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THE ROLE OF SALT IN FOLD-AND-THRUST BELTS

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ABSTRACT

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The style of deformation in thin-skinned fold-and-thrust belts is critically dependent upon the resistance to sliding along the detachment between the mass of deforming sediments and the underlying rocks. Evaporites can provide an extremely weak horizon within which a basal detachment can form and along which only a relatively small shear traction can be supported. Fold-and-thrust belts that form atop a salt layer, such as the Appalachian Plateau, the Franklin Mountains in northwestern Canada, and the Jura of the Alps, among others, share several readily observable characteristics. As predicted by a simple mechanical model for fold-and-thrust belts, a detachment in salt permits a thrust belt to have an extremely narrow cross-sectional taper. In addition, predicted orientations of the principal stress axes over a salt décollement are consistent with the commonly observed lack of a consistently dominant vergence direction of structures within the thrust belt. Other common attributes of salt-basal thin-skinned deformation include the presence of several widely but regularly spaced folds and abrupt changes in deformational style at the edge of the salt basin.

INTRODUCTION

The mechanics of overthrusting has been a subject of debate ever since the recognition of large-scale horizontal overthrusts (Rogers and Rogers, 1843; Heim, 1871). A commonly recognized dilemma in structural geology derives from the fact that rocks within the overlying plate are too weak to permit such movements without fracturing internally (e.g., Smoluchowski, 1909). This "paradox of overthrusts" can be partially resolved by taking into account the role of any excess pore-fluid pressures that existed at the time of thrusting (Hubbert and Rubey, 1959).

A common feature of foreland thrust belts is the presence of a basal surface of detachment or décollement which dips toward the interior of the mountain belt, and below which there is relatively little deformation. The horizon along which the décollement is located is often a relatively weak one. The overall cross-sectional taper of the thrust belt above this horizon has been demonstrated to be related to the relative strengths of the thrust belt and its basal detachment (e.g., Chapple, 1978; Davis et al., 1983; Stockmal, 1983; Dahlen et al., 1984). In essence, such "bulldozer" models state that a relatively weak basal detachment zone can be overthrust by a body of nearly rectangular geometry, but greater basal strength requires that the overthrusting body attain a certain cross-sectional wedge taper.

A very wide variety of rocks have remarkably similar frictional strengths under conditions which are common in the top 10 km or so of the crust (Hoshino et al., 1972; Beyerlee, 1978). Exceptions to this rule include clays and shales, which are relatively weak. However, evaporites (and, in particular, rock salt) are vastly weaker than any other common rock type. Salt is below its brittle–ductile transition even in the top few kilometers of the crust and flows at geologically important strain rates in response to shear stresses of less than 1 MPa (Carter and Hansen, 1983). Because overthrusts appear to seek out horizons which provide even a modest reduction in resistance to slip, it is logical to expect that salt may have a major effect upon the deformation in a fold-and-thrust belt.

Evaporite basins, most of which include large quantities of halite, in addition to

TABLE 1

Examples of thin-skinned deformation which has taken place at least in part atop a salt layer

Fold belt	Location	Peak folding	Evaporite age	References *
Franklin Mountains	NW Canada	L. Cret.–E. Ter.	Camb.	1, 2
Parry Island Fold Belt	Canadian Arctic	L. Dev.–E. Miss.	Ord., Perm.	3, 4
Appalachian Plateau	NE United States	L. Pen.–Perm.	Sil.	5, 6
Sierra Madre Oriental	NE Mexico	E. Ter.	U. Jur.	7, 8
Cordillera Oriental	Colombia	L. Mioc.–Present	L. Jur.	9, 10, 11
Atlas Mountains	Morocco, Algeria	Eoc.	Tri.	12
Pyrenees	France, Spain	Eoc.	Tri.	13, 14
Jura	Switzerland	Eoc.	Tri.	15, 16
Carpathians	Rumania	Plio.	Mioc.	17
Zagros	Iran	active	L. PreC., Mioc.	18
Salt Range	Pakistan	active	Camb.	19
Tadjik Fold Belt	Tadjik SSR	active	Jur.	20, 21
Southern Urals	Russian SSR	L. Paleoz.	L. Paleoz.	22
Amadeus Basin	Central Australia	Dev.	PreC.	23, 24
Verkhoyansk Fold Belt	Siberia	Cret.	Dev.???	25
Hellenic Arc	Aegean Sea	active	U. Mioc.	26

* References: 1—Cook and Aitken (1976); 2—Cook and Bally (1975); 3—Davies (1977), 4—Balkwill (1978); 5—Rodgers (1963); 6—Rodgers (1970); 7—De Cserna (1971); 8—Rogers et al. (1962); 9—Ujeta (1969); 10—Campbell and Bürgl (1965); 11—McLaughlin (1972); 12—Tortochaux (1978); 13—Brinkman and Lögters (1968); 14—Liechti (1968); 15—Spicher (1980); 16—Laubscher (1972); 17—Paraschiv and Olteanu (1970); 18—Farhoudi (1978); 19—Yeats and Lawrence (1985), 20—Leith (1984); 21—Keith et al. (1982); 22—Kazantsev and Kamaletdinov (1977); 23—Stewart (1979); 24—McNaughton et al. (1968); 25—Nalivkin (1973); 26—Le Pichon et al. (1982).

anhydrite and gypsum, are common (Zharkov, 1981). In this paper, we examine the ways in which the presence of a relatively weak evaporite-rich detachment influences the style of deformation in a thin-skinned mountain belt. In Table 1, we list sixteen examples of thin-skinned deformation which has taken place at some time, and at least in part, atop a layer of weak evaporites, usually including salt.

MECHANICS OF DETACHMENT IN SALT

Let us now consider the effect of a weak basal layer upon the mechanics of fold-and-thrust belts. The overall mechanics of thin-skinned fold-and-thrust belts and their marine analogs, accretionary prisms, have been modeled as analogous to that of a wedge of soil in front of an advancing bulldozer (Davis et al., 1983; Dahlen et al., 1984). The critical taper is that cross-sectional wedge taper maintained when the entire thrust belt is on the verge of horizontal compressive failure. A wedge that is too narrowly tapered (such as one which has undergone erosion) will not slide along its basal décollement when pushed from behind. Instead, the failure criterion is exceeded within a narrowed portion of the wedge, leading to internal thrust faulting which shortens and thickens the wedge to reestablish the critical taper. The mechanics of the Taiwan fold-and-thrust belt appears to be consistent with the assumption that it deforms into a wedge until the critical taper is attained, after which the wedge continues to broaden at a constant taper as new material is added at the front (Davis et al., 1983).

The failure criterion used to calculate the critical taper for fold-and-thrust belts consisting of rocks that have normal stress dependent strengths (Hoshino et al., 1972; Byerlee, 1978) is the Coulomb criterion. This criterion for shear traction τ at failure is of the form

$$\tau \doteq S_0 + \mu\sigma_n(1 - \lambda) \qquad (1)$$

where S_0 is cohesion, μ is the friction coefficient, σ_n is the normal stress, and λ is the pore-fluid pressure ratio, as defined by Hubbert and Rubey (1959). The Coulomb failure criterion, with μ between roughly 0.6 and 0.85 and with S_0 between roughly 5 and 20 MPa, describes the strengths of a very wide range of upper crustal rocks during brittle deformation.

Experimental deformation of salt (e.g., Carter and Hansen, 1983) demonstrates a different sort of behavior which is not suitably modeled by the Coulomb criterion. Even at the temperature and pressure conditions found at shallow depths in the earth, salt is in the ductile regime (Fig. 1). At typical depths for a basal detachment (2–6 km), geological strain rates ($10^{-14 \pm 1}$ $\sec^{-1}$) and geothermal gradients (20°–35°C km^{-1}), the yield strength τ_0 for salt is between roughly 100 kPa and 1 MPa (Carter and Hansen, 1983). In a salt-dominated basal décollement, the normal stress dependence of eqn. (1) disappears. Instead, it becomes more appropriate to write:

$$\tau = \tau_0 \leqslant 1 \text{ MPa} \qquad (2)$$

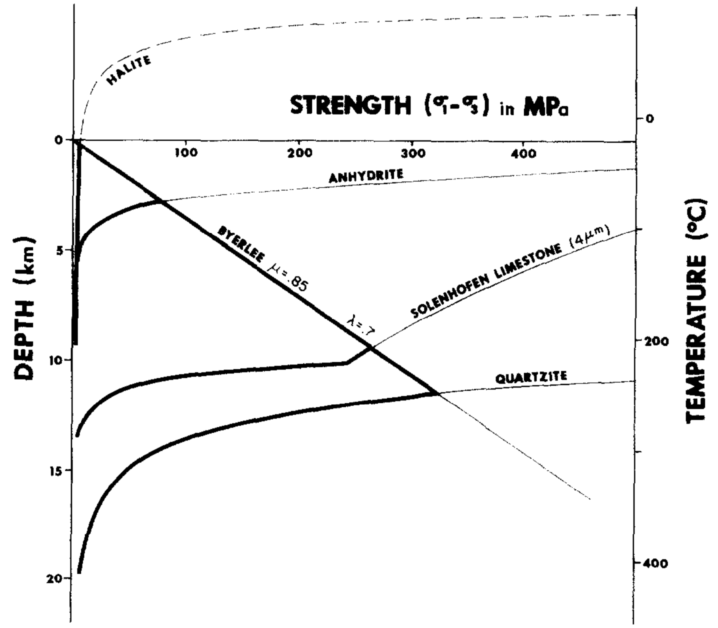

Fig. 1. Diagram illustrating the strength versus depth of various rock types. Note the comparative weakness of salt.

Thus, under conditions which are appropriate to a basal detachment, salt is between 1 and 2 orders of magnitude weaker than most other rocks.

One effect of the extreme weakness of salt in ductile flow is illustrated by the critical taper equation of Davis et al. (1983) and Dahlen et al. (1984). This expression relates the critical taper angle to the strength and pore pressures in the wedge and along the basal décollement. In particular, a weaker coupling along the basal detachment permits overthrusting of a sediment mass having less taper (in other words, one with a more nearly rectangular cross-sectional shape). Similar results are obtained using the models of Chapple (1978) and Stockmal (1983) with very small values of χ, their dimensionless ratio of detachment strength to wedge strength.

If the basal décollement occurs along the salt horizon, the critical taper may be very small. Let us assume a pressure-independent (i.e., plastic) yield stress τ_b along the basal décollement, with the overlying rock having a strength dominated by a friction coefficient $\mu = \tan\phi$ and with S_0 negligible. In the weak-basal limit (Davis et al., 1983; Dahlen et al., 1984) the critical taper is:

$$\alpha + \beta \approx \frac{\beta + (\tau_0/\rho g H)}{1 + (1-\lambda)\left(\dfrac{2}{\csc\phi - 1}\right)} \tag{3}$$

where ρ is the mean rock density, g is the acceleration of gravity, H is the depth to the basal detachment, and α and β are the mean topographic and basal angles, respectively. If $\tau_0 = 1$ MPa a few km deep at the base of a fold-and-thrust belt, then essentially no taper ($\sim 1°$) is required for the overlying sediments to be pushed horizontally toward the foreland. In contrast, even with moderately overpressured pore fluids ($\lambda \approx 0.7$) decreasing the basal shear traction, the fold-and-thrust belt of Taiwan, which has no salt, requires a taper of about 9° in order to be stable under compression. Thus, fold-and-thrust belts which ride atop a basal salt layer should be more narrowly tapered than strong-basal wedges. The presence of salt will permit folding and thrusting to occur over an extremely wide belt, giving the impression in map-view that the mountain belt has projected far outward. At the edges of the salt basin, the contrast in shear traction between areas with and without salt (typically between 1 and 2 orders of magnitude) is large enough to have a major effect on the outward progression of structures, leading to major salt-termination related drag-related structures such as the Burning Springs anticline on the Central Appalachian Plateau (Rodgers, 1963).

Another important parameter controlled by the presence of a very weak basal detachment is the dip ψ_b at which the axis of maximum compressive stress $\bar{\sigma}_1$ dips toward the foreland with respect to the basal detachment. This is illustrated by a Mohr-Coulomb diagram in Fig. 2. The magnitude of ψ_b at the base of a deforming wedge is very strongly dependent upon shear traction which can be supported across the basal décollement. Beneath the toe of the Taiwan fold-and-thrust belt, $\psi_b \approx 12°$ (Dahlen et al., 1984). If the coupling were weakened by the presence of salt, then ψ_b would be approximately 1°.

The orientation of the principal stress axes is important because of its relation to deformation. The Coulomb failure criterion is satisfied most readily along planes at either of two orientations inclined about the $\bar{\sigma}_1$ axis at angles θ defined by the simple relation:

$$\theta = \pm(45° - \phi/2) \tag{4}$$

Because the two candidate slip planes are symmetric about the $\bar{\sigma}_1$ axis, which dips toward the foreland at an angle ψ_b, the forward (toward the foreland) verging plane dips more shallowly (at an angle $\delta_f = \theta - \psi_b$) than does the backward one ($\delta_b = \theta + \psi_b$), as shown by Hafner (1951). This difference in dip (Fig. 3) probably explains why forward-verging thrusts are the more common of the two in most thrust belts and accretionary prisms. The shallower dip permits a greater amount of horizontal shortening for the same increase in gravitational potential energy. It is also favored because of stratigraphic strength anisotropy. However, in a weak-basal wedge, the predominance of forward-vergent thrusts should be less clear because the two candidate slip planes have more nearly equal dips (Fig. 4). If folds in salt-basal fold belts are related to blind thrusts near the basal detachments (Gwinn, 1964), then the folds should also have a relatively symmetrical form.

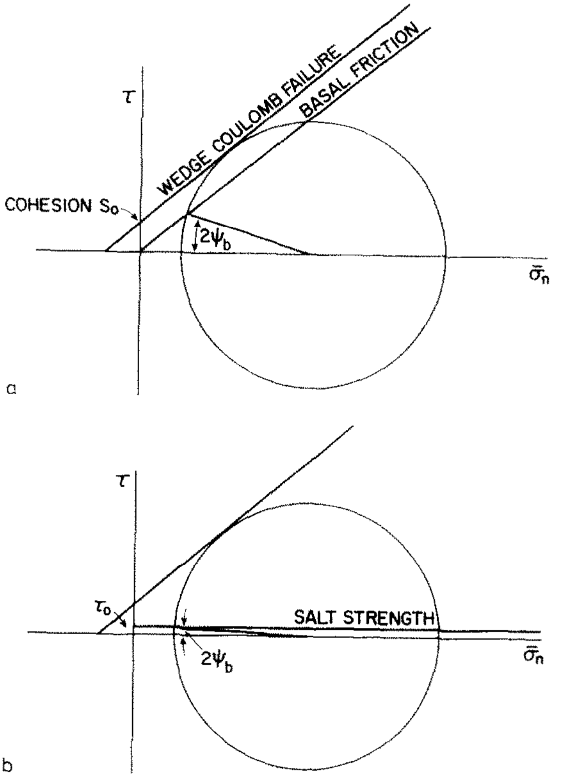

Fig. 2. Mohr-Coulomb diagram showing the contrast in ψ_b, the dip of the axis of maximum compressive stress with respect to the basal décollement, for (a) a strong and (b) a weak, salt décollement.

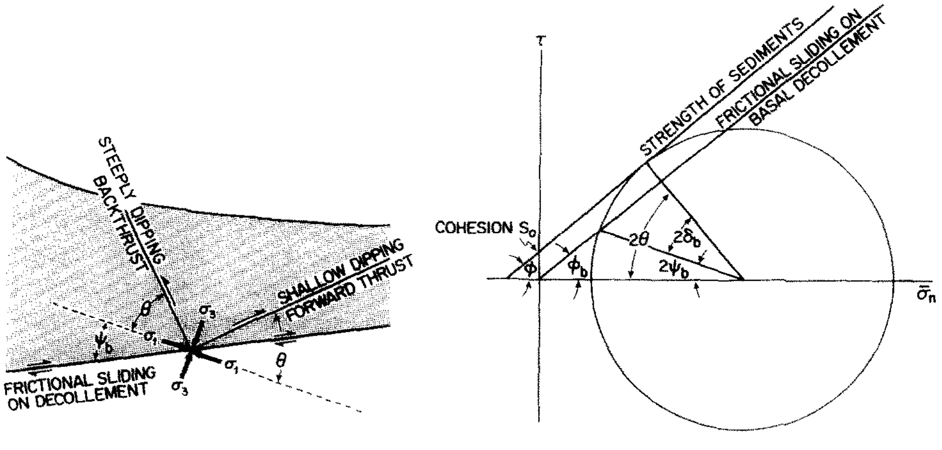

Fig. 3. Illustration of why a forward verging candidate thrust plane dips more shallowly than a backward verging one.

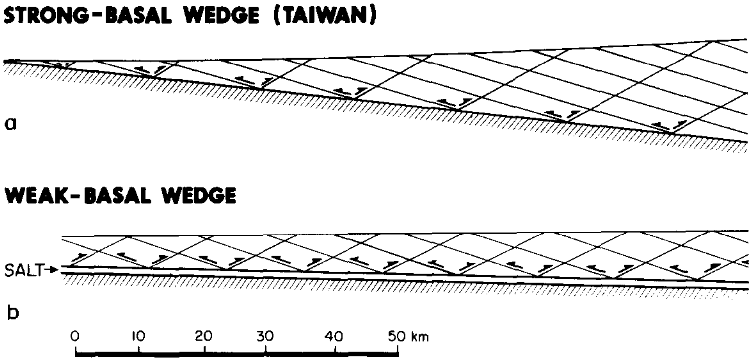

Fig. 4. The orientations of candidate slip planes in (a) a strong-basal wedge and (b) a wedge with a weak detachment in salt. Note the lack of a relatively shallow forward-verging thrust plane in the weak-basal case.

The mobility of salt contributes to both the growth and symmetrical form of folds. Salt can flow under relatively small stresses into an anticlinal fold core. An incipient stage of this process is found on the Appalachian Plateau (Wiltschko and Chapple, 1977) and is carried to an extreme in the Zagros (Farhoudi, 1978). Once it attains a sufficiently large amplitude, a gravitational instability will probably tend to continue to grow because, in addition to being weak and ductile, salt has a lower density than most other sedimentary rocks. The result would be a salt-cored anticline whose form carries little evidence of its origin in horizontal compressive tectonics.

CORRELATIONS WITH SALT

Theoretical modeling predicts many of the unique aspects of the deformation observed in salt-basal thin-skinned tectonics. In fact, their characteristics can be used to infer the boundaries of salt basins beneath fold belts and the presence or absence of salt beneath poorly explored fold belts. Here we identify the most common characteristics of décollement tectonics on salt.

Broad belts with narrow taper

Fold-and-thrust belts that ride atop a basal salt layer are typically characterized by their narrow cross-sectional taper and the anomalous width of the folded zone. Typically, the fold belt extends farther out toward the foreland where there is a basal salt layer compared with areas along strike where salt is missing. Some folded zones over salt have widths ranging up to as much as 500 km. There are, of course, other factors which can influence the width (but not the cross-sectional taper) of a fold belt, such as the dip of a subducting slab beneath the plate (e.g., Jordan et al., 1983).

The cross-sectional wedge taper of salt-basal thin-skinned mountain belts is

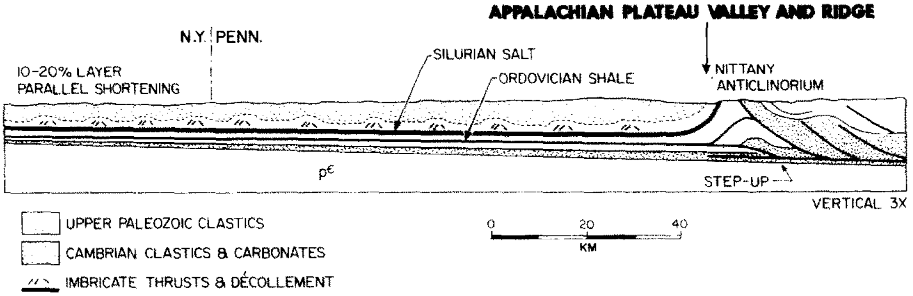

Fig. 5. Schematic cross-section of the Appalachian Plateau and the Valley and Ridge Province, with an approximate vertical exaggeration of 3 : 1. Note the step-up of the basal décollement into salt, permitting Appalachian Plateau folding.

typically very narrow (often $\leqslant 1°$), compared with strong-basal (non-salt) wedges, which commonly exceed 8° in taper. This observation is directly related to the outward projection of structures described above. If for some reason (such as reduced basal shear traction) a fold belt can maintain a very narrow taper under horizontal compression, then it follows that for a given thickness above the detachment it will be able to form a correspondingly wide folded belt. One example is the Appalachian Plateau (Fig. 5). Although erosion has removed some material from the wedge, the taper at the time of active folding was probably quite narrow.

The Appalachian Plateau (Fig. 6), which lies to the north and west of the Valley and Ridge province of the Appalachians, is a well-documented example of a salt-related outward propagation of folding. The importance of salt in controlling structures in the Appalachian Plateau is made most clear with a comparison of the geographic extents of the folding and of the salt (Fig. 6). The limit of relatively thick ($\geqslant 75$ m) salt in the Syracuse Formation is essentially the same as the limit of "more than very mild folding", as noted by (Rodgers, 1963).

Perhaps the best known evaporite-based fold belt of all is the Jura Mountains. This fold belt extends roughly 300 km along strike and 70 km wide, and is separated from the northern Alpine front by the 30 to 50 km wide molasse basin of the Swiss Plain. Its southern end merges with folds in the Western Alps, and its northeastern end is marked by folds that die out into the Table Jura, 60 km in front of the Alpine front. Jura folding is characterized by Mesozoic sediments folded into long narrow anticlinal ridges and synclinal valleys, all riding atop an evaporite-rich décollement. The evaporites, averaging approximately 100 m in thickness, are of Muschelkalk and Keuper (Triassic) age, and include gypsum, anhydrite, and salt (Gwinner, 1978; Anderson, 1978).

The Franklin Mountains of northwestern Canada lie in front of the Mackenzie salient. The arcuate structure of the Mackenzie salient is largely determined by the form of Hadrynian (Precambrian) basins (Aitken and Long, 1978). However, the structure of the Franklin Mountain appears to be the result of thin-skinned

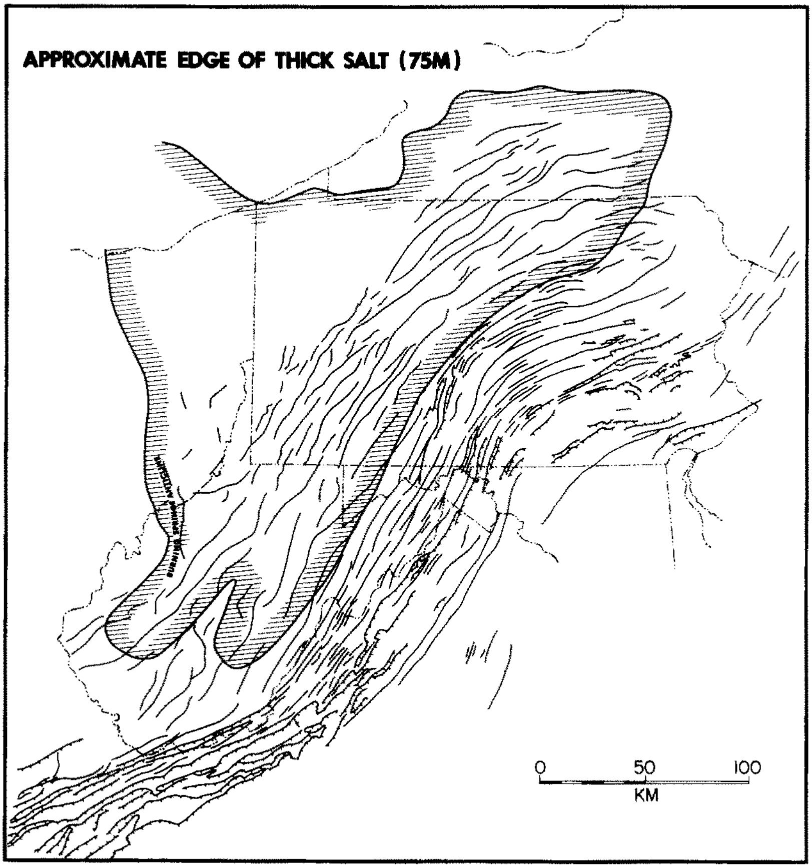

Fig. 6. Map of the Appalachian Plateau area showing the trends of anticlines (solid lines) and thrust faults (hatchured lines). Shading shows the approximate locations of the salt zero edge and 75 m isopach (Fergusson and Prather, 1968; Frey, 1973; Chen, 1977; Mesolella, 1978).

deformation over the Cambrian Saline River Formation (Fig. 7) which includes thick beds of halite, anhydrite and gypsum over an extensive region (Hills et al., 1981). Evaporite thickness locally reaches 670 m, but averages closer to 200 m.

The Franklin Mountains (Fig. 7) are characterized by narrow, often somewhat arcuate ridges typically only 300 m high that are separated by broad, flat-bottomed synclines (Cook and Aitken, 1973; Aitken et al., 1982). The ridges are anticlines that show no consistent vergence and which are cored by flow-thickened evaporites. They are separated from the Mackenzie Mountains front by the Mackenzie Plain synclinorium, a nearly flat region broken by occasional uplifts like those found in the Franklin Mountains. Along strike to the northwest are the Peel Plateau and Peel Plain, a flat expanse devoid of folding. The contrast in styles between the Peel Plain and Peel Plateau appears to be related to the location of the Saline River Formation. This formation is found beneath the Franklin Mountains and the Mackenzie Plain.

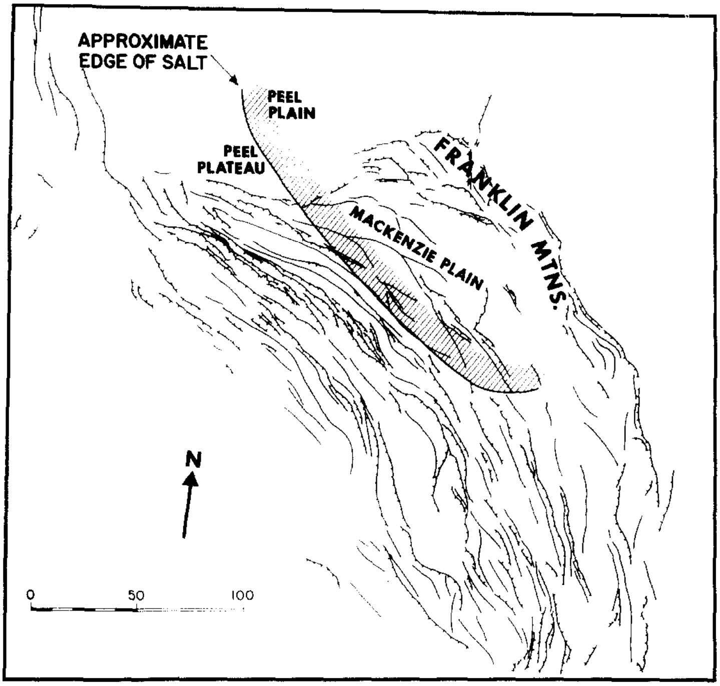

Fig. 7. Map of the Franklin Mountains area, after Ziegler (1969), Douglas (1970), and Aitken et al. (1982). The shading indicates the approximate edge of the Saline River Formation salt (Ziegler, 1969; Aitken et al., 1982).

Its southwestern edge is found at the western end of the Franklin Mountain structures, and then, beneath the easternmost Peel Plateau its southwestern boundary turns away from the Mackenzie front (Aitken et al., 1982). The role of the Saline River evaporites in determining and limiting the lateral development of the folds of the Franklin Mountains, Mackenzie Plain and Peel Plain and Plateau may be similar to that of the Triassic evaporites beneath the Jura.

Step-up of décollement into salt

In the Appalachian Plateau (Fig. 5), the level of décollement steps up section at the margin of the salt basin, eventually reaching the Silurian salt beneath the Appalachian Plateau (Rodgers, 1963). A similar process appears to take place in the Franklin Mountains, and plays a major role in determining the regional structural style. Apparently, the presence of the Saline River Formation evaporites allowed slip to be transferred from the deeper horizons found in the Mackenzie Mountains to the shallower Saline River Formation. Once the most cratonward edge of the slipped rock had transferred to a horizon which provided so little resistance, it could be propagated far forward at a negligible cross-sectional taper; this same effect is seen at the Allegheny front of the Appalachians. Where the evaporites are absent along the Mackenzie front, Cambrian and younger strata were not decoupled from deeper formations and thus were constrained from moving with respect to deeper formations (Aitken et al., 1982). Thus, despite the presence of the Saline River Formation beneath parts of the Peel Plateau and Peel Plain away from the Mackenzie front, the absence of evaporites at the Mackenzie front (Fig. 7) made it impossible for slip to step up onto a weak plane, and hence structures such as those beneath the Franklin Mountains are absent on the Peel Plain.

Folds: long-symmetric, with broad synclines

Folds in salt-basal fold belts are commonly continuous over lengths of 100 km or more, and are typically comprised of narrow anticlines separated by broad, relatively flat synclines. The folds also tend to exhibit a great deal of cross-sectional symmetry, either as box folds (Laubscher, 1972) or as drape folds over salt-cored structures including splay faults (e.g., Gwinn, 1964; Fox, 1984).

Folds in both the Appalachian Plateau and the Valley and Ridge provinces of the Appalachians are generally parallel on a local scale, and individual fold axes often exceed 100 km in length. However, folds in the Appalachian Plateau are much smaller (with lower amplitudes and gentler dips) than they are in the Valley and Ridge province in the Appalachian Plateau area (Rodgers, 1963). Folds in the Appalachian Plateau are generally symmetrical, and lack the consistent northwestward steepening of those in the Valley and Ridge province. The Plateau is characterized by relatively gentle cylindrical folding at the surface, and complex folding and blind thrusting at depth above a décollement in Silurian salt (Bradley and Pepper, 1938).

The distribution of evaporites beneath the Appalachian Plateau (Fig. 6) has been mapped in detail (e.g., Kreidler, 1963; Cate, 1963; Fergusson and Prather, 1968; Chen, 1977). The Upper Silurian Saline Group includes several beds of halite, with the two most massive (the "D" and "F" Salts) occurring in the Syracuse Formation. The aggregate depositional thickness was generally close to 100 m and locally exceeds 200 m (Kreidler, 1963; Cate, 1963; Fergusson and Prather, 1968). Movement of salt into anticlines produced local salt thicknesses well over 500 m (Wiltschko and Chapple, 1977; Mesolella, 1978). An anhydrite zone above the youngest salt is locally thickened within anticlines. The readjustment of salt associated with folding (Prucha, 1968; Frey, 1973) also included a complimentary thinning in the broad synclines between the relatively narrow anticlines.

Folds and blind thrusts in the overlying rock appear to have no major expression below the Syracuse Formation, which dips southeastward at a bit over 1° (Prucha, 1968). The structural relief associated with the folds generally increases with salt thickness and decreases with distance from the structural boundary with the Valley and Ridge province. Once a fold over splay faults had been initiated, the relief

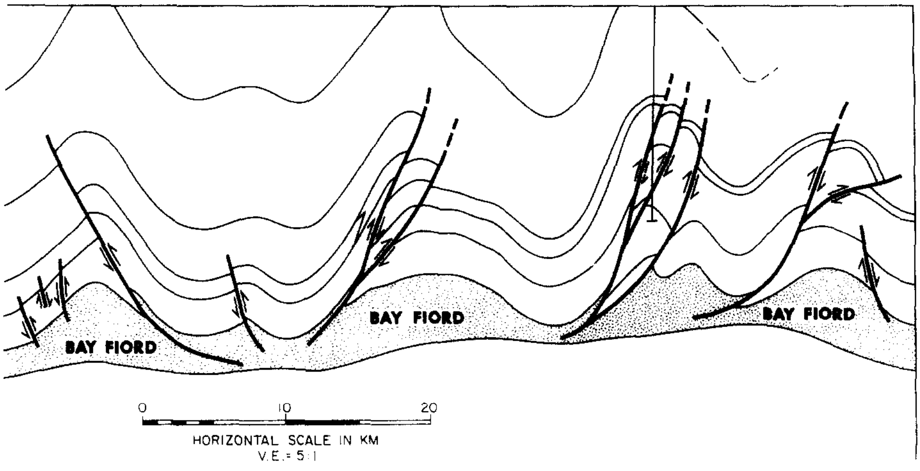

Fig. 8. Line drawing of a seismic reflection line through the Parry Islands fold belt (after Fox, 1984), showing structures above the Bay Fiord Evaporite.

apparently continued to increase by progressive broadening of the flat central part of synclines (Fig. 8) to produce broad, flat synclines separated by relatively narrow anticlines (Wiltschko and Chapple, 1977). In parts of West Virginia and south-central Pennsylvania next to the Allegheny front and the Valley and Ridge province, deformation has been sufficiently intense that the supply of salt was inadequate to fill the interior of the anticlines. Some slip there was also accommodated within other layers (Gwinn, 1964).

The Canadian Arctic Islands are crossed by several orogenic belts of various ages which lie above sizeable quantities of evaporites. The Parry Island fold belt, which has a total length of roughly 600 km and covers most of Bathurst and Melville Islands, underwent folding above a décollement during the Ellesmerian (latest Devonian–Early Mississippian) orogeny. The décollement is at the level of the Mid-Ordovician Bay Fiord formation, which contains a great deal of gypsum and anhydrite, as well as locally thick salt (Davies, 1975; Christie et al., 1981). Individual folds are relatively symmetrical in form, extend as much as 160 km in length, and are typically separated from their neighbors by a wavelength of 13 to 24 km (Douglas, 1970; Smith and Wennekers, 1977). The broad, shallow synclines and narrow anticline have interpreted to indicate flow of evaporites at depth (Smith and Wennekers, 1977). This interpretation is consistent with reflection seismic data (Fox, 1984), which shows a great deal of flowage of evaporites and a rather confused set of fault orientations associated with the anticlines (Fig. 8).

Anticlinal salt flow and box folds

The folds of the Appalachian Plateau are typically characterized by splay faults off the basal décollement which produce salt-cored anticlinal uplift (Figs. 5, 9a). Salt

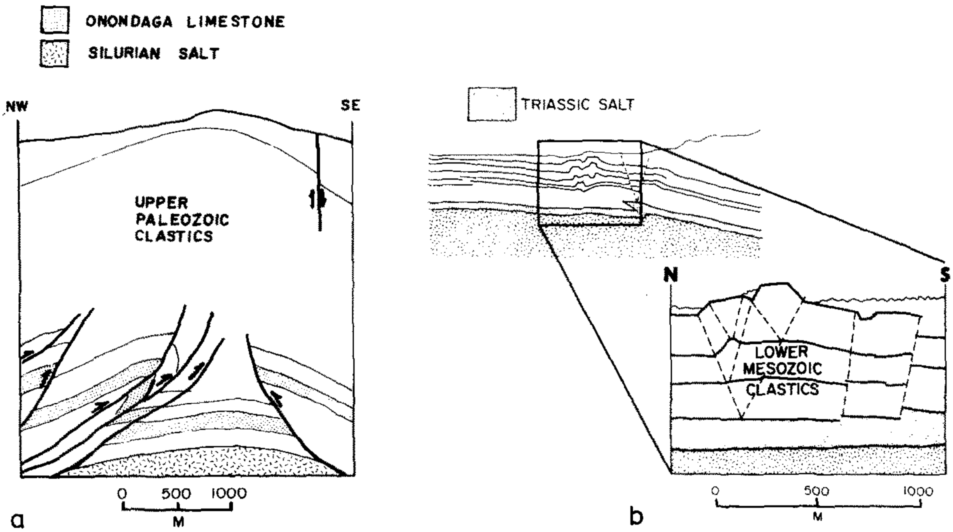

Fig. 9. Structure of folds over salt. a. Appalachian Plateau salt-cored anticline (after Gwinn, 1964). b. A large Jura box fold (after Laubscher, 1977).

has thickened under these regularly spaced anticlines (Wiltschko and Chapple, 1977). Another type of folding observed above salt is that found in the Jura, where folds have been described as a superposition of different kinds of instabilities in space and time which are never sinusoidal in form (Laubscher, 1976, 1977). Instead, they are more realistically modelled as box fold structures, or very large (several hundreds of meters across) kink bands with rounded edges (Fig. 9b). Laubscher (1977) suggests that instabilities in the sedimentary cover that produce box folds commonly initiate at irregularities along the basal décollement layer.

The structure of the Zagros mountains is dominated by the presence of very large quantities of salt at both shallow and very deep levels. The latest Precambrian Hormuz salt, typically about 300 m thick, underlies the Simply Folded Belt of the Zagros, which rides over it with a taper of 1° or less. There is also a Miocene salt horizon which is typically thinner than the Hormuz, although it was so mobile that it is locally very thick (Colman-Sadd, 1978). Lying in front (to the southwest) of a highly deformed imbricate belt is the very wide (well over 200 km in places) Simply Folded Belt, which is characterized by large anticlinal mountains with non-uniform vergence and synclinal valleys. Most observed faults are associated with anticlines. Salt movement is much more extensive in the Zagros (Farhoudi, 1978) than in the Appalachian Plateau.

Colman-Sadd points out that the southwestern (forward) limbs of the anticlines in the Zagros Simply Folded Belt are almost invariably steeper than the other limb. He suggests that this geometry may be related to the extreme mobility of the salt, which resulted in the relative depletion of salt in the synclines. This would then have produced more drag at the synclines than at the anticlines and retarded the development of the back limb to produce the observed asymmetry. Salt depletion in the Lurestan–Khuzestan region may also be related to the shorter fold wavelengths and the greater prominence of thrust faults at the surface there (Colman-Sadd, 1978; Farhoudi, 1978).

The extreme mobility of the salt beneath the Zagros is a very special attribute of that mountain belt. The combination of salt bed thickness and burial depth apparently favors the generation of salt diapirs, which have grown to the point of overwhelming many of the pre-existing thin-skinned tectonic structures. In addition, the broad expanse of salt at depth permits the generation of a fold belt of exceptional width (≥ 200 km).

Strain over salt and blind thrusts

Relatively unfolded sediments beyond (cratonward of) frontal folds in the Appalachian Plateau have undergone layer-parallel shortening through a pressure solution mechanism. This shortening is accompanied, at depth, by blind thrusts. Strain indicators in the layer-parallel shortened rocks include deformed fossils, pencil cleavage, mechanical twinning, and overcoring strain relaxation. Strain measured in front of the frontal folds in western New York State (Engelder, 1979; Engelder and Geiser, 1979) indicates that the magnitude of strain is closely related to the distribution of the Silurian salt (Fig. 10). Along any chosen traverse, compressive strain increases rapidly from very low levels ($\leq 2\%$) over areas without significant salt to a fairly constant 15% over areas with salt. A blind thrust must separate the strained strata above the salt from the presumably unstrained layers below the salt (Fig. 5).

Differential drag

The form of the syntaxes and salients in the Himalayas of eastern Pakistan may be related to the distribution of salt (Sarwar and De Jong, 1979; Seeber et al., 1981), although the distribution of promontories in the basement may also be an important factor (Powell, 1979; Sarwar and De Jong, 1979). The marked contrast in the style and geometry of thin-skinned deformation on either side of the northwestern Himalaya syntaxis is probably related to the fact that salt is present on the west and is apparently absent to the east. The thick wedge taper and locally intense deformation to the east of the syntaxis contrasts strongly with the narrow taper and a broad overthrusting zone to the west of the syntaxis. Burbank (1983) suggests that sediments on either side of the syntaxis originally occupied comparable positions along strike, but have been offset differentially along a salt basin boundary because of a large difference in the degree of basal coupling. Recent geologic and seismic reflection studies (Yeats and Lawrence, 1985; R.J. Lillie, pers. commun., 1985) show

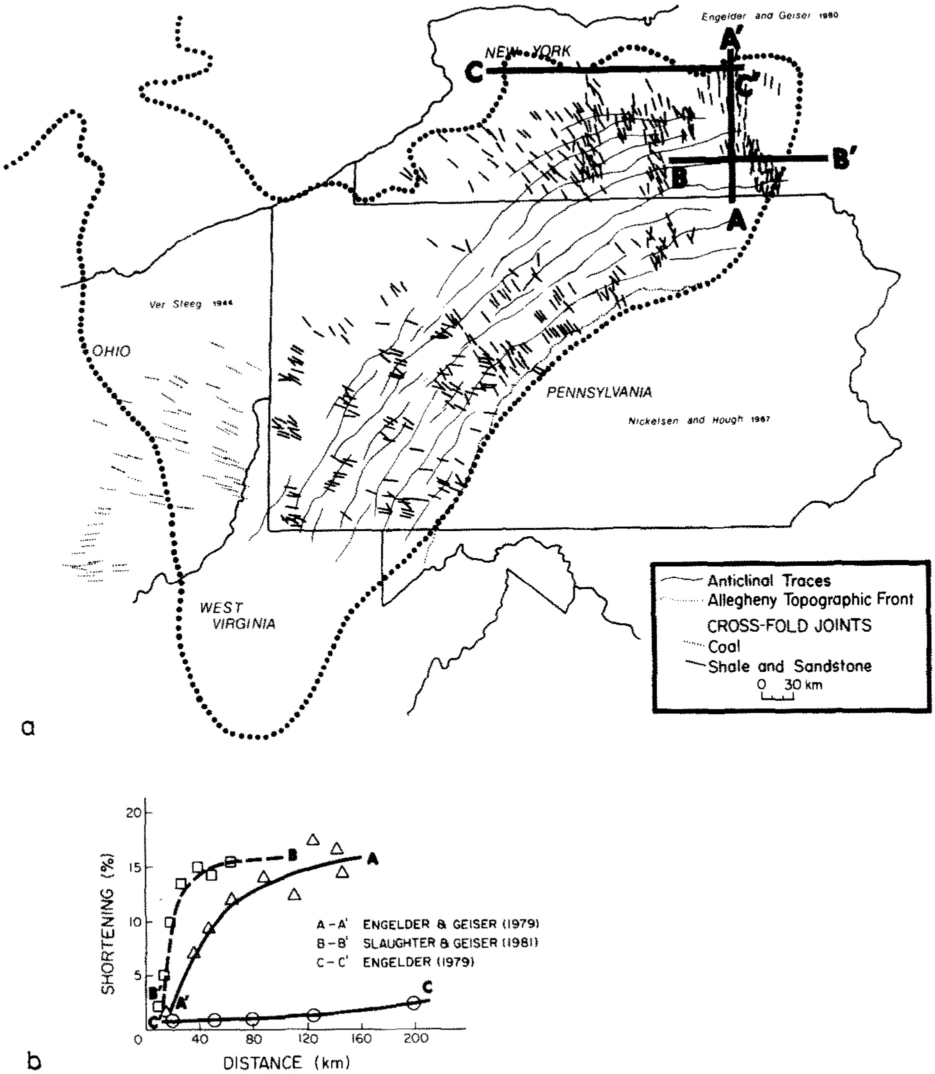

Fig. 10. a. A map of the Appalachian Plateau area, showing the limit of Silurian salt and the locations of three lines along which the amount of measured shortening has been plotted in (b).

that the Potwar Plateau has little or no taper. The basal salt layer steps up over a major basal uplift and forms the basal detachment for the Salt Range, which is also essentially untapered.

Differential drag over a short distance along strike might be expected to cause rotation of the overlying sediments as those over the salt progress a greater distance forward than those not over salt. Interestingly, there is paleomagnetic evidence which suggests that such a counter-clockwise rotation has taken place (Crawford, 1974). This is consistent with the idea that the Salt Range has slid far southward on the Cambrian salt (Seeber and Jacob, 1977), in contrast to the strong coupling of younger sediments to the basement in the absence of salt.

Salt-boundary related bending of folds

The Burning Springs anticline, in the Appalachian Plateau near the West Virginia–Ohio border (Fig. 7), contains an instructively anomalous set of splay faults off a blind thrust. The anticline trends roughly N–S, in contrast with the NE–SW trend of most other folds on the Appalachian Plateau. It is higher and steeper than any other fold within 100 km. These characteristics have been related to the southwestern termination of the Silurian salt. Rodgers (1963) remarked that "where the salt layers gave out, so that the force required for the bedding slip increased greatly, the slip surface had to cut upward to the surface, producing the aberrantly trending anticline." The condition of low basal shear traction that is required for Appalachian Plateau-style folding breaks down at the boundary of the Silurian salt, which cuts obliquely across the strike of the Appalachian Plateau folds near the Ohio–West Virginia border (Fig. 6). In response, accumulated basal slip had to abruptly pile up into splay faults within the anomalously oriented Burning Springs anticline.

A similar differential drag mechanism along strike apparently has a marked effect upon fold trends in marginal areas along the Mackenzie Mountain front (Aitken et al., 1982). The folds bend sharply southwestward along the western edge of the Franklin Mountains (Fig. 7). The sediments were apparently free to advance (on evaporites) to the east, in the Franklin Mountains, but were held back in the west. The result is an en échelon form to the anticlines along the northern front of the Franklin Mountains and a similar set, of opposite sense, on the eastern front (Norris, 1972).

Low stresses over salt layers

Differential stresses measured using several techniques appear to be relatively low in sedimentary rocks that are thrusted over salt compared to those in sediments not underlain by salt (Fig. 11). The magnitude of the differential stress acting to drive the Appalachian Plateau wedge to the northwest has been estimated in a number of ways. The axial canals of crinoid columnals within the wedge acted as stress concentrators and caused twinning adjacent to these canals. From this observation Engelder (1982) inferred that the crinoids were subject to a differential stress of 6.2 MPa. Rocks containing these crinoids also contain a solution cleavage, a fabric generally believed to form under low differential stress conditions (Rutter 1976). A specimen of bedded rock salt from Lansing, New York (i.e., within the Appalachian Plateau décollement zone (Prucha, 1968) contains 1 mm crystals with subgrain sizes that indicate a differential stress of 5.7 MPa (Carter et al., 1982). Residual stress

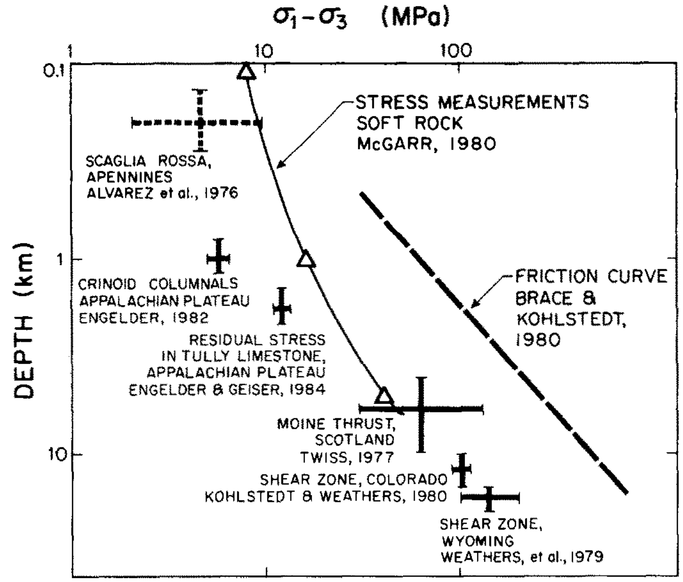

Fig. 11. Estimates of stress versus depth in fold belts. Data after Alvarez et al. (1976), Twiss (1977), Weathers et al. (1979), McGarr (1980), Kohlstedt and Weathers (1980), Brace and Kohlstedt (1980) and Engelder and Geiser (1984).

measured in rocks from the more deeply buried portions of the Appalachian Plateau (but still above the salt) averages 11 MPa (Engelder and Geiser, 1984). All of these values are lower than average crustal stresses as estimated from techniques such as in situ measurements (McGarr, 1980), measurements of fabrics such as dislocation density and subgrain size (Twiss, 1977; Weathers et al., 1979; Kohlstedt and Weathers, 1980), and laboratory estimates (Brace and Kohlstedt, 1980) (Fig. 11).

CONCLUSIONS

The overall mechanics of fold-and-thrust belts are significantly different in the presence of salt than in its absence, because at typical shallow-crustal pressures and temperatures salt is exceptionally weak. The same can be said, to a lesser degree, for other evaporites.

The presence of salt beneath the Appalachian Plateau is responsible for many of its distinctive characteristics. Its breadth in map-view is a reflection of a narrow cross-section and small taper made possible by the weak coupling in salt along the basal detachment. The long wavelength, broad synclines and sharp anticlines and symmetry of folds also appear to be related to the weakness of salt. The boundary of salt deposition appears to control the magnitude of strain at the front of the fold belt and the generation of anomalously trending structures such as the Burning Springs anticline. Evidently, salt is the mechanically preferred horizon for the accommodation of décollement slip because of its roles as a weak decoupling layer and as an easily flowing material which can facilitate folding by flowing into anticlines. Similar salt-related deformational styles can be identified in many other mountain belts.

The reduced basal coupling in the presence of salt permits the fold-and-thrust belt to maintain a much narrower cross-sectional taper (1° or less) than in the absence of salt (8°–12°). The reduced coupling also results in an axis of maximum compression which is less inclined to the horizontal and much less inclined to the basal detachment than in the case of a strong-basal fold-and-thrust belt. Hence, the mechanical preference for forward verging structures is strongly reduced. Instead, fairly symmetric salt-cored anticlines are very common.

It is difficult for an overthrust to step up from salt to a new stratigraphic horizon without then having to slide on something other than salt. Since salt is so strongly preferred as a horizon for overthrusting, it would in such a case be more likely for deformation to continue along the salt horizon, and for major slip along thrusts stepping up from the salt to be discouraged. In fact, those thrusts that do occur over salt are commonly blind splay thrusts associated with the growth of anticlines.

Where the salt is both fairly thick ($\geqslant 100$ m) and quite deep ($\geqslant 3$ km), it is very common for salt-cored anticlines to become so gravitationally unstable (due to the relatively low density of salt) that they continue to grow diapirically.

In its simplest expression, salt permits fold belts to grow to anomalously great widths of 150 to 500 km. Seen in map view, folds in a region with salt at depth appear to explode outward toward the foreland, relative to salt-less areas along strike. In the process it is quite common for differential drag on either side of a salt/no-salt boundary to cause structures to rotate or to seem to pile up along that boundary in response to the sharp contrast in basal traction.

In summary, salt and other evaporites can be so important in the development of a mountain belt that those with a basal salt layer can be viewed to comprise a distinct class, possessing a number of clearly identifiable attributes.

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