in the western Interior Plains (modified after Belyea, 1966; Meijer Drees, 1986). The Stettler study area (T30-T32, R20-R22W4M) is situated within the cross-hatched area denoted as comprised partially of anhydrite and halite facies.

Figure 7. West-to-east geologic cross-sections illustrating the discontinuous nature of the Wabamun Group rock salts in south-central Alberta (Figure 3). As is indicated on the cross-sections, these rock salts attain a maximun net thickness on the order of 40 m. Both present-day and reconstructed profiles for the Viking horizon are displayed on the cross-sections. Ideally, the reconstructed profile represents the pattern of structural relief which would be observed if partial dissolution of the Wabamun rock salt had not occurred after the deposition of the Viking Formation. Near the Wabamun subcrop, the dissolution of the rock salt is thought to have been initiated by the near-surface exposure of these evaporites; further to the west, leaching is thought to have triggered by faulting and/or fracturing during the mid-Late Cretaceous (Anderson and Brown, 1992).

Figure 8. Interpreted seismic line across a salt-collapse feature in the Stettler study area. Anderson (1992) indicates that this structure is oriented NNE/SSW, and can be correlated across several parallel seismic lines. These interpretations support the thesis that the dissolution Wabamun rock salt in the Stettler study area was initiated during upper Colorado time (mid-Late Cretaceous) by regional faulting and/or fracturing. At this time, the depth to the rock salt was on the order of 850 m.

Figure 9. The hypothesized fault and/or fracture plane and the envisioned upward-expanding zone of subsidence are superposed on the interpreted seismic line of Figure 8. The curved nature of the zone of subsidence on the seismic line is partially a product of the acoustic velocity function within the subsurface; as demonstrated by Anderson (1992), the acoustic velocity increases more-or-less

continuously with depth. As noted in the text, minor subsidence has probably occured outside of this zone, in response to both lateral creep and dissolution.

Figures 10a-10f. Schematic illustration of the dissolution of rock salt in response to regional faulting and/or fracturing, and glacial loading and unloading.

In Figure 10a (analogous to early-Late Cretaceous time in the Stettler study 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.

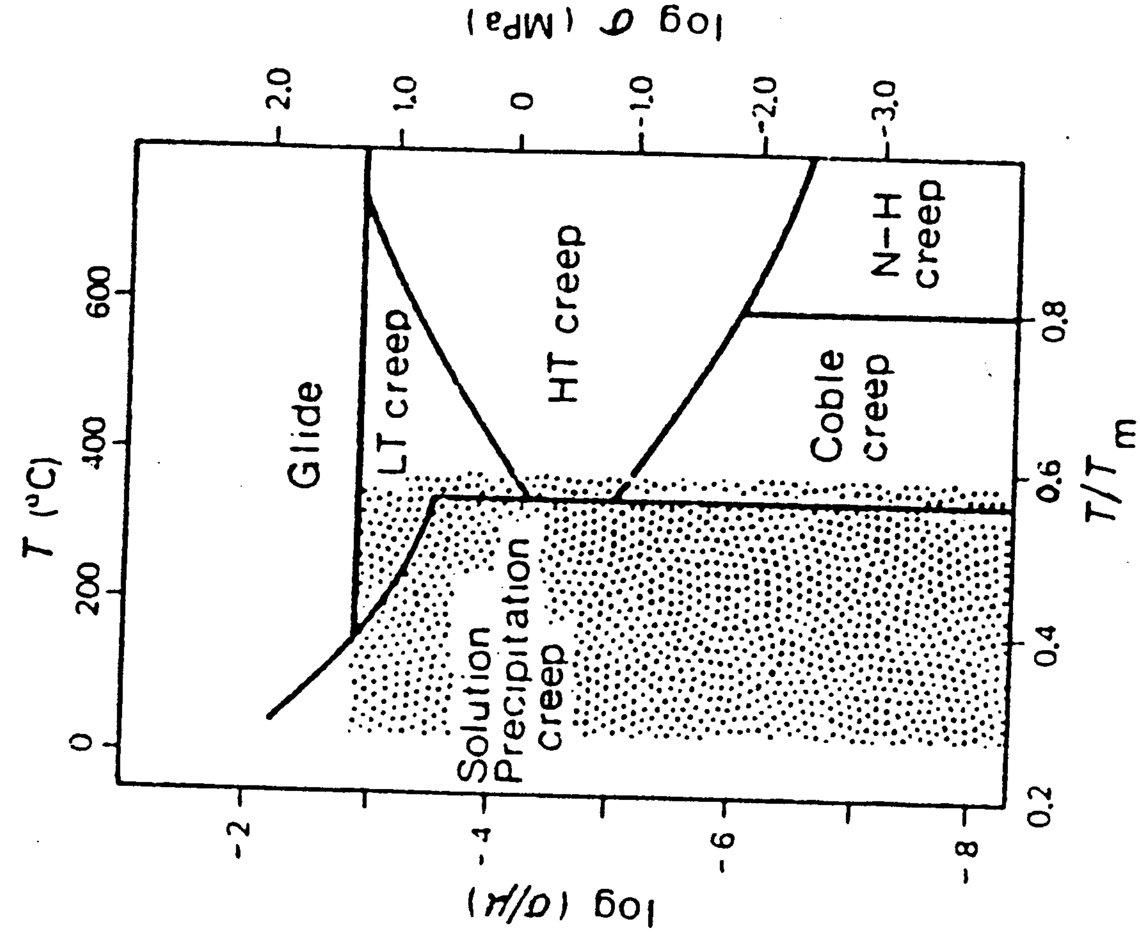
In Figure 10b (analogous to mid-Late Cretaceous) regional faulting and/or fracturing has occurred. A conduit between the rock salt and the underlying aquifer has been created; the transport of brine waters by free and forced convection has been initiated. The initial rate of dissolution is relatively rapid. Leaching, once initiated, appears to have been self-perpetuating; a process whereby fractures, created by the collapse of overlying strata, provide a conduit for unsaturated waters, thereby facilitating further dissolution.

In Figure 10c (analogous to mid-Late Cretaceous) the post-salt 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.

In Figure 10d (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 rate at which dissolved salts are transported out of the system) is relatively low. As a result, the regressive migration of the zone of measurable subsidence and the creep of the residual rock salt have slowed considerably.

In Figure 10e (analogous to Pleistocene) the study area is overlain by a 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 of fluids). These changes increase both the rate at which the rock salt creeps (increased temperature and stress differential) and the rate of transport. As a result the rates of dissolution and subsidence are relatively high.

In Figure 10f (analogous to Holocene) the glacial ice has retreated. This rapid removal of this load is envisioned as having changed the hydrologic environment in the study area; from centripetal-flow to centrifugal flow (margin to basin flow of fluids). As a consequence of the sudden influx of relatively fresh waters (some of glacial origin), the rates of dissolution and subsidence remain relatively high. In the schematic model, the permeability (and rate of fluid flow) within the fault/fracture plane is envisioned as having increased due to rebound-induced fracturing along the pre-existing planes of weakness.



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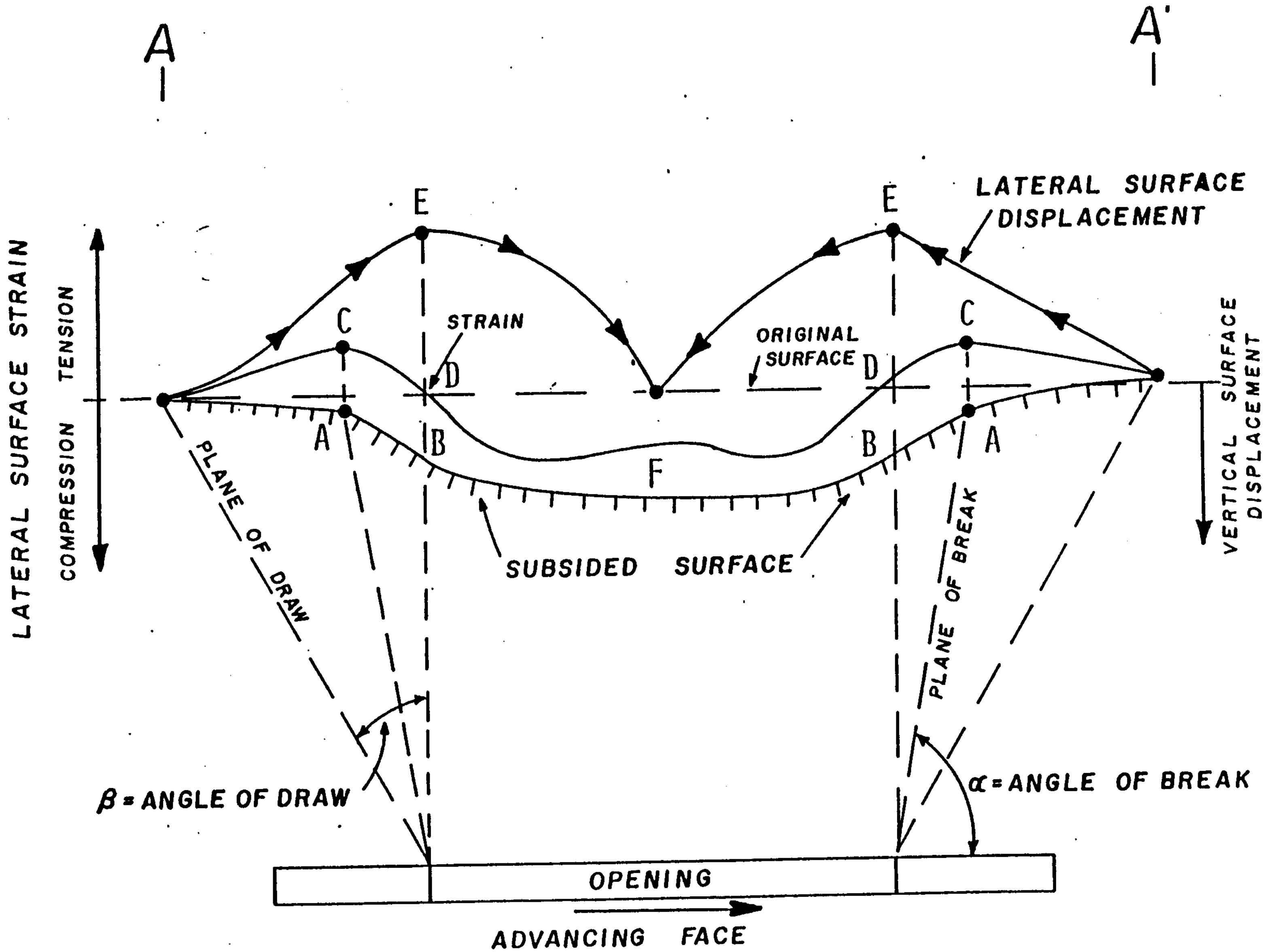

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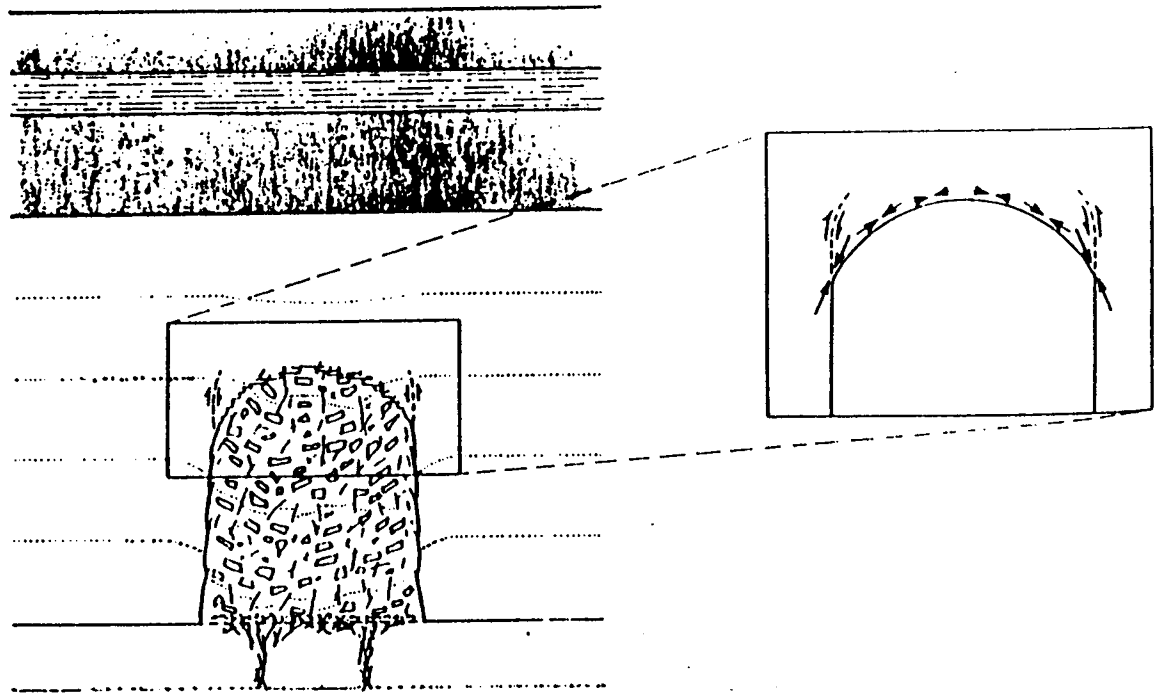

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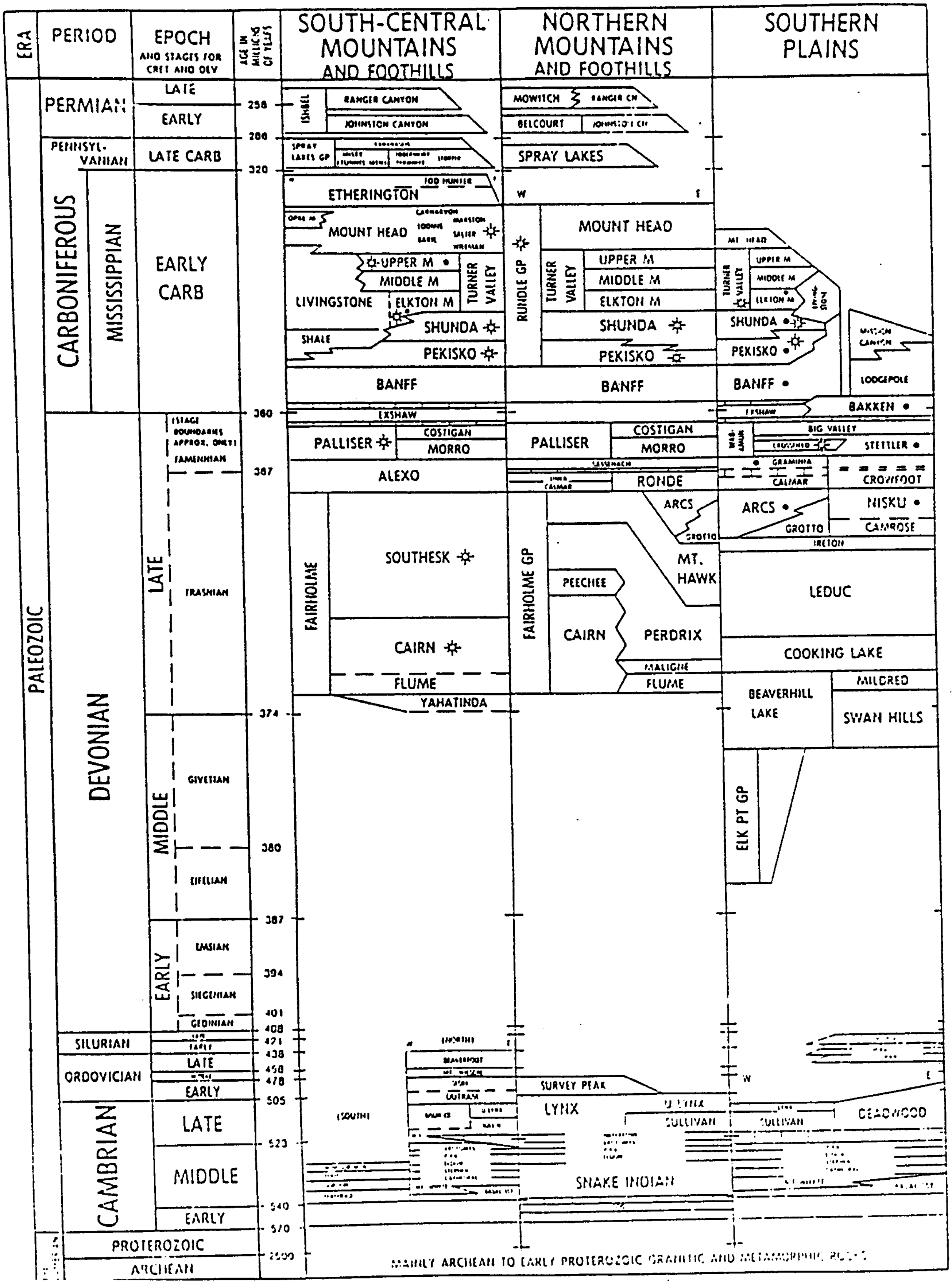

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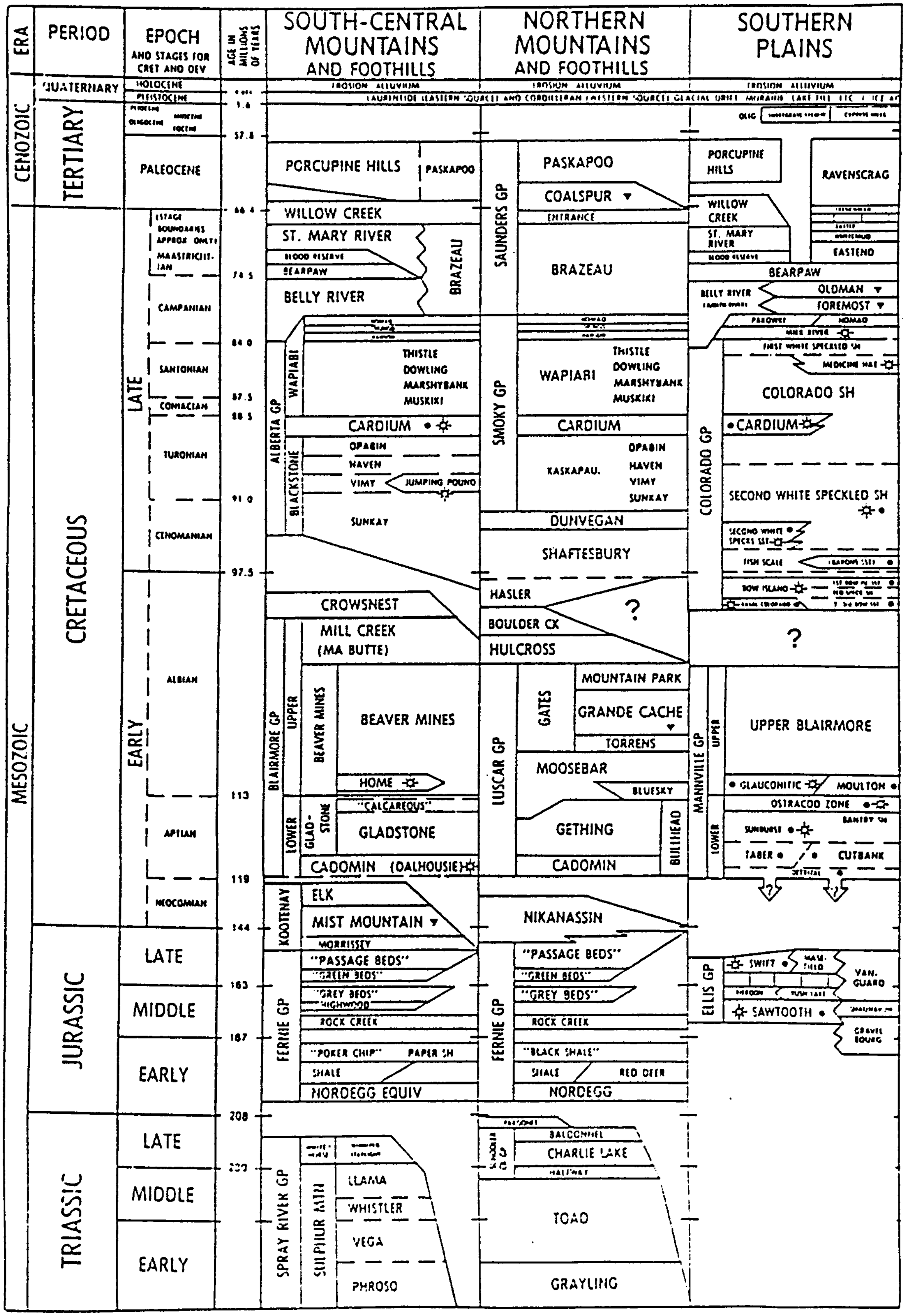

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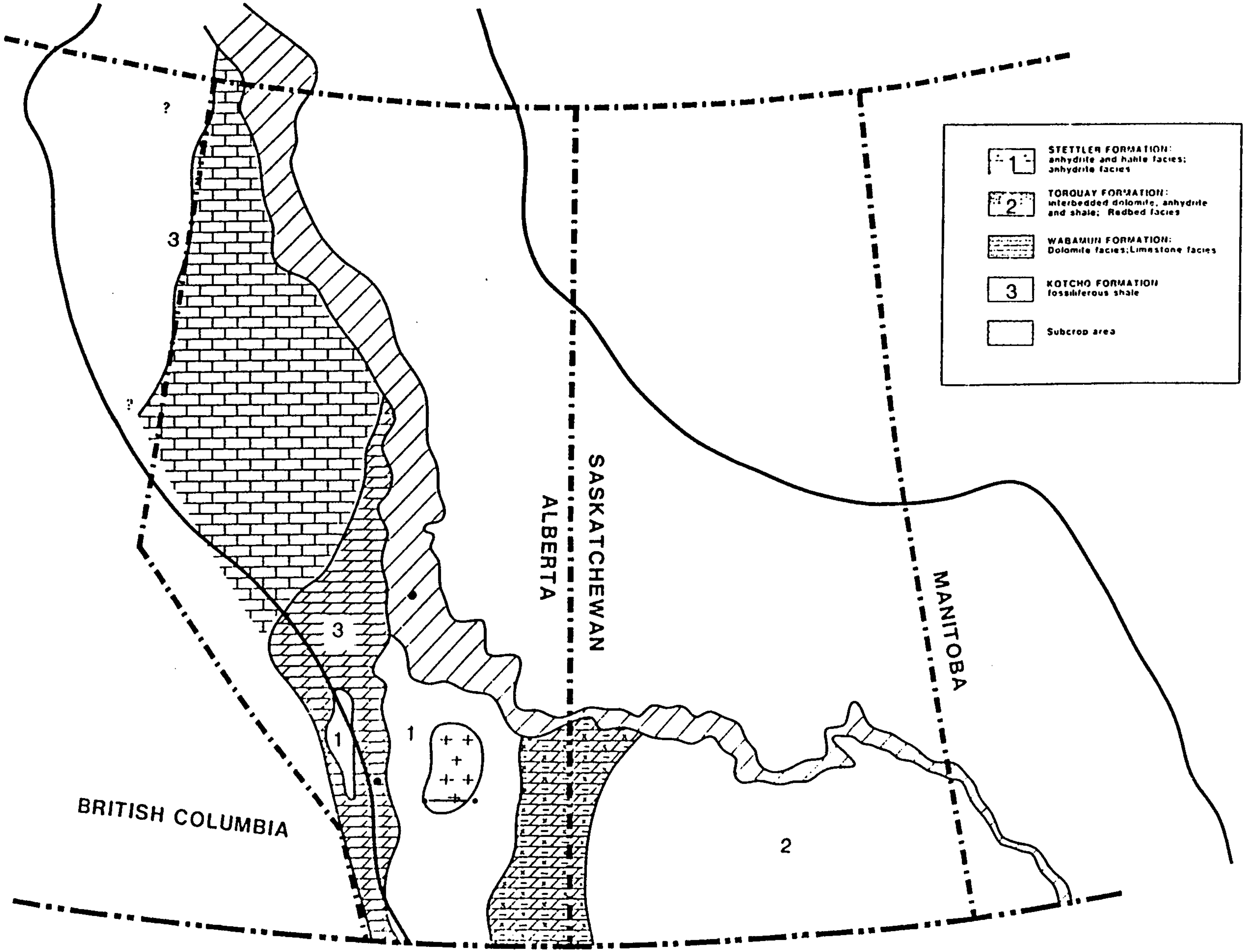

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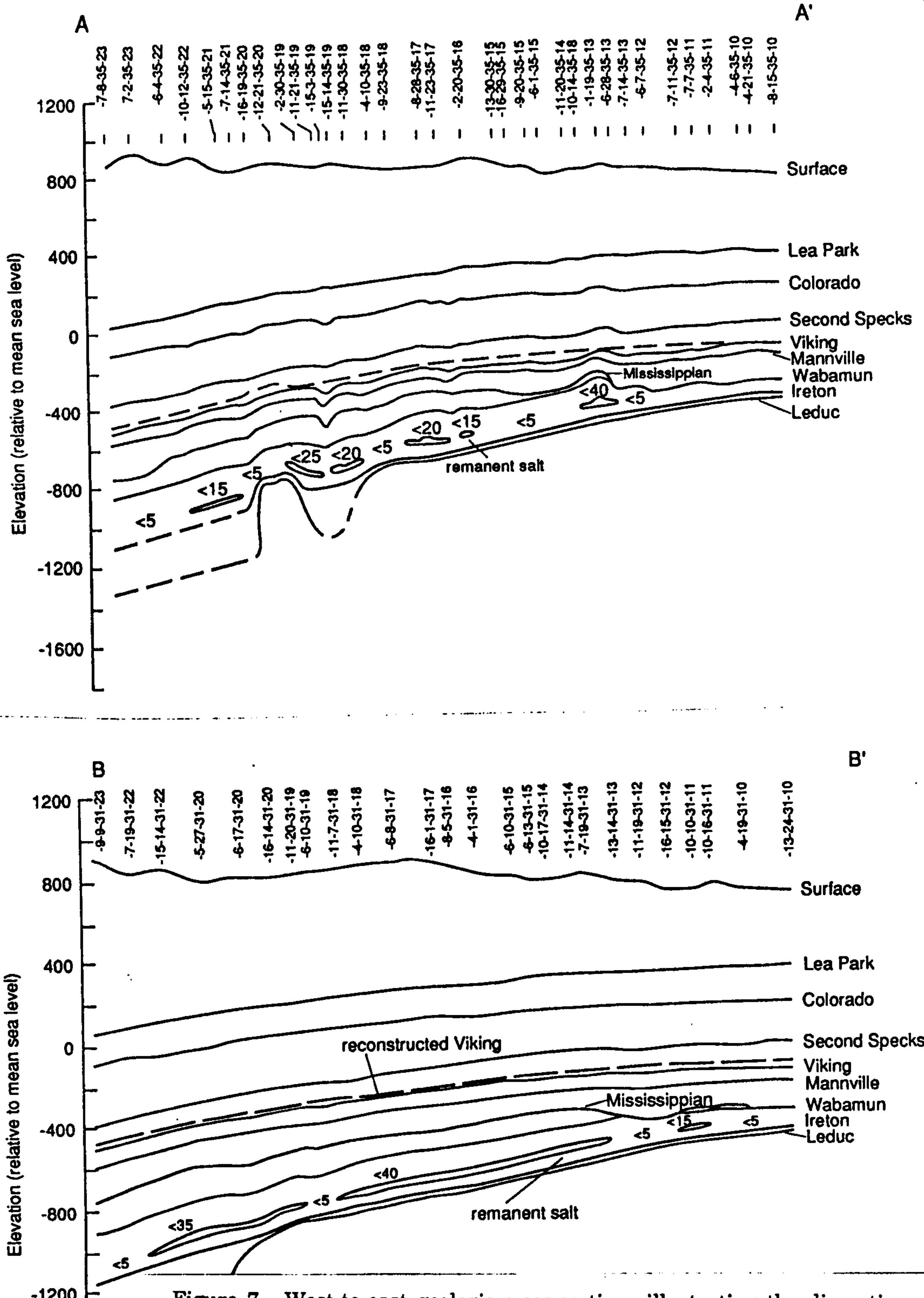

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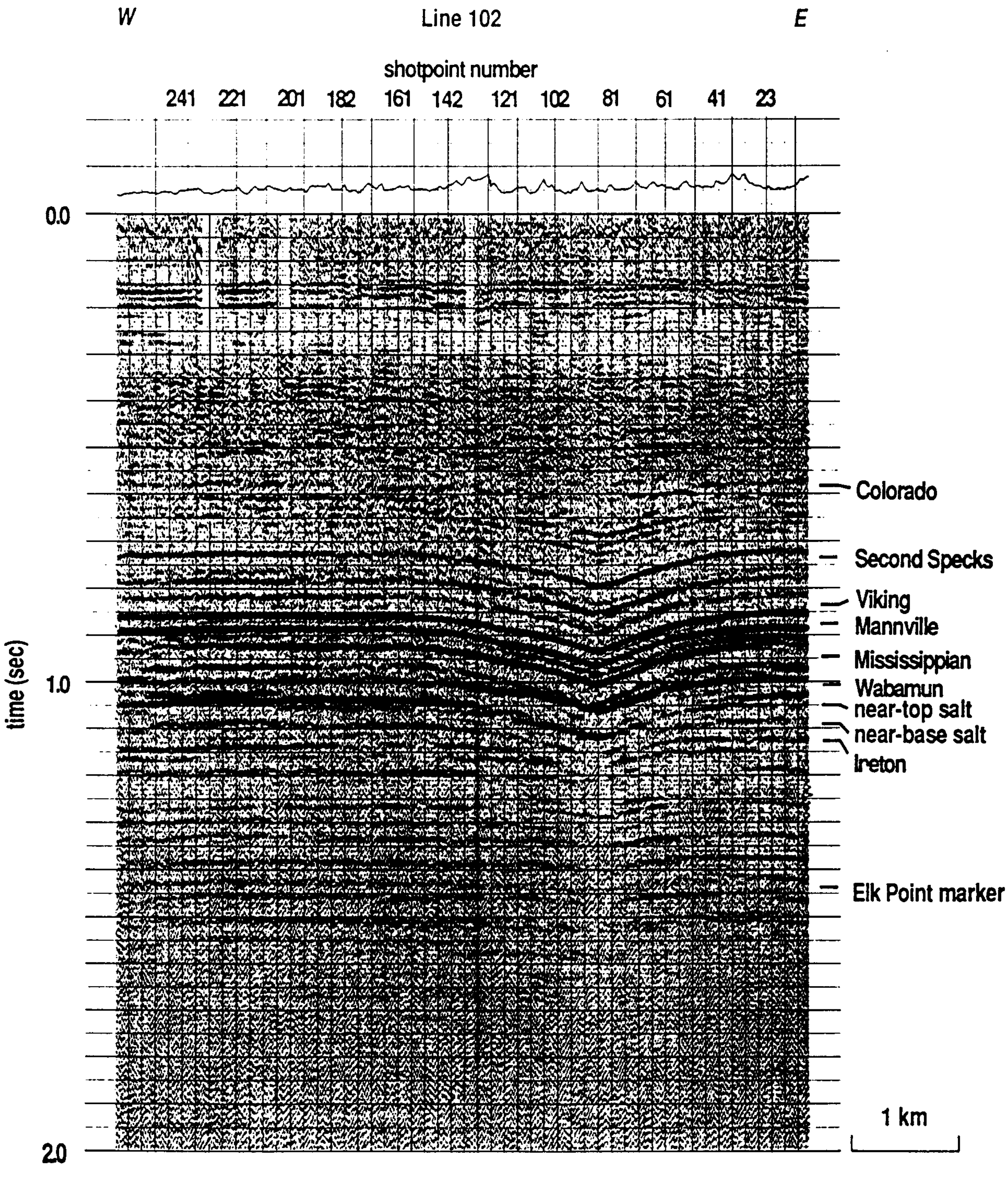

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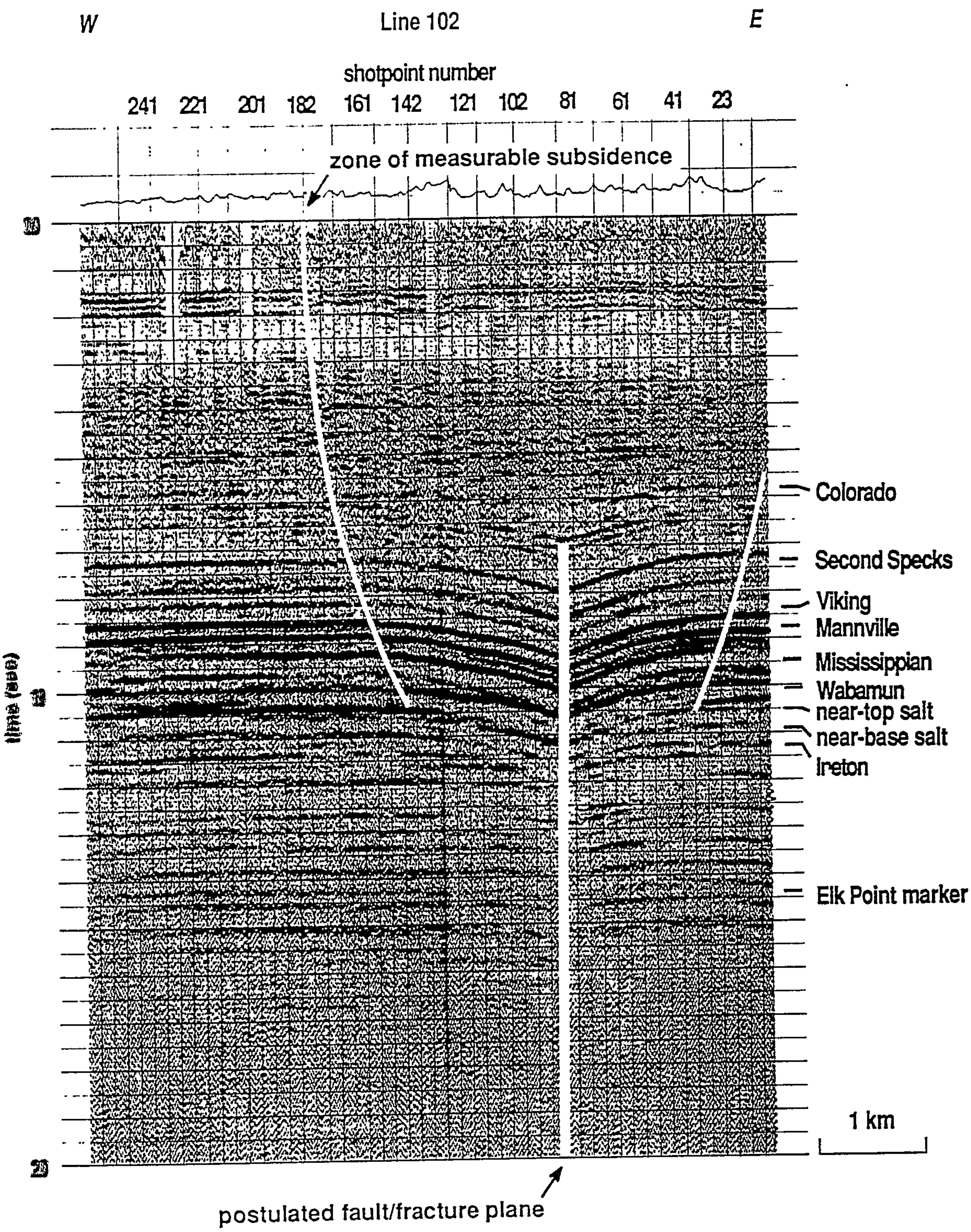

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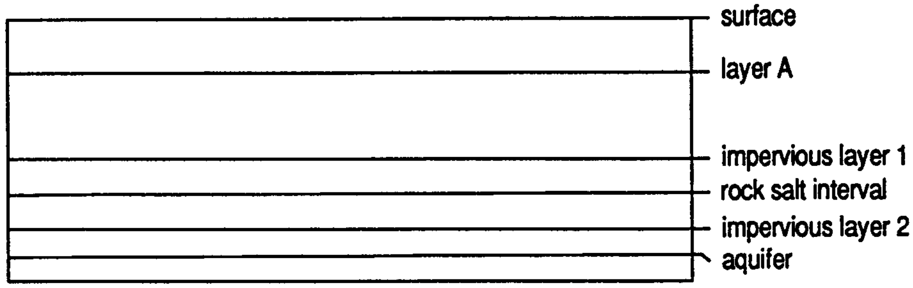
Stage 1



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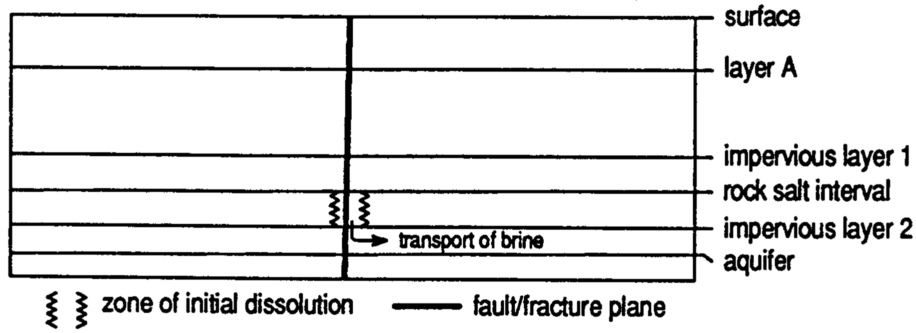
In Figure 10a (analogous to early-Late Cretaceous time in the Stettler study area) the rock salt is shown to be uniformly deposited and relatively undisturbed. At this time there is no effective communication between the rock salt and the underlying aquifer.

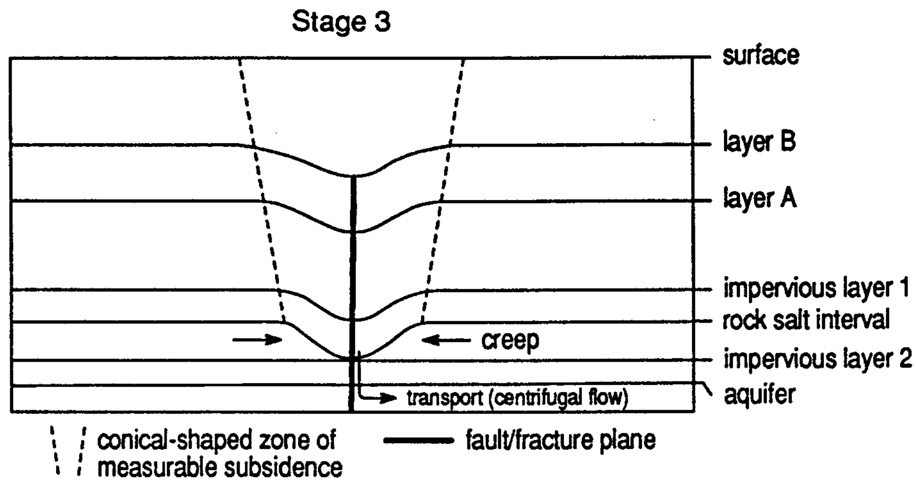
fig 1

Stage 2



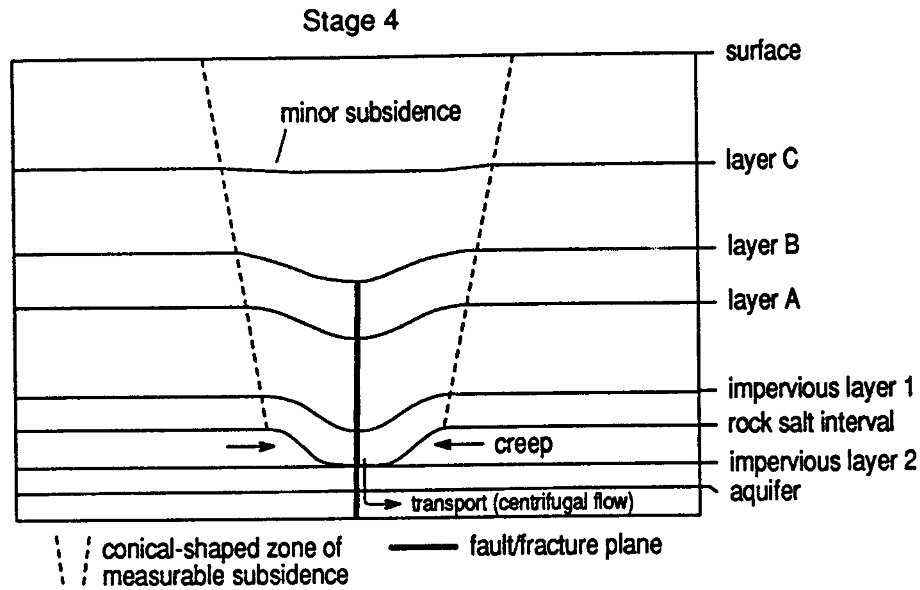
In Figure 10b (analogous to mid-Late Cretaceous) regional faulting and/or fracturing has occurred. A conduit between the rock salt and the underlying aquifer has been created; the transport of brine waters by free and forced convection has been initiated. The initial rate of dissolution is relatively rapid. Leaching, once initiated, appears to have been self-perpetuating; a process whereby fractures, created by the collapse of overlying strata, provide a conduit for unsaturated waters, thereby facilitating further dissolution.

fig 2



In Figure 10c (analogous to mid-Late Cretaceous) the post-salt 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.

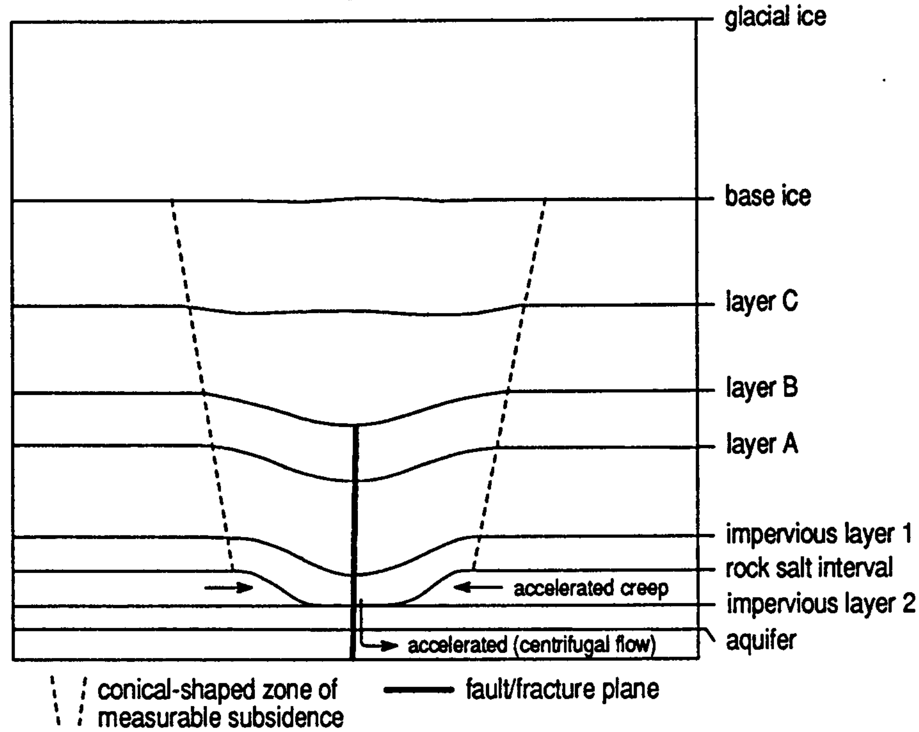
fig 3



In Figure 10d (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 rate at which dissolved salts are transported out of the system) is relatively low. As a result, the regressive migration of the zone of measurable subsidence and the creep of the residual rock salt have slowed considerably.

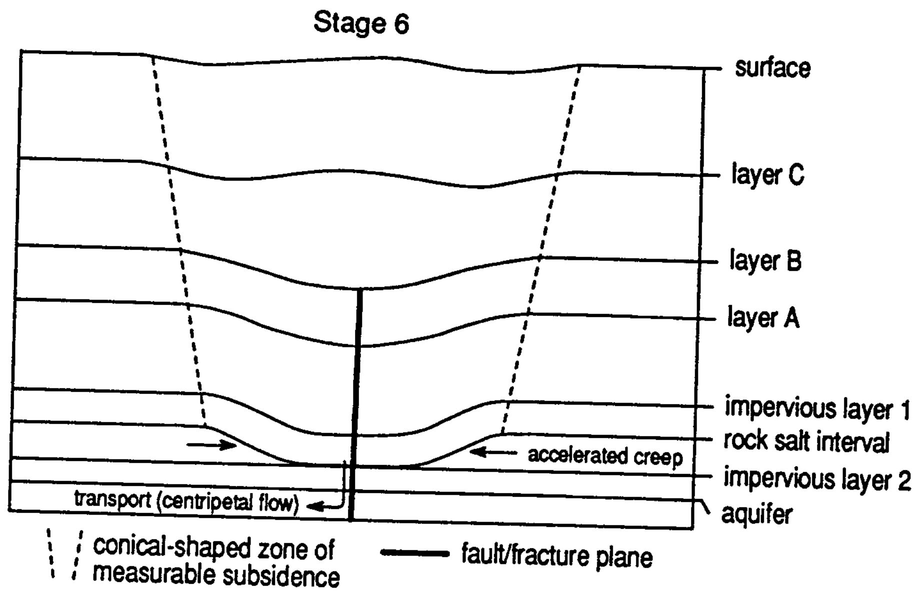
fig 4

Stage 5



In Figure 10e (analogous to Pleistocene) the study area is overlain by a 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 of fluids). These changes increase both the rate at which the rock salt creeps (increased temperature and stress differential) and the rate of transport. As a result the rates of dissolution and subsidence are relatively high.

fig 5



In Figure 10f (analogous to Holocene) the glacial ice has retreated. This rapid removal of this load is envisioned as having changed the hydrologic environment in the study area; from centripetal-flow to centrifugal flow (margin to basin flow of fluids). As a consequence of the sudden influx of relatively fresh waters (some of glacial origin), the rates of dissolution and subsidence remain relatively high. In the schematic model, the permeability (and rate of fluid flow) within the fault/fracture plane is envisioned as having increased due to rebound-induced fracturing along the pre-existing planes of weakness.