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Terra infirma: Understanding salt tectonics

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Abstract

Following common usage, we broaden the term “salt” to include all rock bodies composed primarily of halite (NaCl). Salt is mechanically weak and flows like a fluid, even at geologically rapid strain rates. Salt is also relatively incompressible so is less dense than most carbonates and all moderately to fully compacted siliciclastic rocks. Salt’s fluid rheology and incompressibility make it inherently unstable under a wide range of geologic conditions.

The primary driving force for salt tectonics is differential loading, which may be induced by gravitational forces, by forced displacement of one boundary of a salt body relative to another, or by a thermal gradient. Buoyancy, long considered a key driver for salt tectonics, is of secondary importance in many settings. Two factors resist salt flow: strength of the overburden and boundary drag along the edges of the salt body. Salt will move only if driving forces exceed the resistance to flow.

In order for a salt diapir to be emplaced into its overburden, any rock previously occupying that space must be removed or displaced. Emplacement may occur by extension, erosion, or uplift of the overburden or by overthrusting of the salt. Once salt reaches the surface, it can continue to rise by passive diapirism, in which the diapir grows as sediments accumulate around it. A rapidly rising passive diapir may spread over the sediment surface to form an allochthonous salt sheet. A variety of salt-sheet lineages are possible, depending on the geometry of the feeder and the tectonic setting.

Because salt is weak, its tectonism is closely tied to regional deformation. In extension or transtension, diapirs rise up graben axes, taking advantage of the space created by thinning and separation of fault blocks. Later, once the salt source layer is exhausted, diapirs may fall as they continue to widen. In addition, salt typically acts as a detachment in both gravity-driven and basement-involved extension. In compression or transpression, preexisting diapirs are rejuvenated as salt is displaced upward by lateral shortening. This rise is enhanced by buckling and disruption of the diapir roof. In the absence of precursor structures, salt’s primary role in compression is to act as a detachment. Some salt sheets may be emplaced in the hanging walls of thrust faults.

Keywords: diapirism; orogenic belts; passive margins; review; salt tectonics

1. Introduction

1.1. What is salt?

Strictly speaking, rock salt is a crystalline aggregate of the mineral halite (NaCl) (Jackson, 1997a,b). Given the paucity of pure halite sequences in nature, most salt-tectonic literature uses “salt” for all rocks composed

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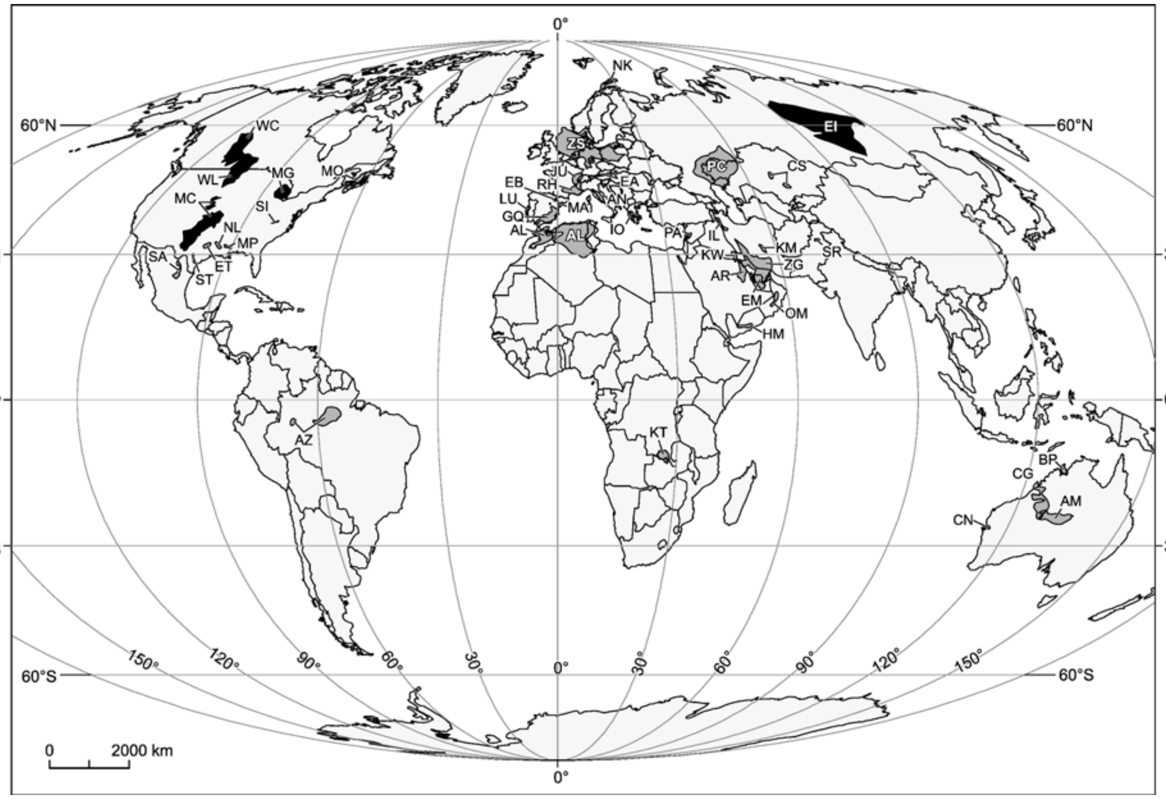


Fig. 1. Equal-area Mollweide projections showing global distribution of major cratonic salt basins. These include epicontinental basins and regions of diffuse intracontinental extension. Black basins lack significant salt tectonics, unlike the dark-gray basins. AL Atlas; AM Amadeus; AN Appenines; AR Arabian; AZ Amazon; BP Bonaparte; CG Canning; CN Carnavon; CS Chu–Sarysu; EA East Alpine; EB Ebro; EI East Siberia; EM Emirates; ET East Texas; GQ Guadalquivir; HM Hadhramaut–South Yemen; IL Iljac–Tabriz; IO Ionian; JU Jura; KM North Kerman; KT Katanga; KW Kuwait; LU Lusitanian; MA Maestrat; MC Mid-Continental U.S.; MG Michigan; MO Moncton; MP Mississippi; NK Nordkapp; NL North Louisiana; OM Oman–Fahud; PA Palmyra; PC Pricaspian; RH Rhodanian; SA Sabinas; SI Saltville; SR Salt Range; ST South Texas; WC West Canada; WL Williston; ZG Zagros; ZS Zechstein.

mostly of halite, a usage we follow here. Salt bodies may thus contain varying amounts of other evaporites (especially anhydrite or its hydrated form, gypsum), as well as nonevaporite rocks. Most nonhalite inclusions in salt were originally interbedded with the halite. However, salt inclusions may also be igneous intrusions, foundered roof blocks, sediments trapped between converging salt bodies, or (rarely) material plucked from the substrate beneath the salt.

Evaporites are precipitated from saturated surface or near-surface brines by hydrologies driven by solar evaporation (Warren, 1999). Evaporite facies typically vary laterally, controlled partly by the crystallization sequence from increasingly concentrated hypersaline waters. Thus, a rim of evaporitic carbonates, which become increasingly Mg-rich with increasing salinity, typically surrounds an aureole of gypsum, which, in turn, surrounds halite, which begins to precipitate at seawater concentrations of 340–360%. Bittern salts (K or Mg sulfates or chlorides) finally precipitate from brines concentrated to 70–90 times the original saltwater (Warren, 1999). Evaporites are deposited in restricted basins, where outflow of water by evaporation exceeds inflow. Such basins tend to lie at roughly 30° latitude, where cold, dry, high-pressure air descends in Hadley circulation cells to create arid and semiarid regions.

Little systematic work has addressed the influence of salt composition on structural style. However, the sequence of increasing creep mobility tends to be as follows: anhydrite, gypsum, halite, bittern salts. Large percentages of mechanically competent materials within the evaporite interval, including siliciclastic and carbonate layers, tend to inhibit salt creep and diapirism.

Evaporites have been deposited in four main settings: (1) cratonic basins (Fig. 1), (2) synrift basins (Fig. 2), (3) postrift passive margins (Fig. 3), and (4) continental collision zones and foreland basins (Fig. 4). About 120 of these evaporite basins have been affected by salt tectonics (Fig. 5), defined as deformation involving flow

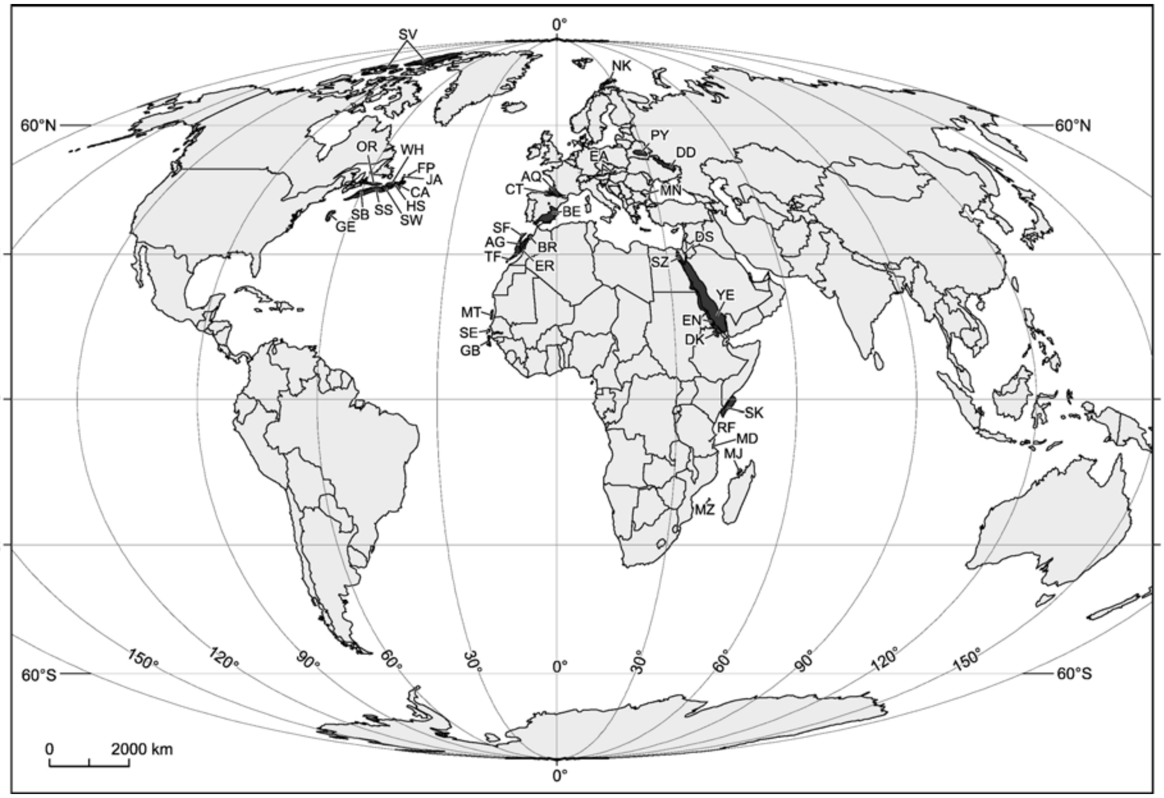


Fig. 2. Equal-area Mollweide projections showing global distribution of major synrift salt basins. These include both mature rifts and failed rifts. AG Agadir; AQ Aquitaine; BE Betic; BR Berrechid; CA Carson; CT Cantabrian–West Pyrenees; DD Dnepr–Donetz; DK Danakil; DS Dead Sea; EA East Alpine; EN Eritrean; ER Essaouira; FP Flemish Pass; GB Guinea-Bissau; GE Georges Bank; HS Horseshoe; JA Jeanne d'Arc; MD Mandawa; MJ Majunga; MN Moesian; MT Mauritania; MZ Mozambique; NK Nordkapp; OR Orpheus; PY Pripyat; RF Rufiji; SB Sable; SE Senegal; SF Safi; SK Somali–Kenya; SS Scotian Slope; SV Sverdrup; SW South Whale; SZ Suez; TF Tarfaya; WH Whale; YE Yemeni.

of salt. Salt tectonics can involve regional extension and shortening or can comprise deformation driven purely by gravity (halokinesis) in the absence of significant lateral tectonic forces.

Many cratonic basins have not undergone salt tectonism, probably because of limited differential loading of salt or absence of regional tectonism. These basins may be deformed by salt dissolution, but this type of structure does not concern us here.

1.2. What makes salt tectonics unique?

Deformational styles of salt basins and nonsalt basins have some similarities, but their differences can be quite profound. For example, salt-involved passive margins tend to have much more updip extension and downdip shortening than margins without salt; moreover, salt-involved parts of mountain belts are typically much wider than their nonsalt equivalents (Davis and Engelder, 1987; Letouzey et al., 1995). Also, sedimentary facies patterns in salt basins are commonly fundamentally different from those in basins that lack salt (e.g., Worrall and Snelson, 1989; Warren, 1999).

These differences are all rooted in the fact that evaporites have mechanical properties different from those of most clastic and carbonate rocks. Under unusually high strain rates, such as those associated with mining and magmatic dike intrusion, salt fractures like most other rocks. In contrast, under geologic conditions, most evaporites deform viscoelastically (Weijermars et al., 1993). Because of the relatively high speed of relaxation, however, the elastic component of geologic deformation can be ignored and strain treated as purely viscous. Thus, under typical geologic strain rates, salt flows like a fluid in the subsurface and at surface. Fluids have negligible yield strength, so salt bodies and layers are much more easily deformed than are other rocks. Salt's mechanical weakness is the Rosetta Stone of salt tectonics — the principle that makes all other observations comprehensible. Completely dry rock salt deforms largely by dislocation creep. In contrast, slightly damp (as little as 0.05 wt.%)

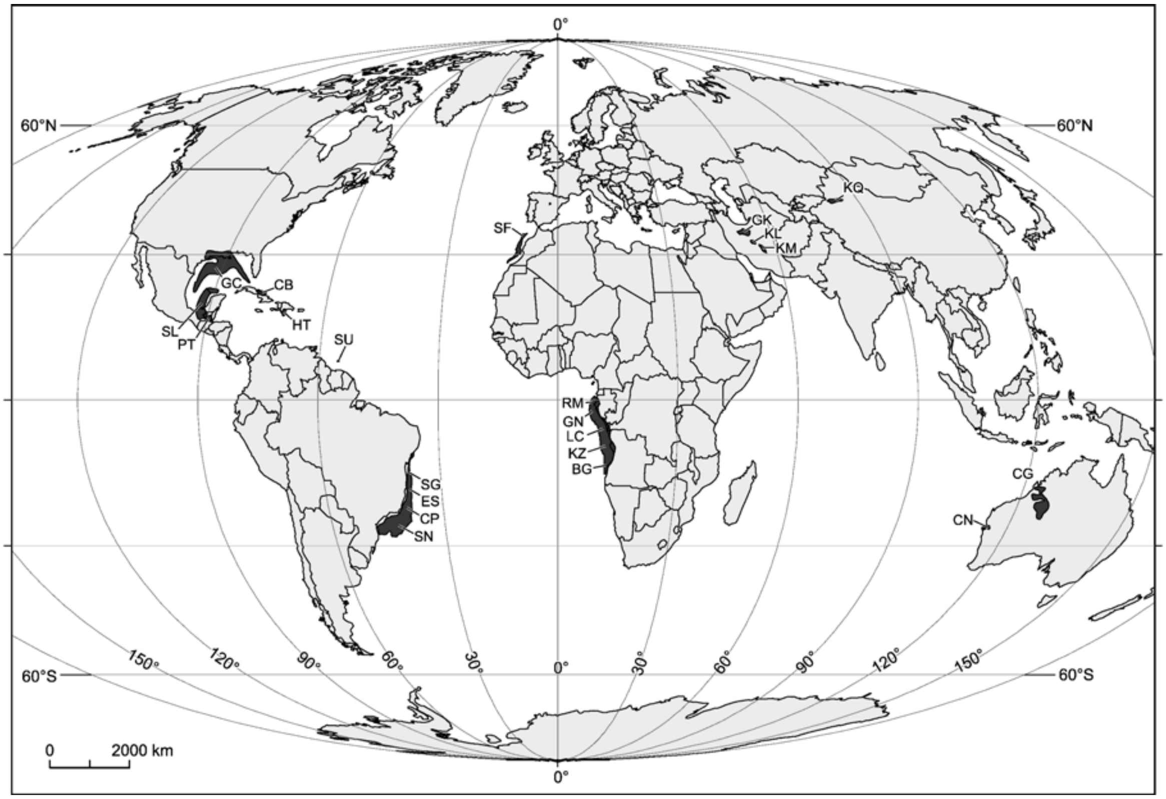


Fig. 3. Equal-area Mollweide projections showing global distribution of major passive-margin salt basins. BG Benguela–Namibe; CB Cuban; CG Canning; CN Carnavon; CP Campos; ES Espirito Santo; GC Gulf Coast; GK Great Kavir–Garmsar–Qom; GN Gabon; HT Haitian; KL Kalut; KM North Kerman; KQ Kuqa; KZ Kwanza; LC Lower Congo; PT Petenchiapas; RM Rio Muni; SF Safi; SG Sergipe–Alagoas; SL Salina–Sigsbee; SN Santos; SU Suriname.

rock salt is even weaker; it deforms largely by diffusion creep (also called "solution–precipitation creep"), especially when the rock is fine grained and when the strain rate and differential stresses are low.

A second unique aspect of salt is that as a crystalline rock it is relatively incompressible. Because slightly impure rock salt has an approximate density of 2200 kg/m^3, it is less dense than most carbonates and moderately to fully compacted siliciclastic rocks. Salt buried beneath denser overburden is therefore buoyant. Because of this density inversion, the system is gravitationally unstable and is liable to lose potential energy by overturning. Buoyant salt rise could begin beneath an uncompacted shelf-carbonate overburden, but it typically requires burial beneath at least 650 m (and more typically 1500 m) of siliciclastic overburden before the deepest sediments compact to densities equivalent to that of rock salt. Burial of at least 1600 m (and more typically 3000 m) is required before average density of the entire siliciclastic overburden exceeds that of salt, which is necessary for a diapir to reach the surface by buoyancy alone (e.g., Baldwin and Butler, 1985; Nelson and Fairchild, 1989).

The uniqueness of salt tectonics is thus firmly rooted in rock mechanics. Salt's rheology and incompressibility make it inherently unstable under a wide variety of conditions. As a result, basins having salt tend to deform much more easily than basins lacking salt, with significant effects on basin tectonics and stratigraphy.

1.3. Why study salt tectonics?

Salt tectonics receives little attention in most structural geology texts, possibly owing to the paucity of high-quality, accessible salt exposures. However, salt tectonics is of major interest to many practicing geologists, as indicated by the burgeoning of salt-tectonic articles in the professional literature. Of the approximately 5500 publications on salt tectonics, more than half were published after 1990 (GeoRef database).

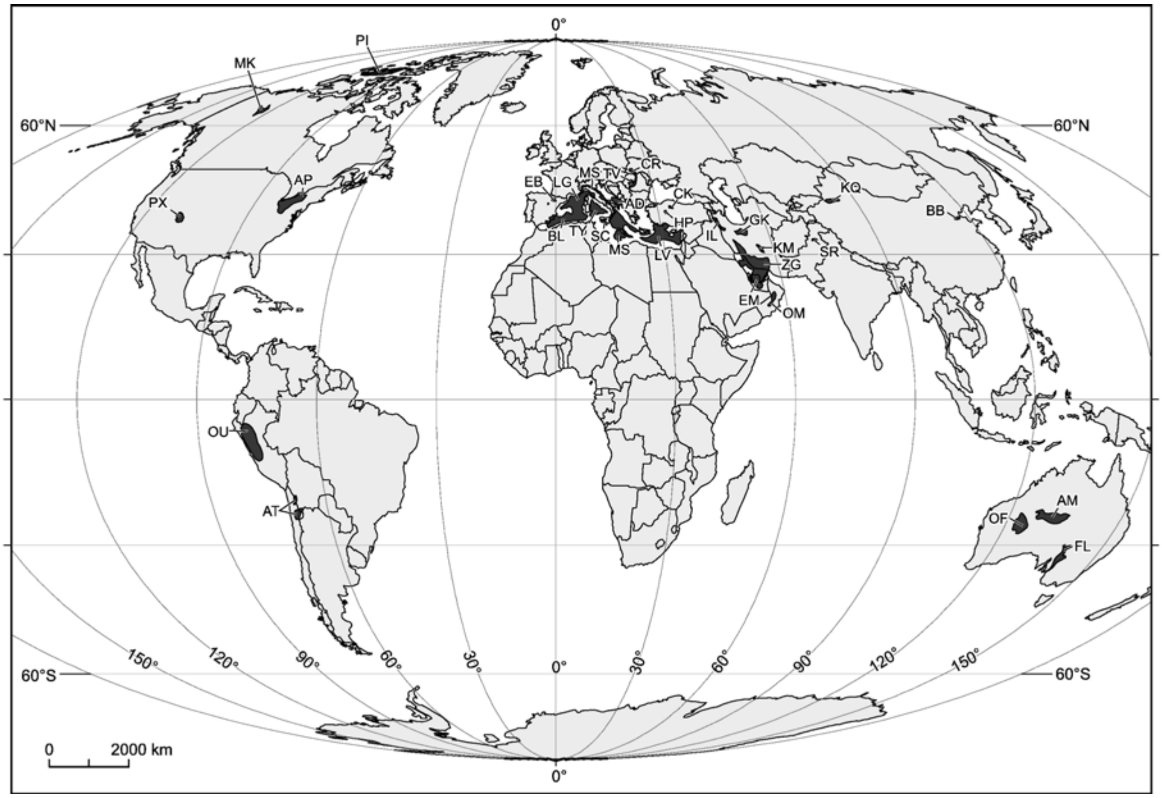
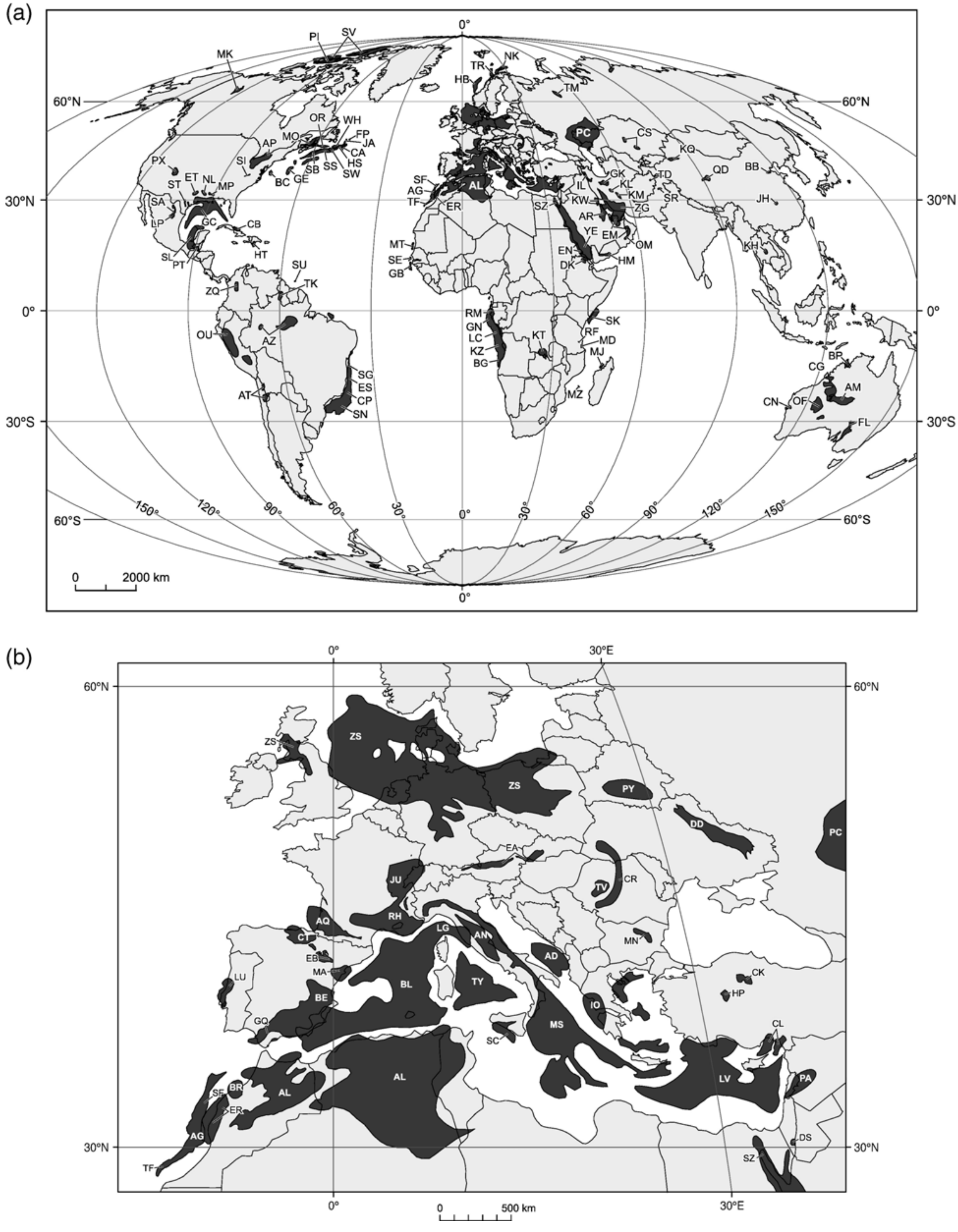


Fig. 4. Equal-area Mollweide projections showing global distribution of major collisional salt basins. These include active continental margins, foredeeps, and intermontane basins. AD South Adriatic; AM Amadeus; AP Appalachian Plateau; AT Atacama; BB Bohai Bay; BL Balearic; CK Cankiri; CR Carpathian; EB Ebro; EM Emirates; FL Flinders; GK Great Kavir–Garmsar–Qom; HP Haymana–Polatli; IL Iljac–Tabriz; KM North Kerman; KQ Kuqa; LG Ligurian; LV Levantine; MK Mackenzie; MS Messinian; OF Officer; OM Oman–Fahud; OU Oriente–Ucayali; PI Parry Islands–Central Ellesmere; PX Paradox; SC Sicilian; SR Salt Range; TV Transylvanian; TY Tyrrhenian; ZG Zagros.

The prime interest in salt tectonics comes from the oil industry because many of the world's great hydrocarbon provinces lie in salt basins (e.g., Gulf of Mexico, Persian Gulf, North Sea, Lower Congo Basin, Campos Basin, and Pricaspian Basin). Furthermore, the presence of salt in a basin affects virtually all aspects of a hydrocarbon system. Aside from the role of salt flow in creating structural traps and influencing reservoir distribution, salt is itself a seal to fluid migration. Salt is also an effective conductor of heat, elevating the thermal maturity of rocks above salt structures and cooling rocks that lie below or adjacent to salt bodies. An understanding of salt tectonics is therefore critical to effective exploration for oil and gas in many parts of the globe. Hot brines can also transport metals, so evaporites can focus, trap, or precipitate metal deposits. Finally, evaporites provide economic resources of potash salts, sodium salts, gypsum, sulfur, borates, nitrates, and zeolites (Warren, 1999).

Even beyond salt's importance to resources, however, advances in salt tectonics shed light on a wide range of scientific problems. For example, advances in the understanding of diapiric processes are influencing work in shale tectonics and in extraterrestrial geology (e.g., Schenk and Jackson, 1993; Pappalardo and Barr, 2004). Because salt's mechanical weakness makes it a sensitive strain gauge, the growth histories of salt structures have been used to develop detailed models of passive-margin evolution (e.g., Nilsen et al., 1995; Hudec and Jackson, 2004) and even orogeny (Talbot, 1998; Canérot et al., 2005). Finally, because subsurface salt flow can rapidly create accommodation space for sediments, it provides stratigraphers with high-resolution datasets to investigate the relationship between tectonism and sea-level change in controlling facies distributions (e.g., Beauboeuf and Friedman, 2000; Prather, 2000).

Salt's unique deformational style, widespread occurrence, and massive deformational overprint on some passive margins make salt tectonics an important component of the analysis of sedimentary basins. This paper aims to summarize the mechanics of salt flow, the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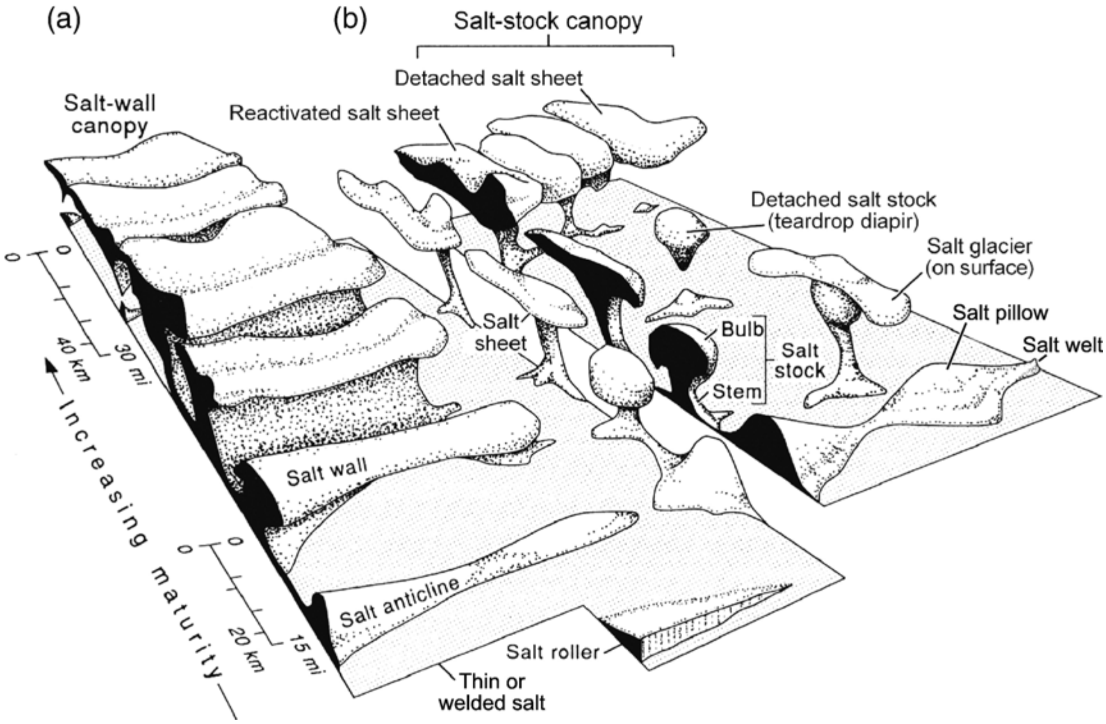

Fig. 6. Block diagram showing schematic shapes of salt structures. Structural maturity and size increase toward the composite, coalesced structures in the background. (a) Elongated structures rising from line sources. (b) Structures rising from point sources. Simplified from Jackson and Talbot (1991).

processes of diapir growth, and the ways that these processes interact with regional deformation to produce the staggering variety of salt structures known (Fig. 6).

2. Mechanics of salt flow

2.1. Overview

For most of the past 70 years, the prevailing view of salt tectonics was that its mechanics were dominated by salt buoyancy (see Jackson, 1995, 1997a,b for historical reviews). Sediments were envisioned as a dense fluid having negligible yield strength. Such a fluid would sink into a less-dense fluid salt layer, displacing the salt upward to form diapirs (defined as "masses of salt that have flowed ductilely and appear to have discordantly pierced or intruded the overburden" by Jackson and Talbot, 1991). In the late 1980s, the concept of a fluid overburden fell out of favor after workers began to recognize the importance of roof strength as a control on

Fig. 5. Equal-area Mollweide projections showing global distribution of basins containing salt structures (dark-gray areas). Basins containing only undeformed salt are omitted. (a) Global distribution of basins. (b) Detail of European basins. AD South Adriatic; AG Agadir; AL Atlas; AM Amadeus; AN Appenines; AP Appalachian Plateau; AQ Aquitaine; AR Arabian; AT Atacama; AZ Amazon; BB Bohai Bay; BC Baltimore Canyon; BE Betic; BG Benguela–Namibe; BL Balearic; BP Bonaparte; BR Berrechid; CA Carson; CB Cuban; CG Canning; CL Cicilia–Latakia; CK Cankiri; CN Carnavon; CP Campos; CR Carpathian; CS Chu–Sarysu; CT Cantabrian–West Pyrenees; DD Dnepr–Donetz; DK Danakil; DS Dead Sea; EA East Alpine; EB Ebro; EM Emirates; EN Eritrean; ER Essaouira; ES Espirito Santo; ET East Texas; FL Flinders; FP Flemish Pass; GB Guinea-Bissau; GC Gulf Coast; GE Georges Bank; GK Great Kavir–Garmsar–Qom; GN Gabon; GQ Guadalquivir; HB Haltenbanken; HM Hadhramaut–South Yemen; HP Haymana–Polatli; HS Horseshoe; HT Haitian; IL Iljac–Tabriz; IO Ionian; JA Jeanne d'Arc; JH Jianghan; JU Jura; KH Khorat; KL Kalut; KM North Kerman; KQ Kuqa; KT Katanga; KW Kuwait; KZ Kwanza; LC Lower Congo; LG Ligurian; LP La Popa; LU Lusitanian; LV Levantine; MA Maestrat; MD Mandawa; MJ Majunga; MK Mackenzie; MN Moesian; MO Moncton; MP Mississippi; MS Messinian; MT Mauritania; MZ Mozambique; NK Nordkapp; NL North Louisiana; OF Officer; OM Oman–Fahud; OR Orpheus; OU Oriente–Ucayali; PA Palmyra; PC Pricaspian; PI Parry Islands–Central Ellesmere; PT Petenchiapas; PX Paradox; PY Pripyat; QD Qaidam; RF Rufiji; RH Rhodanian; RM Rio Muni; SA Sabinas; SB Sable; SC Sicilian; SE Senegal; SF Safi; SG Sergipe–Alagoas; SI Saltville; SK Somali–Kenya; SL Salina–Sigsbee; SN Santos; SR Salt Range; SS Scotian Slope; ST South Texas; SU Suriname; SV Sverdrup; SW South Whale; SZ Suez; TD Tadjik; TF Tarfaya; TK Takutu; TM Timan; TR Tromsø; TV Transylvanian; TY Tyrrhenian; WH Whale; YE Yemeni; ZG Zagros; ZQ Zipaquira; ZS Zechstein.

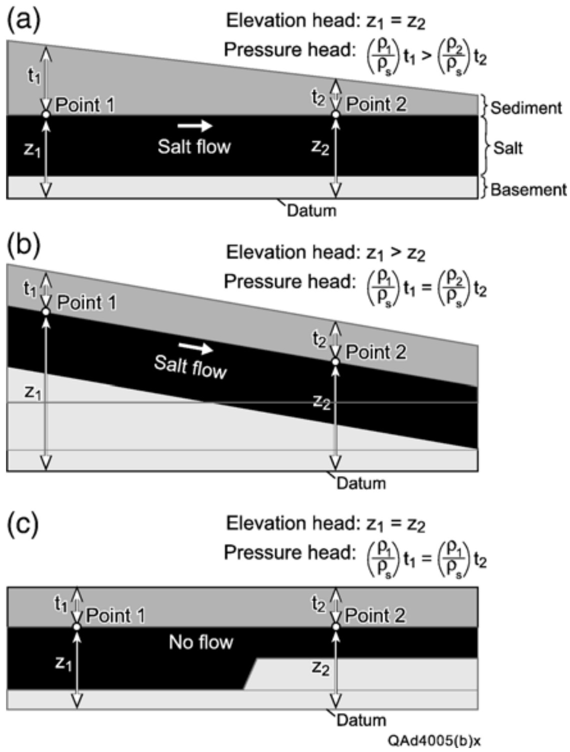

Fig. 7. Examples of hydraulic head-gradient analysis in salt tectonics. (a) A laterally varying overburden thickness above a horizontal, tabular salt layer produces a pressure head gradient from Point 1 to Point 2 but no elevation head gradient. Salt will flow from left to right along the pressure head gradient. The load variation may be produced by sedimentation (e.g., a river delta) or deformation (a stack of thrust slices at the left end of the section) or by erosion. (b) A uniform overburden thickness above an inclined, tabular salt layer produces an elevation head gradient from Point 1 to Point 2 but no pressure head gradient. Salt will flow from left to right down the elevation head gradient. (c) A uniform overburden thickness above a flat-lying salt layer produces neither elevation nor head gradients, even though the salt thickness varies. Salt remains at rest because there is no hydraulic head gradient. Note that the shape of the base of the salt layer is not important for producing a head gradient (although it may influence the geometry of flow once it begins).

diapir growth. Diapirs were no longer pictured as blobs rising through a yielding overburden, as in a giant lava lamp. Instead, the position and shape of the viscous salt bodies were seen to depend on how the brittle, mechanically competent overburden deformed.

Modern interpretations of salt tectonics stress differential loading as the dominant force driving salt flow. Opposing the flow of salt are two principal resisting forces: strength of the overburden and boundary friction within the salt layer. If driving forces are sufficient to overcome resisting forces, then salt flows. Otherwise, salt can remain static in the subsurface for tens or even hundreds of millions of years, subject only to groundwater dissolution, diagenesis, and metamorphism. Buoyancy can still be important in some circumstances (see Section 3.2), but it is no longer considered an important factor in *initiating* diapirism.

2.2. Driving force-differential loading

Three types of loading can drive salt flow: gravitational loading, displacement loading, and thermal loading. Which is most important in a given situation depends on the depth of salt burial, geometry of the salt body, geologic setting, and thermal conditions of the salt. The flow of salt from areas of high load is termed “salt withdrawal” or, more accurately, “salt expulsion” because the former term erroneously implies that a diapir sucks salt from its surroundings. Instead, salt is forced from its source layer into the diapir by loading. Mechanical interpretation of salt tectonics typically reduces to documenting the direction of salt flow, then deducing the source of the differential loading driving that flow.

Gravitational loading is produced by a combination of the weight of rocks overlying the salt and the gravitational body forces within the salt. Because salt behaves as a fluid over geologic time scales, it is convenient to simplify the effects of gravitational loading by using the concept of hydraulic head in fluid statics (Kehle, 1988). All fluids flow in response to head gradients, from areas of high head to low head. Conversely, if the hydraulic head is everywhere constant, the fluid remains at rest.

Total hydraulic head has two components: elevation head and pressure head. Elevation head is the elevation of a particle of fluid above some arbitrary horizontal datum. Pressure head is the height of a fluid column that could be supported by the pressure exerted by the overlying rock. Mathematically,

$$h = z + \frac{P}{\rho_s g}$$

where h is the total head, z is the elevation head (elevation above a horizontal datum), P is the lithostatic pressure exerted by the overburden, ρ_s is the density of salt, and g is the acceleration of gravity. Substituting $\rho_o g t$ for the lithostatic pressure, this equation simplifies to

$$h = z + \frac{\rho_o}{\rho_s} t$$

where ρ_o is the average overburden density and t is the thickness of the overburden. Salt-flow directions in

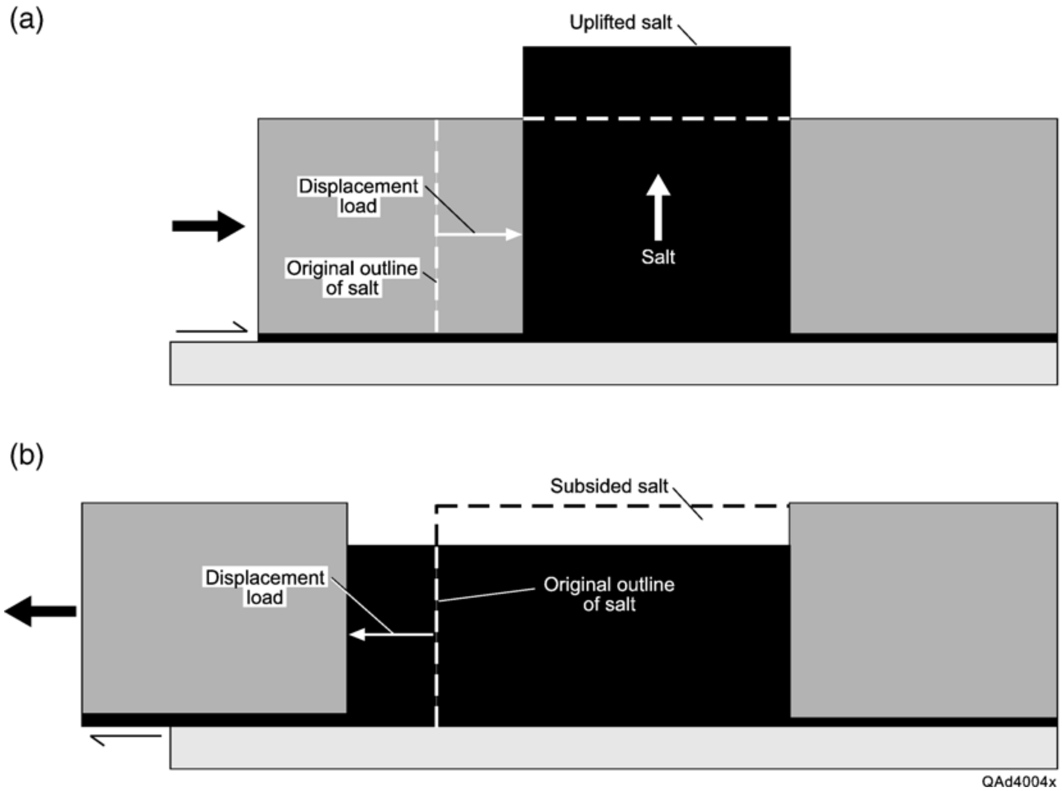

Fig. 8. Schematic diagrams showing the effects of displacement loading on preexisting salt structures. (a) During shortening, salt is loaded horizontally by inward movement of one or both sidewalls. The horizontal displacement load then exceeds the vertical gravitational load, forcing salt to rise. In a natural example, the salt would flow out over the sediment surface rather than form a vertical column. (b) In extension, the salt is unloaded horizontally by outward movement of one or both sidewalls. The vertical gravitational load then exceeds the horizontal displacement load, so salt subsides.

response to gravitational loading can easily be predicted for most simple geologic situations by estimating the head gradient (Fig. 7).

Because head and pressure are different concepts, it is incorrect to say that fluids flow in response to pressure gradients. For example, pressure increases downward in a pond of water, but the water does not flow because there is no head gradient. Likewise, uniformly loaded salt with a horizontal upper surface does not flow, even though a vertical pressure gradient exists within it (Fig. 7c).

Displacement loading results from the forced displacement of one boundary of a rock body relative to another (e.g., Suppe, 1985). In salt tectonics, this type of loading occurs when the flanks of a salt body move toward or away from one another during regional shortening or extension (Fig. 8). This type of displacement is common where basins having preexisting salt structures are deformed because the weak salt structures typically focus regional strain (as expounded in Sections 3.3, 4.2, and 4.3).

Thermal loading results from volume changes caused by changes in temperature. Hot salt expands and becomes buoyant, producing intrasalt convection. Thermal convection within salt layers has been proposed for the Danakil Depression, Eritrea, and the Boulby potash mine, England (Talbot, 1978; Talbot et al., 1982). Thermal convection is enhanced by (1) increase of temperature gradient or thermal expansivity or layer thickness or (2) decrease in thermal diffusivity and kinematic viscosity. The effects of thermal convection on diapirs encased in sediment have never been proven, but it seems reasonable that thermal effects could help evacuate hot salt from the deeply buried source layer into the cooler, shallower diapir. Indeed, it is difficult to account for the coiled margins (vortex structures) of some diapirs in the Great Kavir of Iran without invoking thermal convection (Jackson et al., 1990).

2.3. Factors resisting salt flow

There are so many ways of generating differential loads in nature that it is safe to assume that virtually all salt bodies are subject to some type of driving force for

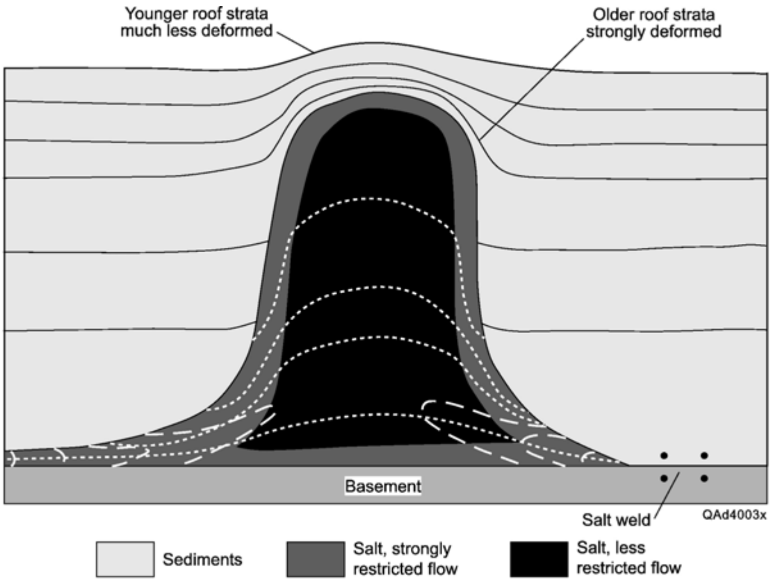

Fig. 9. Sketch illustrating factors resisting salt flow. First, diapir rise requires deformation of the overlying roof. This deformation is easily accomplished if the roof is thin and weak but becomes progressively more difficult as roof thickness increases. Second, salt is strongly sheared near the edges of salt bodies during flow, which resists deformation. If a salt layer becomes too thin, flow is inhibited.

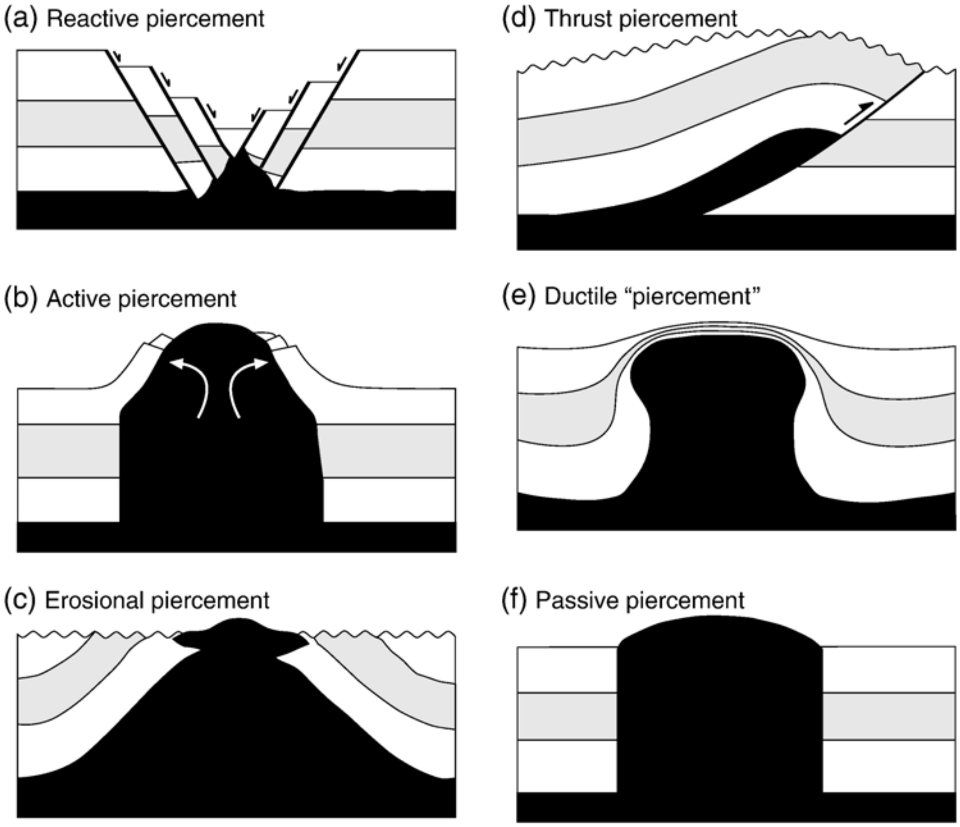

Fig. 10. Modes of diapir piercement, shown in schematic cross sections. The overburden is brittle except in (e).

flow. However, not all salt bodies deform. Two factors limit the ability of salt to move (Fig. 9).

The first factor is the strength of the overlying sediment. Down to the brittle–ductile transition, at least 8 km deep in the crust, sedimentary rocks typically increase in both shear strength and frictional strength as depth of burial and confining pressure rise. Thick sedimentary roofs are therefore generally more difficult to deform than thin roofs. Roofs more than several hundred meters thick are unlikely to be deformed by salt of modest structural relief without assistance from either regional extension or shortening.

The ability of salt to flow within a buried layer is also limited by boundary drag along the top and bottom surfaces of the salt layer. The periphery of most salt bodies is marked by a zone of restricted flow, as the salt

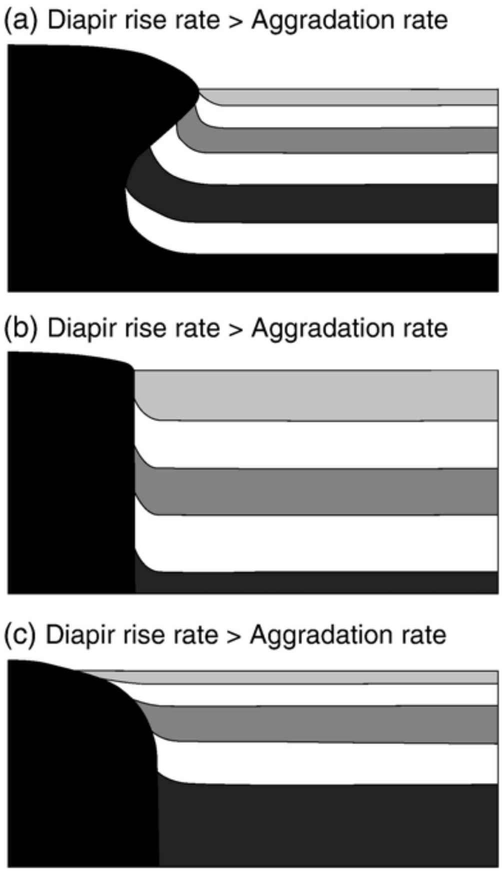

Fig. 11. The cross-sectional shapes of passive diapirs are tied to the relative rates of net diapir rise (salt rise minus erosion and dissolution) and sediment aggradation. (a) Where diapir rise rate exceeds aggradation rate, diapirs widen upward and may ultimately form extrusive sheets. (b) Where diapir rise rate is equal to aggradation rate, diapirs have vertical walls. (c) Where diapir rise rate is less than aggradation rate, diapirs narrow upward and may ultimately become completely buried. Modified from Giles and Lawton (2002).

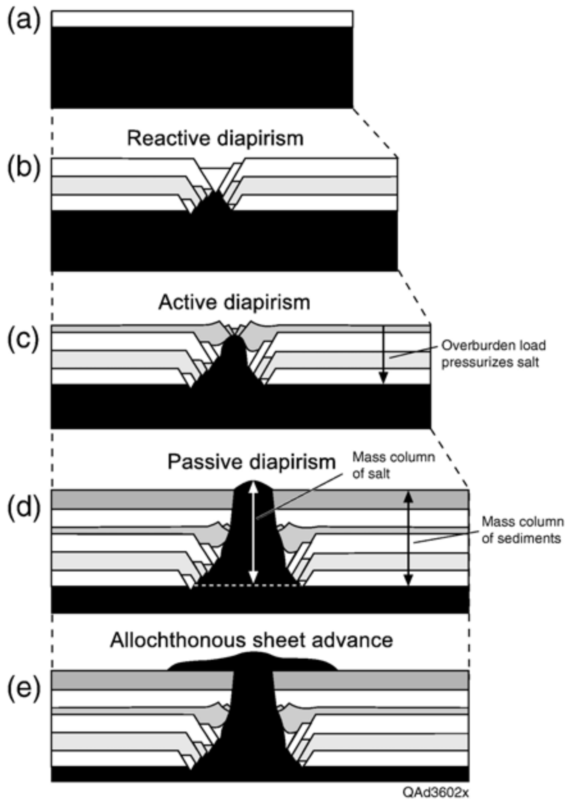

Fig. 12. Diapir piercement during regional extension. Diapirs do not necessarily progress through all of these stages. The maturity of a given structure depends on availability of salt, total amount of extension, and relative rates of extension and sedimentation. Modified from Vendeville and Jackson (1992a).

is sheared past the nonflowing country rocks. For a salt layer of given thickness, this boundary shear zone will be wider if the salt flow is Newtonian viscous (constant dynamic viscosity) and narrower and more intense if the flow is power-law viscous (where the apparent dynamic viscosity decreases as rate of shear increases toward the boundary of the fluid). The flow law depends on a variety of factors, the most important of which are grain size and differential stress (e.g., Van Keken, 1993; Spiers and Carter, 1998; Schléder and Urai, in press). In either case, the resistance supplied by viscous shear forces is less important for thick salt layers, where only a small percentage of salt thickness is affected by intense shear along the boundary layers. However, for thin salt layers, the viscous resistance can effectively immobilize the salt. Assuming Newtonian behavior, the volumetric flux of laminar flow within a buried salt layer is proportional to the third power of the layer thickness (Nelson, 2001, his Eq. (1–4). This means, for instance, that halving the layer thickness slows flow by a factor of 8. For power-law flow, this factor is smaller – although certainly present – because of the shear thinning

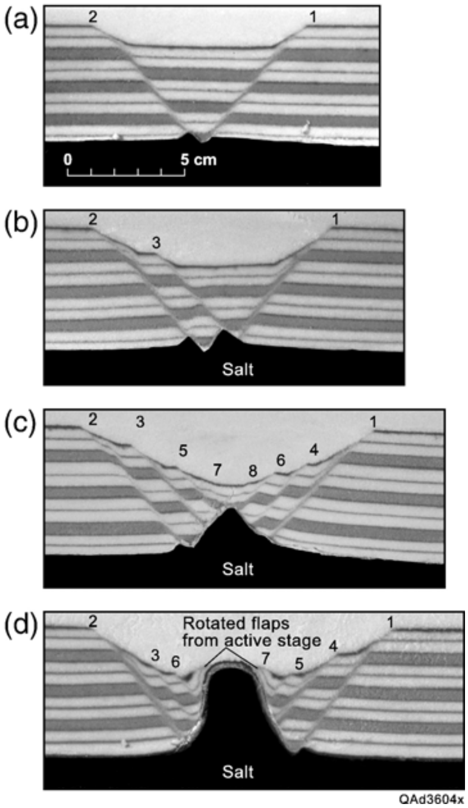

Fig. 13. Photographs of cross sections from physical models showing stages of reactive piercement in extension, in the absence of synkinematic sedimentation. Numbers above fault tips refer to the order in which the faults formed. (a) Onset of extension. A small reactive diapir forms in the footwall of a normal fault. (b) Faulting steps inward to dissect the graben floor. Locus of reactive diapirism shifts inward to lie beneath the thinnest part of the graben. (c) Advanced stage of reactive diapirism. (d) After the roof thins to the point where pressure within the salt is sufficient for the diapir to actively force its way through to the surface, the diapir emerges and becomes passive. The former roof is preserved in steeply dipping flaps against the flank of the dome. Modified from Vendeville and Jackson (1992a).

previously mentioned. Thus, once salt expulsion reduces the thickness of a layer below a threshold thickness of, say, a few tens of meters, the salt may move very little, even if a large differential load is applied. In the extreme case, a dome cannot grow because the supply of nearby salt has become exhausted by a combination of creep flow and dissolution; this exhaustion causes the top and bottom contacts of the salt to merge, forming a salt weld.

3. Processes of diapir growth

3.1. Overview

In order for buried salt to be emplaced into its overburden as a diapir, the rock previously occupying that space must be removed or displaced. This can occur in one of four ways for brittle overburdens (Fig. 10a–d). First, the overburden may be extended, making room for a reactive diapir to rise between separated fault blocks. Second, flaps of overburden may be lifted, rotated, and shouldered aside as the diapir forcibly breaks through them by active diapirism. Third, the roof may be removed by erosion. Finally, salt may be emplaced into its overburden in the hanging wall of a thrust fault. All four processes may occur at various times during the growth of a single salt structure.

Diapirs having fluid overburdens may rise by a fifth mechanism, ductile thinning of the diapir roof (e.g., Nettleton, 1934; Talbot et al., 1991; Fig. 10e). For example, salt plugs in the Great Kavir, Iran, display a ductilely thinned roof composed of fine-grained clastic rocks mixed with halite and gypsum (Jackson et al., 1990). However, roofs of this type are rare in nature, so most diapirs can be assumed to pierce brittle overburdens. Salt bodies of this class are not, strictly speaking, diapirs, because they do not have discordant contacts with surrounding sediments. However, we discuss them here because they have risen with respect to flanking strata, and because the shape of the salt body resembles true diapirs.

If a diapir completely pierces its overburden and is exposed at the sediment surface, a sixth style of piercement becomes possible (Fig. 10f). In this mode, known as passive diapirism or downbuilding, the diapir rises continually with respect to surrounding strata and remains exposed while sediments accumulate around it. Sedimentary strata may lap onto the flank of the exposed diapir, but little or no permanent roof is deposited across the top of salt. Ephemeral roofs may be deposited and later removed, producing a characteristic series of upturned beds and unconformities along the flank of the diapir, known as halokinetic sequences (e.g., Giles and Lawton, 2002; Rowan et al., 2003).

In passive diapirism, salt may rise through thousands of meters of section without ever having to forcibly break through anything more than ephemeral sedimentary veneers. The cross-sectional shape of passive diapirs is controlled by the relative rates of diapir rise and sediment aggradation (e.g., Jackson et al., 1994; Fig. 11; Talbot, 1995). Diapirs that rise faster than the sediment aggrades next to them spread out over the sediment surface, and so widen upward. Conversely, diapirs that rise more slowly than sediment aggrades narrow upward until they are buried.

Most of the world's tall salt domes and walls spent most of their histories as passive diapirs. Passive diapirism may occur in any tectonic setting. However, for passive diapirism to begin, either part of the salt layer must remain

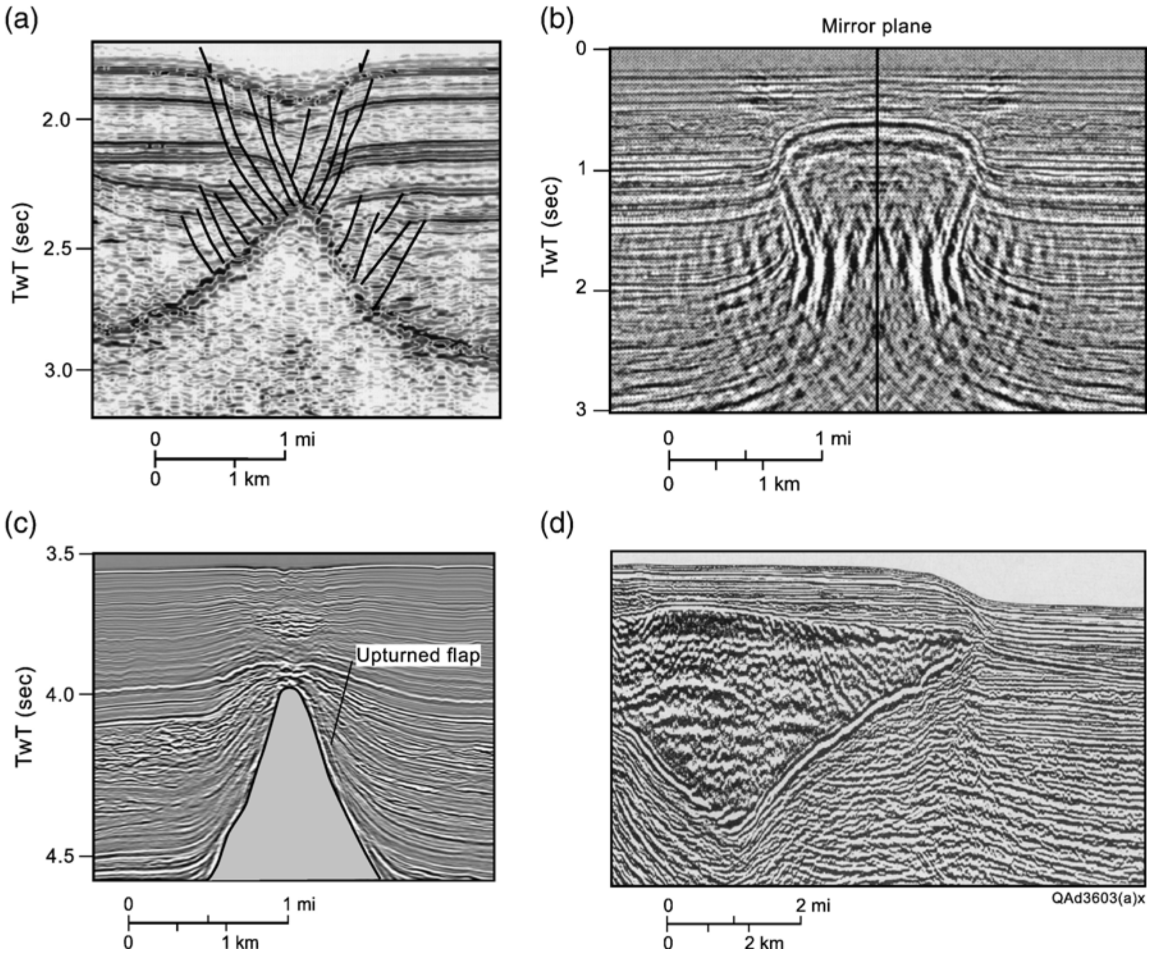

Fig. 14. Seismic examples of salt diapirs. (a) Reactive diapir in the Gulf of Mexico. Modified from Rowan et al. (1999). Reprinted by permission of AAPG, whose permission is required for further use, AAPG©1999. (b) Formerly passive diapir from the Gulf of Mexico, now buried. Passive emplacement is inferred from the relatively undeformed reflectors abutting the diapir. The original image showed only half of the structure and has been mirrored for consistency with other images in this figure. Modified from Hale et al. (1992). Reprinted by permission of the SEG. (c) Formerly active diapir, Lower Congo Basin, Gabon. The active rise is recorded by the arched roof. Onlap of the crestal anticline indicates that uplift has ceased for now. Seismic section courtesy of Total Astrid Marin Gabon and partners. (d) Allochthonous salt sheet, Gulf of Mexico. The feeder has either been pinched off or is not on this line of section. Modified from Hodgkins and O'Brien (1994). Reprinted by permission of the SEG.

exposed during initial burial of surrounding areas, or the salt must break through its overburden to reach the surface.

Besides passive diapirism, three types of diapir growth are particularly common, so are described in more detail next. These are (a) extensional piercement, (b) diapir amplification during shortening, and (c) salt-sheet emplacement.

3.2. Diapir piercement during regional extension

Extension thins and fractures the overburden, simultaneously establishing a lateral load gradient and weakening the overburden (Fig. 12b). Salt begins to rise up the axis of the dismembering graben, filling the space created by thinning of sediment and separation of fault blocks. This phase is termed "reactive diapirism" because in physical models (Fig. 13), diapir rise stops whenever the regional extension stops, so salt is reacting to, and controlled by, the extension (Vendeville and Jackson, 1992a). Seismic (Fig. 14a) and model examples of fault patterns above reactive diapirs shown here are all symmetric. Less symmetric forms with a single dominant fault, called "salt rollers," are also common.

Reactive diapirism thins and weakens the salt's roof. Eventually, the roof may weaken to the point where it can be uplifted and shouldered aside by forcible rise of the underlying diapir (active diapirism; Fig. 12c). In extensional settings this forcible rise is driven by salt buoyancy, so active diapirism will occur only if the salt

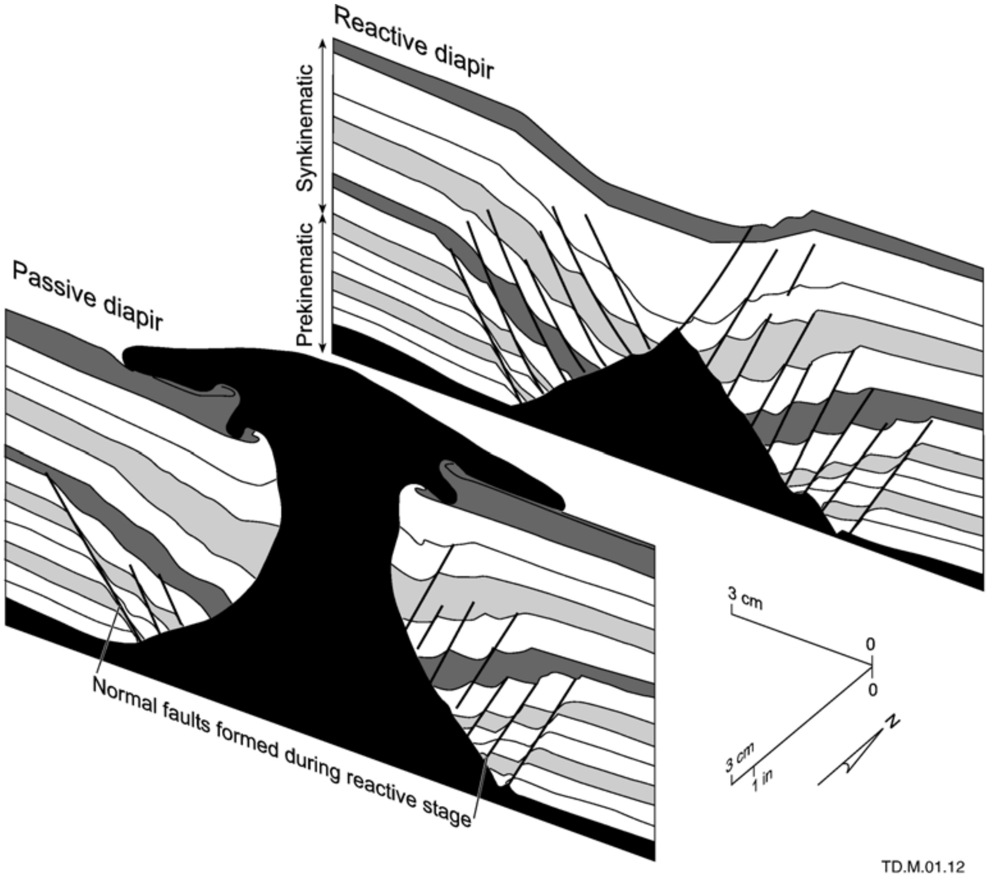

Fig. 15. Serial sections of a diapiric wall formed in an extensional physical model. The northern section intersects a symmetric reactive diapir. In the southern section, this diapir evolved further to form a passive diapir. The inward-dipping array of normal faults above the diapir's pedestal reveals this structure's extensional origin. Modified from Vendeville and Jackson (1992a).

is less dense than its overburden. Because active diapirism is controlled by gravitational forces acting on the salt, it continues even if regional extension stops (Vendeville and Jackson, 1992a). Active diapirs typically break through their remaining roofs quickly and rise to the sediment surface, becoming passive diapirs (Fig. 12d).

Most diapir provinces worldwide initiated during phases of basement-involved or detached extension (Jackson and Vendeville, 1994). This fact suggests that regional extension is the primary trigger for salt diapirism. Swarms of normal faults adjoin the deep flanks of many diapirs, reflecting their early extensional histories (e.g., Fig. 15).

3.3. Diapir amplification during regional shortening

During lateral shortening, the salt's overburden may buckle. Flow of underlying salt into the lower-pressure core of a rising anticline creates a salt-cored anticline. Anticlines can form above previously undeformed salt (e.g., Coward and Stewart, 1995), but they are especially common above preexisting salt structures (e.g., Nilsen et al., 1995; Vendeville and Nilsen, 1995). Because salt structures are weaker than other parts of a basin, during regional compression their roofs tend to shorten much more than adjacent areas of thicker overburden. Shortening thus amplifies preexisting structures by arching their roofs.

During diapir amplification, salt may pierce its roof by some combination of crestal normal faulting, crestal erosion, and active diapirism (Fig. 16). Buoyancy may have a role in this type of active diapirism, but much of the driving force comes from tectonic pressurization of the salt. Thus salt may reach the surface and grow as a passive diapir in compressional settings even if it is not buoyant. The ability to form passive diapirs without buoyant salt in shortening contrasts with extensional and halokinetic settings, in which passive diapirism requires density inversion.

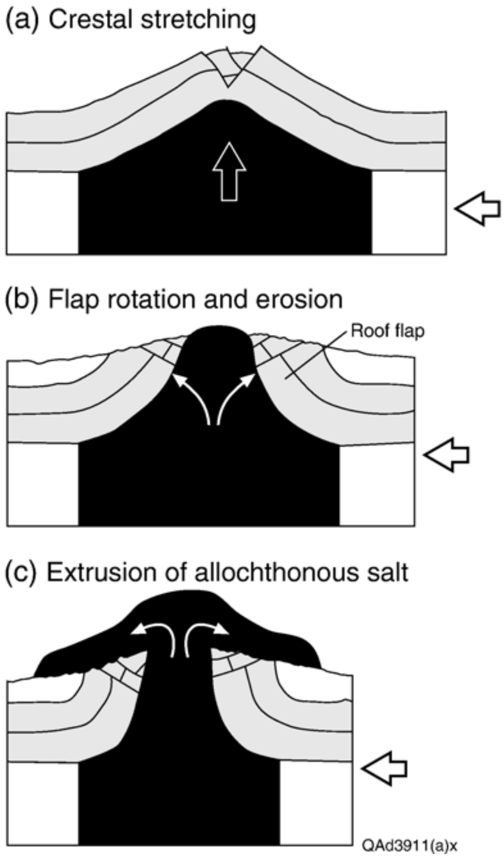

Fig. 16. Diapir piercement during shortening. This example assumes a preexisting diapir, which is the most common scenario for piercement during shortening. Diapirs may not progress through all of these stages; whether they do depends largely on the magnitude of shortening and the roof thickness above the diapir. (a) Arching of the diapir roof produces outer-arc extension, thinning and weakening the roof. (b) The combination of a weakened roof and salt pressurized by lateral squeezing (displacement loading) initiates active diapirism. Salt breaks through the thinned crest of the anticline, and the roof flaps on either side rotate away from the emerged diapir. (c) Rapid extrusion; salt displaced from the squeezed feeder flows out over the surface to form a salt glacier.

Where preexisting salt structures are shortened, a common structure is the teardrop diapir, whose upper part becomes largely detached from its source layer (Fig. 17). The original ascension zone of the salt is marked only by a steep salt weld in the former waist of an originally hourglass-shaped diapir. During shortening, this waist is pinched off. Most of the salt in the waist is expelled upward to promote rise of the upper part of the diapir and arching of its roof. The lower part of the diapir remains to form an autochthonous salt pedestal.

Continued shortening of a teardrop diapir may reactivate the weld as a thrust fault (Fig. 18). Thrusting of this type may allow the teardrop to continue rising, now in the hanging wall of the thrust. This type of rise is favored by more gently inclined feeder welds and is impossible if the weld is vertical.

3.4. Emplacement of allochthonous salt sheets

Where mobilized salt overlies stratigraphically younger rocks, the salt is termed "allochthonous." A salt sheet comprises allochthonous salt sourced from a

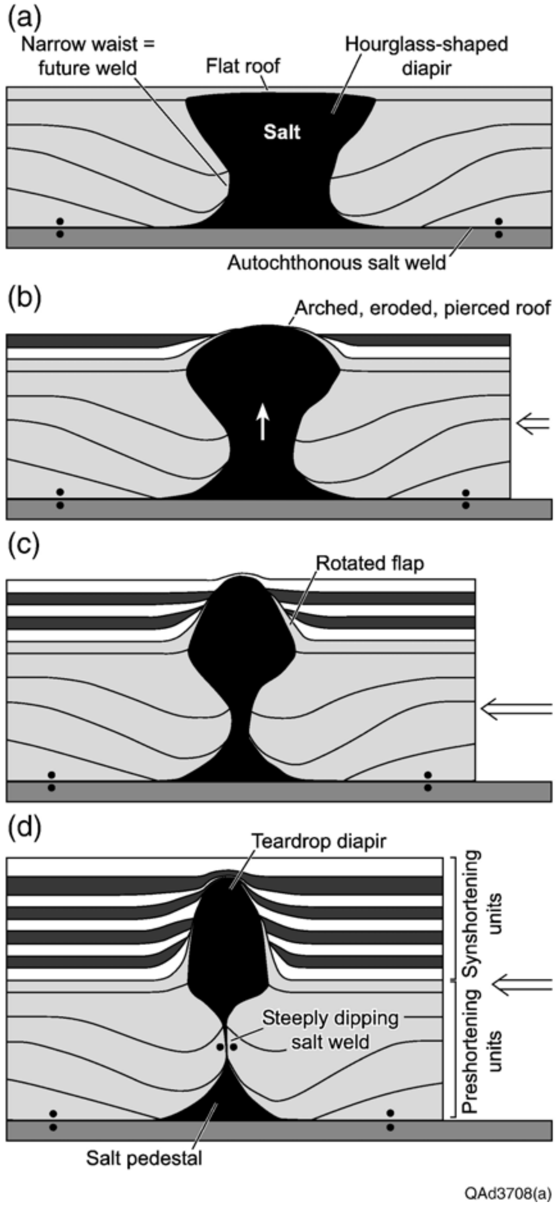

Fig. 17. Structurally balanced forward model showing formation of a teardrop diapir. The roof over the crest of the diapir is arched and eroded, allowing salt to pierce to the surface. Shortening continues until the hourglass-shaped feeder completely pinches off.

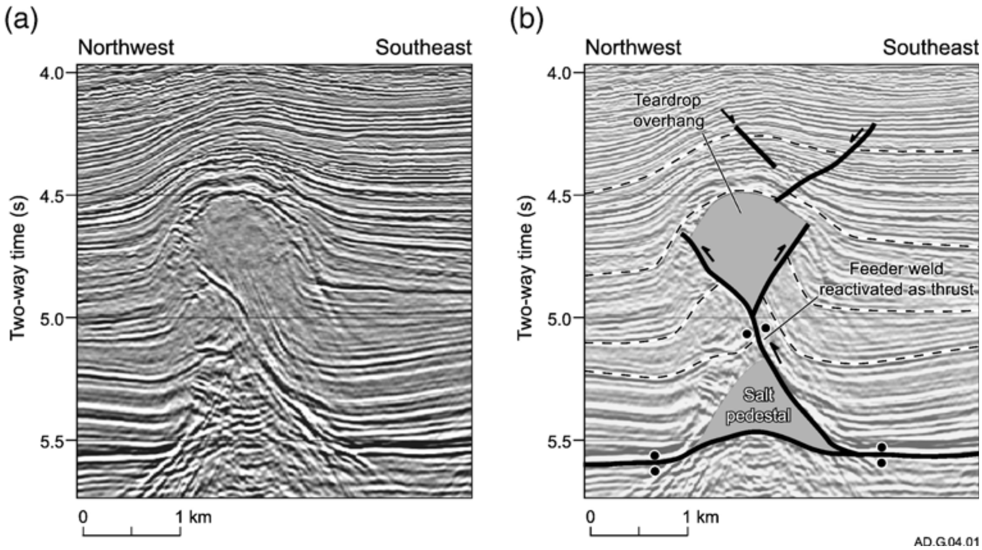

Fig. 18. (a) Uninterpreted and (b) interpreted versions of a 3-D seismic section across a teardrop diapir in the northern Lower Congo Basin, offshore Gabon. The welded feeder has been reactivated as a thrust. Sediments adjacent to the salt have velocities comparable to salt, so the image is minimally affected by velocity pullup. Image courtesy of Total Astrid Marin Gabon.

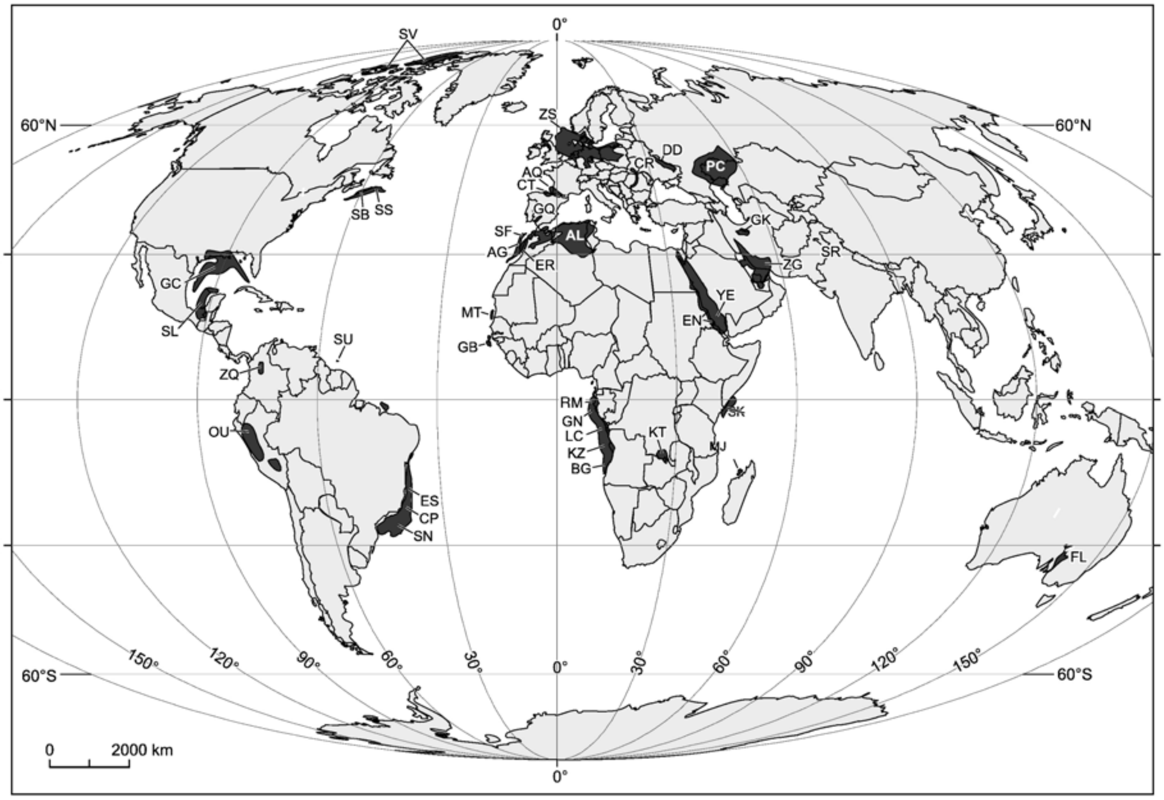

Fig. 19. Salt basins containing allochthonous evaporites. Basin abbreviations: AG Agadir; AL Atlas; AQ Aquitaine; BG Benguela–Namibe; CP Campos; CR Carpathian; CT Cantabrian–West Pyrenees; DD Dnepr–Donetz; EN Eritrean; ER Essaouira; ES Espirito Santo; FL Flinders; GB Guinea-Bissau; GC Gulf Coast–Gulf of Mexico; GK Great Kavir–Garmsar–Qom; GN Gabon; GQ Guadalquivir; KT Katanga; KZ Kwanza; LC Lower Congo; MJ Majunga; MT Mauritania; OU Oriente–Ucayali; PC Pricaspian; RM Rio Muni; SB Sable; SF Safi; SK Somali–Kenya; SL Salina–Sigsbee; SN Santos; SR Salt Range; SS Scotian Slope; SU Suriname; SV Sverdrup; YE Yemeni; ZG Zagros; ZQ Zipaquira; ZS Zechstein. The abundance and documentation of allochthonous evaporites vary greatly among different basins. Modified from Hudec and Jackson (2006).

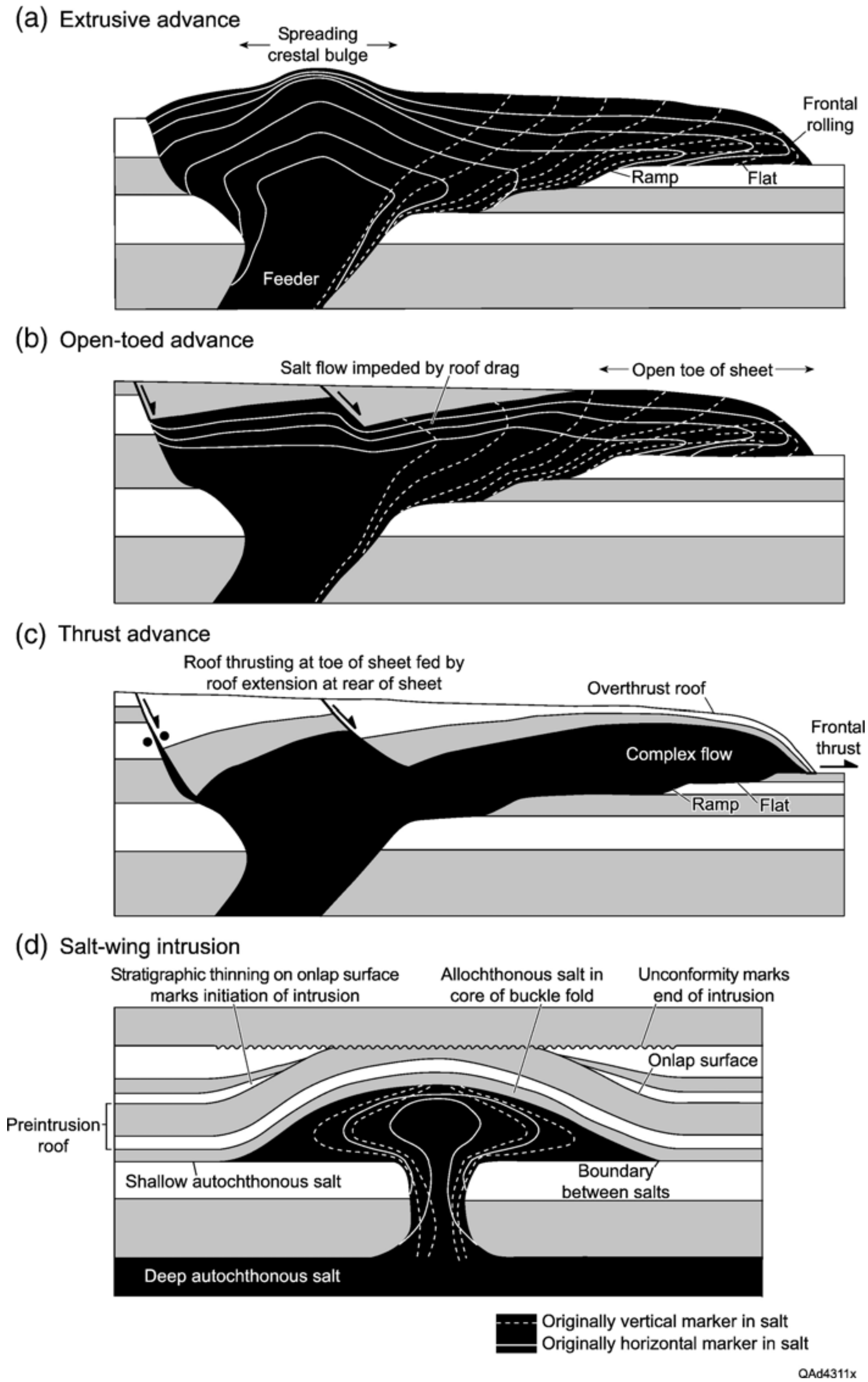

Fig. 20. Four schematic models for salt-sheet advance. White lines within the salt represent selected deformed markers from an originally rectangular grid. The original grid was drawn at an arbitrary earlier time in sheet evolution, so the deformed grid represents incremental, not finite, strain. Modified from Hudec and Jackson (2006).

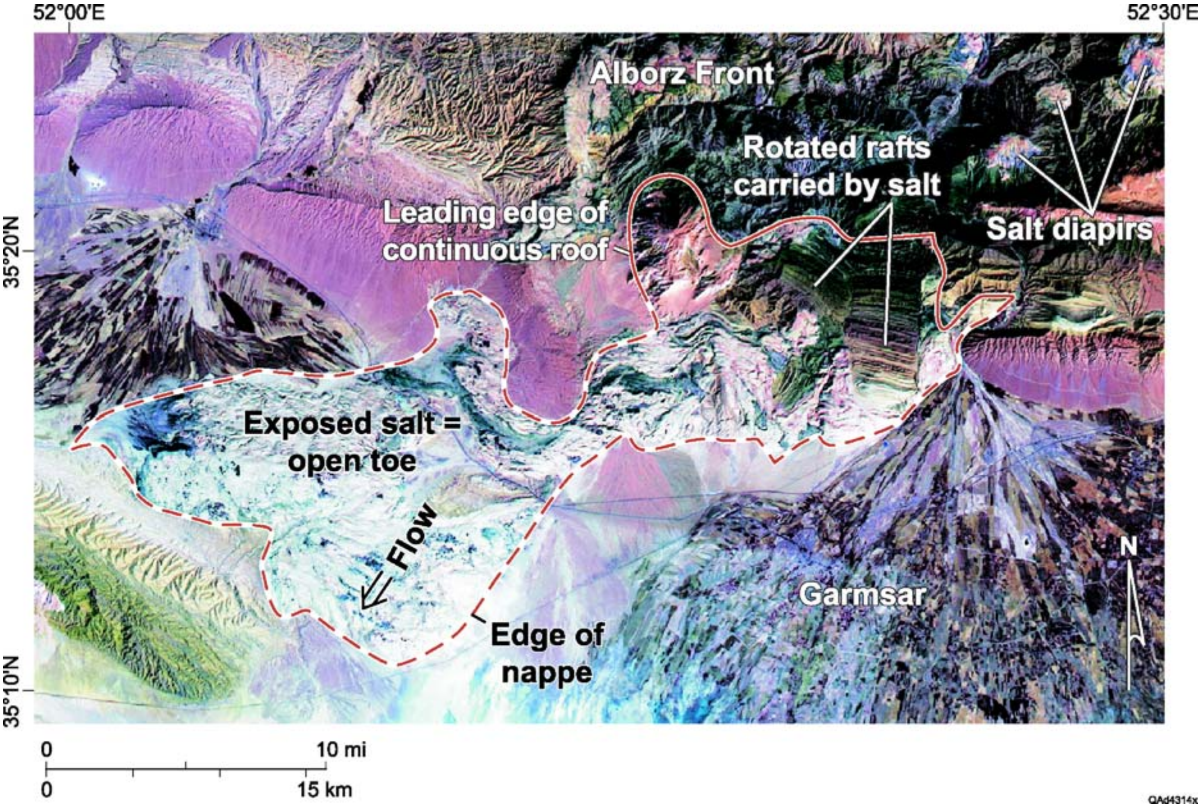

Fig. 21. Satellite image of the Garmsar salt nappe, an open-toed extrusive sheet in northern Iran. Eocene salt has been carried up to the surface in frontal thrusts of the Alborz Mountains. Erosion at the leading edge of this thrust complex has exposed the salt, allowing it to extrude as an open-toed sheet. This sheet is carrying and rotating rafts detached from the leading edge of the roof.

single feeder whose breadth is several times greater than its maximum thickness (Hudec and Jackson, 2006). Salt sheets have been identified in more than 35 basins worldwide (Fig. 19). Salt sheets advance in four ways: (1) extrusive advance, (2) open-toed advance, (3) thrust advance, and (4) salt-wing intrusion (Hudec and Jackson, 2006; Fig. 20). These mechanisms are distinguished by the geometry and thickness of the roof above the advancing sheet.

Extrusive advance (Fig. 20a) occurs when salt emanates and spreads from a passive feeder faster than sedimentation, erosion, and dissolution can contain it (Talbot and Jarvis, 1984; Talbot, 1998). An extrusive sheet advances without a roof or with a roof of negligible mechanical strength, driven by gravity spreading of the weak salt. A salt extrusion is thus an extreme case of passive diapirism, in which the aggradation rate is much lower than the salt rise rate. If the aggradation rate is zero, then salt spreads horizontally across a single bedding surface (Fig. 12e). If aggradation is faster but still slower than salt rise, the salt sheet climbs upsection while advancing over the accumulating sediments (Fig. 14d).

An open-toed sheet (Fig. 20b) is partly buried by a mechanically significant roof, but it still has an extrusive toe. The roof typically advances more slowly than the underlying salt, thus retarding salt flow. Conversely, salt flow exerts traction on the base of the roof, which may be dismembered by extension (Fig. 21) or crumpled against buttresses.

In thrust advance (Fig. 20c), the sheet and its continuous roof advance along a thrust fault at the leading edge of the salt sheet. The thrusting may be driven either by gravity spreading of the sheet or by tectonic shortening. The base-salt shape in an over-thrusting sheet reflects the geometry of the leading-edge thrust, in contrast to the sedimentation-rate-influenced shapes of extrusive and open-toed sheets.

Salt wings are intruded from the flank of a diapir into a preexisting salt layer that abuts the diapir (Fig. 20d). This intrusion requires a salt layer above the main source layer, so it is rare. The only examples known to

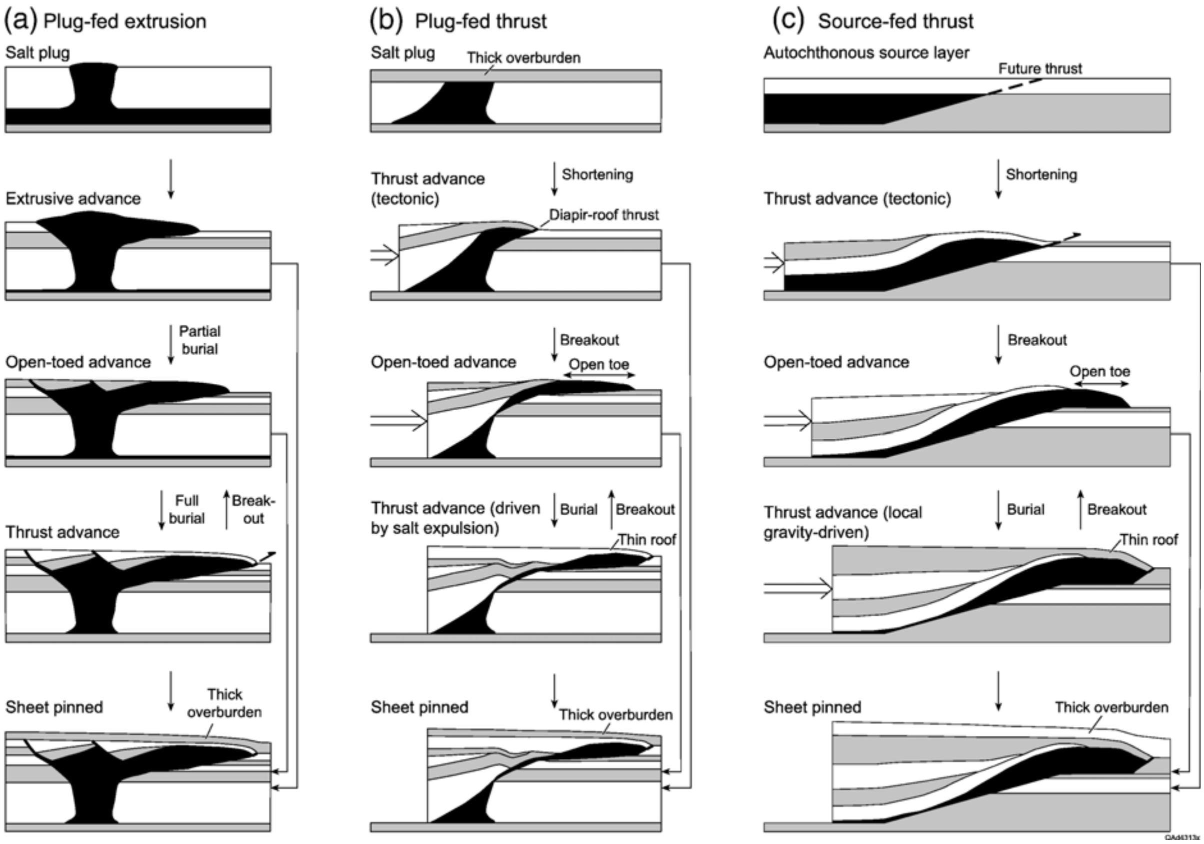

Fig. 22. Three salt-sheet lineages. Vertical arrows between rows connect observed growth sequences. Sheets may stop growing at any stage in the lineage, depending on salt supply, sedimentation, and regional tectonics. Modified from Hudec and Jackson (2006).

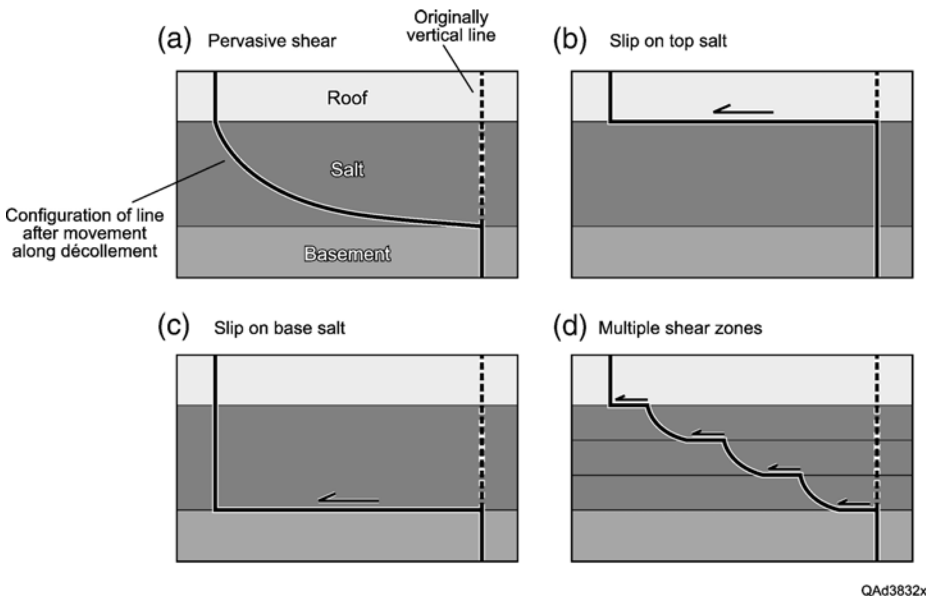

Fig. 23. Schematic of possible detachment geometries in salt. Displacement along a salt décollement could involve various combinations of slip on discrete surfaces and distributed flow within the salt. Outcrop examples and detailed 3-D seismic interpretations suggest that (d) most closely approaches reality.

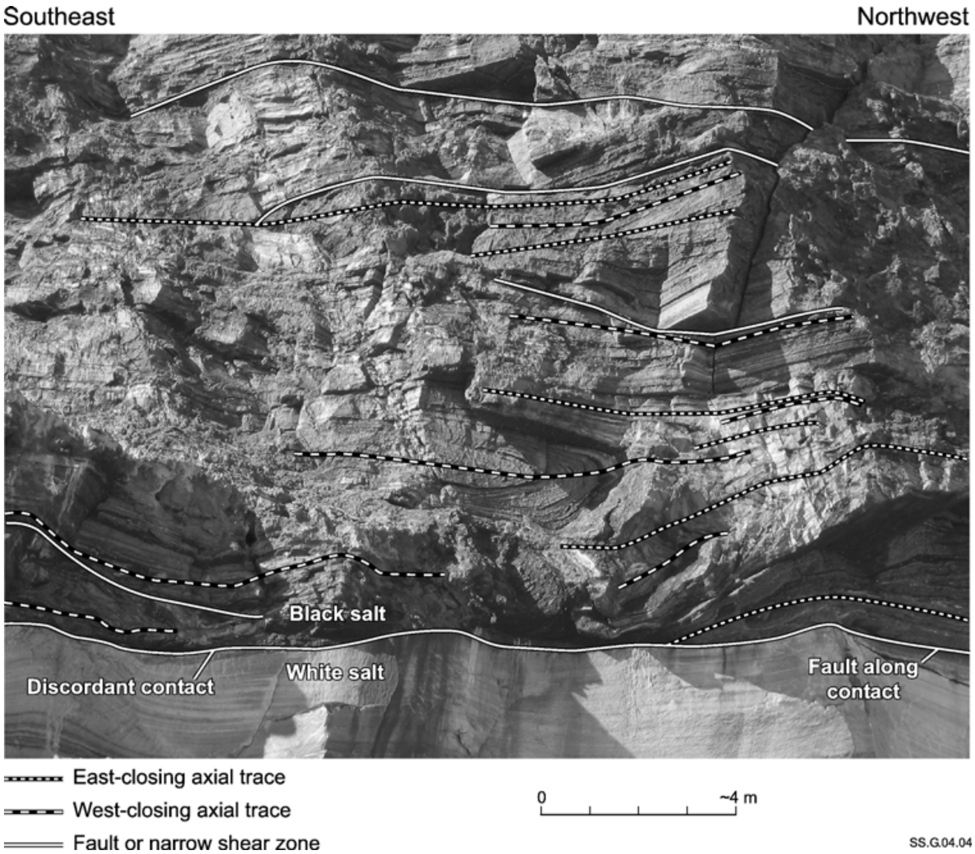

Fig. 24. Combination of brittle and ductile deformation near the toe of the Garmsar salt nappe (Fig. 21), Derakhshan quarry, east of Eivanekey, Iran. Salt here has deformed by a combination of ductile sheath folding and brittle faulting. The fault contact between white salt and overlying black salt locally truncates layering. The overlying black salt contains meter-scale recumbent folds separated by faults or ductile shear zones slightly oblique to the layering. Inferred tectonic transport direction of the nappe is away from the viewer.

us are in the Zechstein salt basin of Europe, where three thin Triassic evaporites lie in contact with diapirs made of Permian Zechstein salt (Kockel, 1990; Baldschuhn et al., 1991; Kockel, 1998; Docherty et al., 1999; Baldschuhn et al., 2001; Hudec, 2004). Even here, where the stratigraphy provided abundant opportunity for salt to intrude into shallow evaporites, salt wings did not form until Late Cretaceous regional shortening began. This shortening caused folds to detach on the shallow evaporites. As a result, the cores of these lift-off anticlines became filled by the salt wings. Hudec (2004) inferred that the salt wings passively filled lower-pressure zones in the core of anticlines created by buckling.

These individual advance modes can combine to form evolutionary histories, or “lineages.” Many lineages are possible, but three lineages are particularly common: plug-fed extrusions, plug-fed thrusts, and source-fed thrusts (Fig. 22; Hudec and Jackson, 2006). All these lineages include extrusive advance, open-toed advance, and thrust advance in various combinations. The nomenclature, however, is based only on the geometry of the feeder structure and the *initial* mode of advance.

Plug-fed extrusions are the most common type on passive margins, so they exemplify salt sheets for many workers. The sheet extrudes from the top of the salt dome or wall (collectively referred to here as “salt plugs” for brevity). Extrusion may be triggered by an increase in diapir rise rate, decrease in sediment aggradation rate adjacent to the diapir, or disruption of the diapir roof. In many cases, extrusion is due to shortening of the salt plug, which both increases the rise rate and disrupts the roof. Plug-fed extrusions may coalesce to form salt canopies, which can cover thousands of square kilometers. Once emplaced,

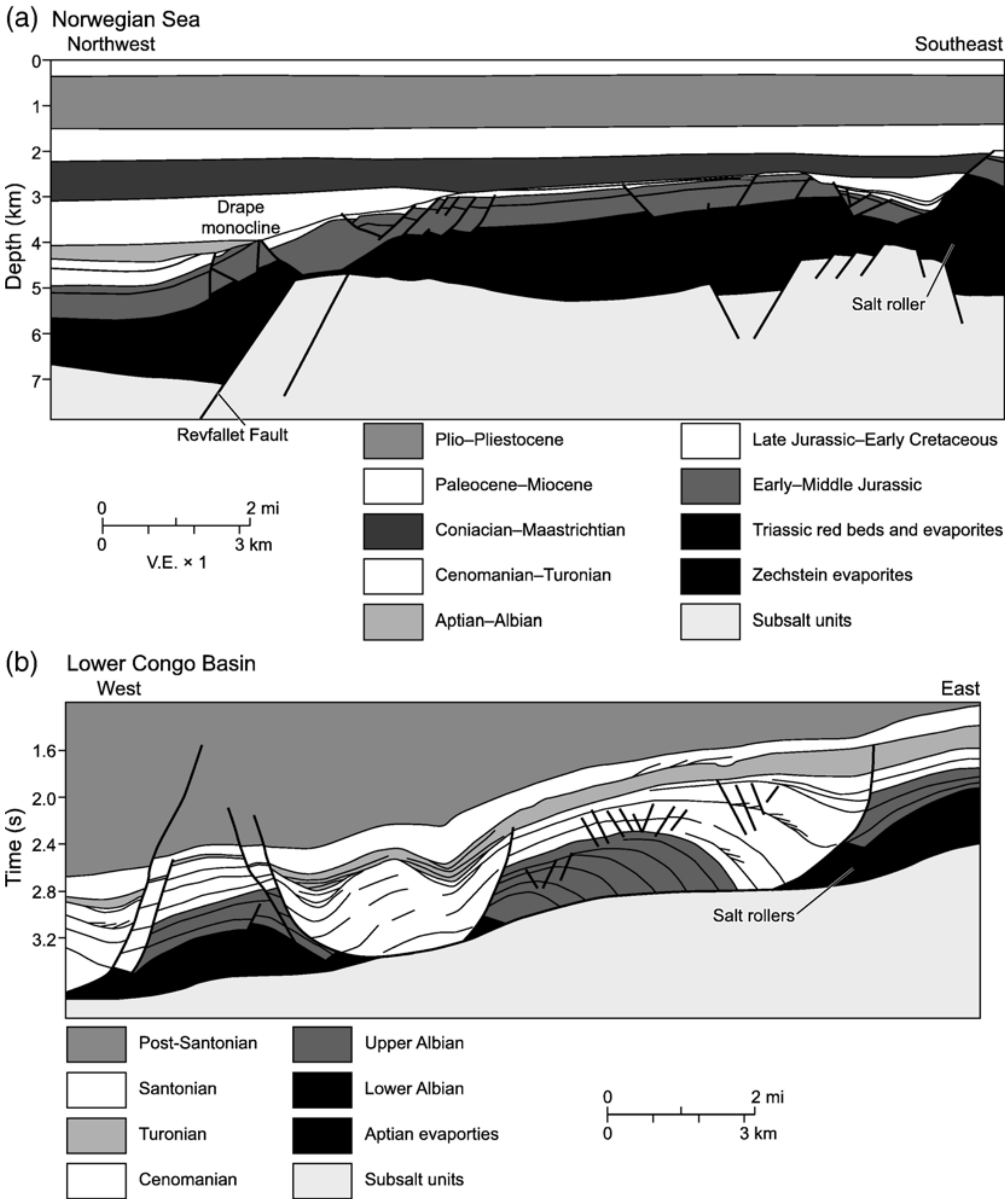

Fig. 25. Examples of extensional salt structures in rifts and passive margins. (a) Salt roller and drape monocline associated with extension on the Revfallet basement fault system, Norwegian Sea. Modified from Pascoe et al. (1999). (b) Salt rollers related to extension detached above thin Aptian salt on the West African passive margin, Lower Congo Basin, Angola. Modified from Rouby et al. (2002). Extension is much greater in b than in a.

individual extrusions or canopies may be remobilized by roof sedimentation (Fig. 22a). Remobilized canopies underlie much of the complex structure in the northern Gulf of Mexico (e.g., Diegel et al., 1995; Peel et al., 1995; Schuster, 1995).

Plug-fed thrusts form when a diapir's overburden is shortened by thrusting, carrying a sheet of salt from the diapir in the base of the thrust hanging wall. This type of deformation is most common in orogenic belts, where compressional stresses are strong enough to deform even the thickest diapir roofs. Examples also exist in compressional toes of some passive margins. The origin of salt sheets as plug-fed thrusts can be obscured by subsequent salt breakout (Fig. 22b).

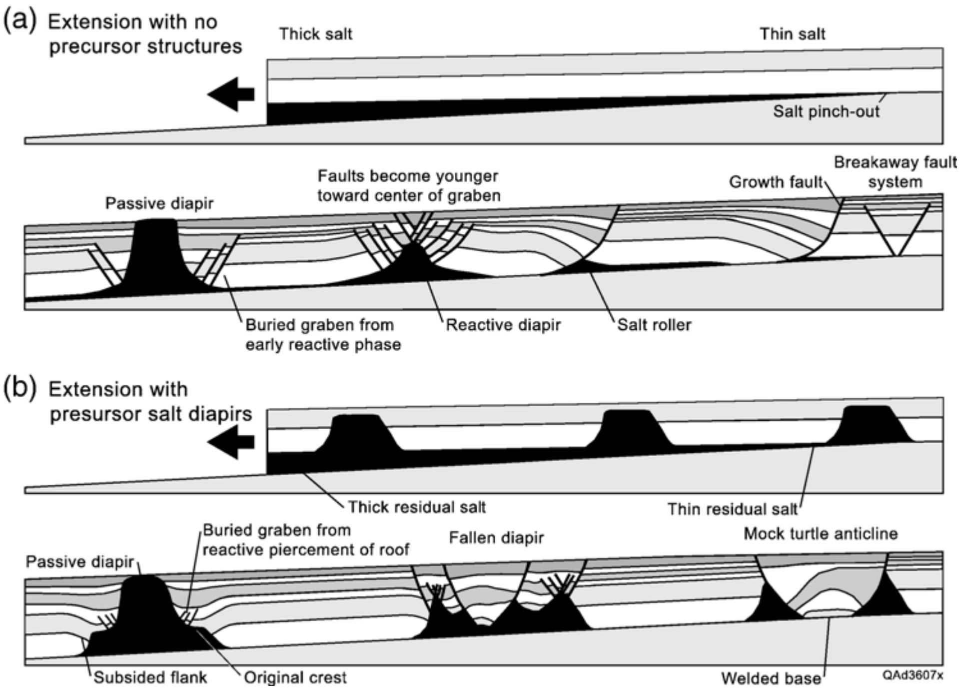

Fig. 26. Schematic forward models of salt tectonics during regional extension, constructed using Geosec-2D.

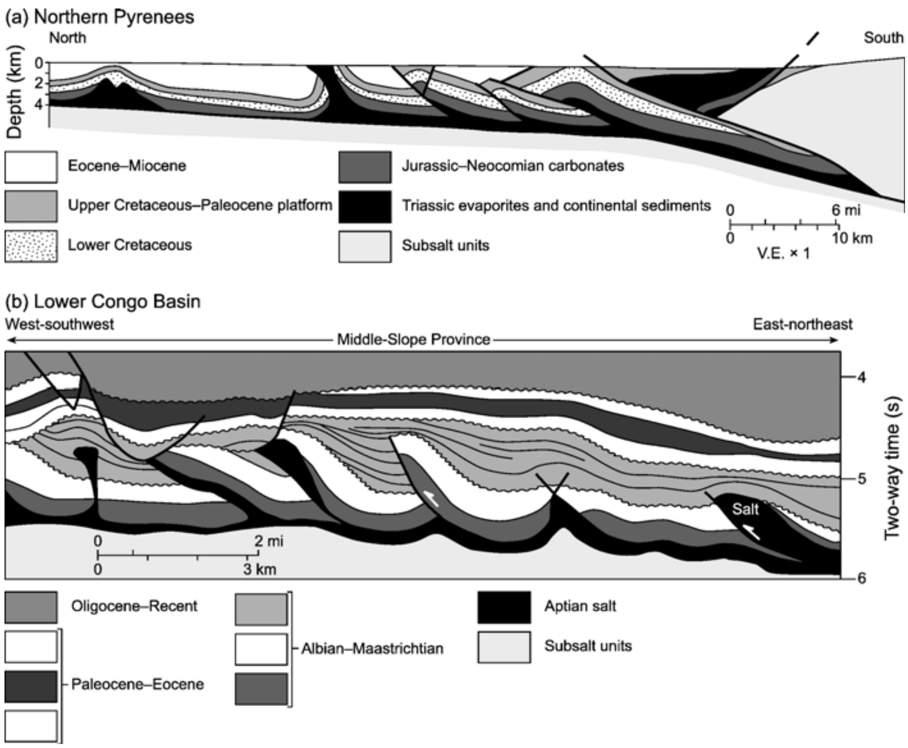

Fig. 27. Examples of compressional salt structures in orogenic belts and passive margins. (a) Overthrust salt, squeezed diapir, and compressional fold in the northern Pyrenees collisional orogen. Modified from Hayward and Graham (1989). (b) Thrusts, anticlines, and squeezed diapirs on the lower slope of the Lower Congo Basin passive margin, Angola. Structural styles are broadly similar regardless of whether the shortening is orogenic or gravity driven, although orogenic belts typically involve more total shortening. Modified from Cramez and Jackson (2000).

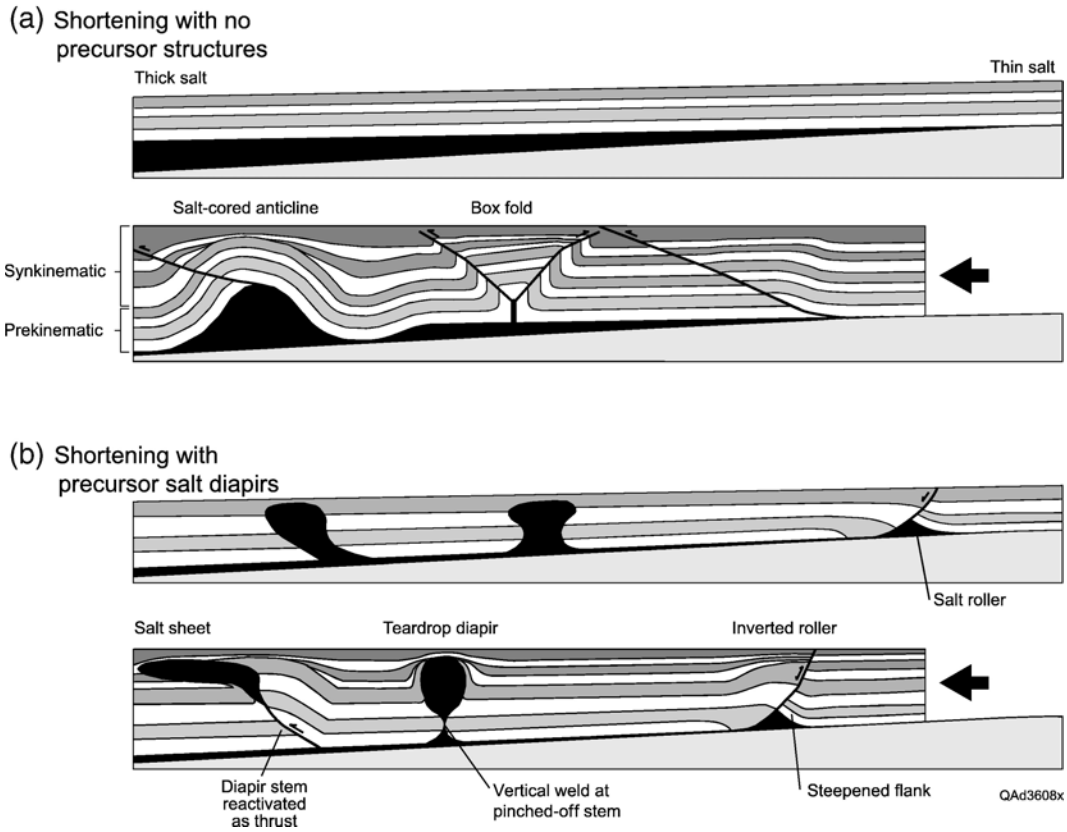

Fig. 28. Schematic forward models of salt tectonics during regional shortening, constructed using Geosec-2D.

Source-fed thrusts form when a thrust imbricate detached on autochthonous salt carries a slice of salt in its hanging wall. The "source" in this terminology refers to the autochthonous salt layer, the source level for all salt structures in the basin. The largest source-fed thrusts rise near the edges of salt basins, where salt-lubricated detachments become thin and translation cuts upsection. These are the largest individual salt structures known (canopies can be larger but form by coalescence of smaller diapirs), and some extend for hundreds of kilometers along strike (Hudec and Jackson, 2006).

4. Salt and regional tectonics

4.1. Overview

Because salt piercement can be related to either extension or contraction of the roof, salt tectonics is closely tied to regional deformation. Salt is typically the weakest link in any rock system, so it tends to accumulate most of the total strain. Thus, preexisting structures usually deform first, as sensitive strain gauges, in preference to the encasing, more-competent sediments. In areas lacking diapirs, salt layers act as extremely efficient décollements, even if the salt is very thin. At regional scale, these décollements can be treated as single layers, but outcrop and high-resolution seismic data show that detailed geometries are more complex (Fig. 23). Salt-involved décollements may comprise complex networks of anastomosing slip surfaces combined with viscous flow of salt (Talbot, 1998, and Fig. 24).

4.2. Salt in regional extension

Extensional salt tectonics is most common in active rift basins and on the outer shelf and upper slope of passive margins (e.g., Fig. 25; Tankard and Balkwill, 1989; Jackson and Vendeville, 1994). Some differences in structural style depend on whether extension is basement involved or basement detached (Vendeville et al., 1995). However, salt tectonics in either setting is dominated by reactive diapir rise (Fig. 10) and extensional diapir fall (Fig. 8; Vendeville and Jackson, 1992b).

In the absence of precursor diapirs (Fig. 26a), the main control on extensional structural style is salt thickness. Thin evaporites localize the detachment but cannot form diapirs or large withdrawal basins. This structural style is dominated by listric growth faults and low-amplitude salt structures such as salt rollers. Above thicker salt, diapirs and adjacent withdrawal basins can grow larger. Some structures progress completely through the reactive and active stages to become passive diapirs, which remain at the surface as long as there is salt to feed them.

Diapirs widen during regional extension, so the most important factor controlling their evolution is the amount of salt available to maintain continued growth (Fig. 26b). If the source layer is exhausted, or if salt is imported from the surrounding source layer too slowly, diapirs will fall. If abundant salt is available, salt diapirs can continue to grow passively or reactively, although they may narrow upward because their older, deeper parts began widening earlier than their youthful diapir crests.

4.3. Salt in regional shortening

Laterally shortened salt structures are found in inverted rift basins, at convergent plate boundaries, and at the downdip toes of passive margins (e.g., Fig. 27; Letouzey et al., 1995; Rowan et al., 2004). There is little difference between basement-involved and basement-detached styles because salt typically acts as a décollement in either setting. Convergent plate boundaries may, however, accumulate hundreds of kilometers of shortening, whereas deep-water fold belts on passive margins typically have only a few tens of kilometers of shortening.

Shortening thickens and therefore strengthens the overburden above salt, which retards the formation of new diapirs, unless anticlines in the fold belt become deeply eroded (Fig. 10c). In the absence of preexisting salt structures (Fig. 28a), salt functions mainly as a décollement. Above thin salt, structures are dominated by thrusts and narrow box-fold anticlines. More open, larger-amplitude detachment folds are possible where thicker salt can fill the cores of anticlines.

Preexisting diapirs are preferentially reactivated during shortening because they are mechanically weak (Fig. 28b, see Section 3.3). Salt bodies therefore shorten early and nucleate folds and thrust faults. These folds and thrust faults then propagate laterally, in places linking preexisting diapirs, commonly producing trends oblique to the regional shortening direction.

Salt sheets are another key element of compressional salt terranes. Because plug-fed thrusts and

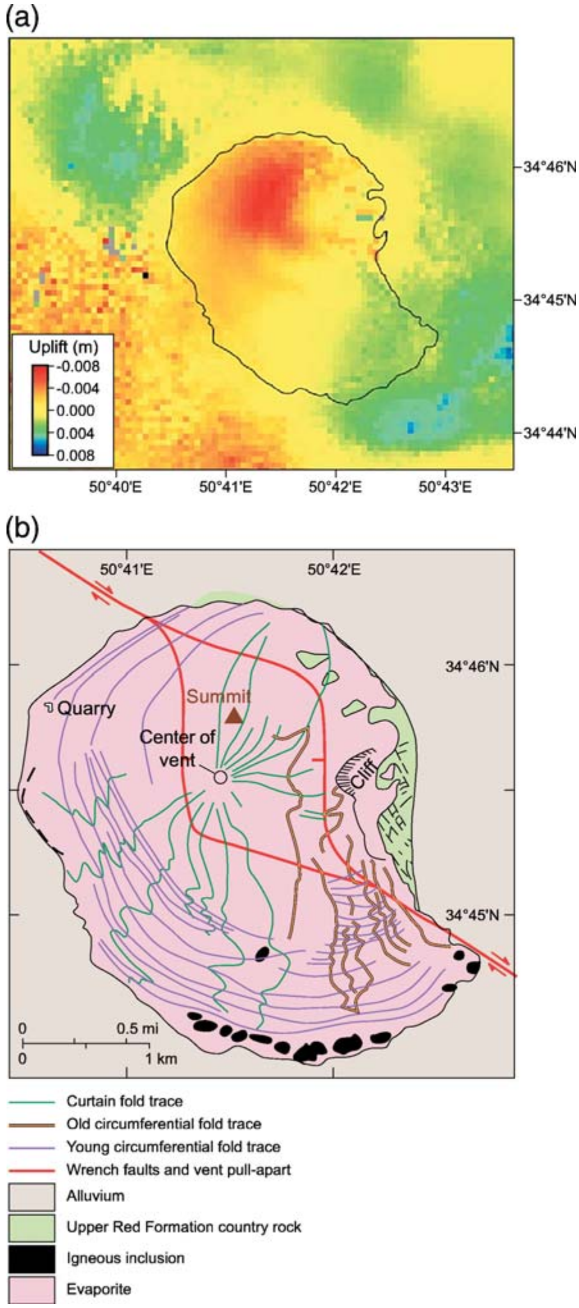

Fig. 29. (a) Satellite interferometry shows an uplifted region over the crest of the Qom Kuh diapir, Iran. Millimeter-scale uplift occurred over a 9-month period during 1998–1999. Areas of greatest uplift (red) are negative because of reduced distance to the satellite. Coarse speckled pattern outside the diapir is caused by variations in humidity. Interferogram courtesy of E. J. Fielding. (b) The uplifted region is the vent of an active salt diapir, rising up through what may be a releasing bend or extensional stepover in the Alborz fault system. Map after Talbot and Aftabi (2004).

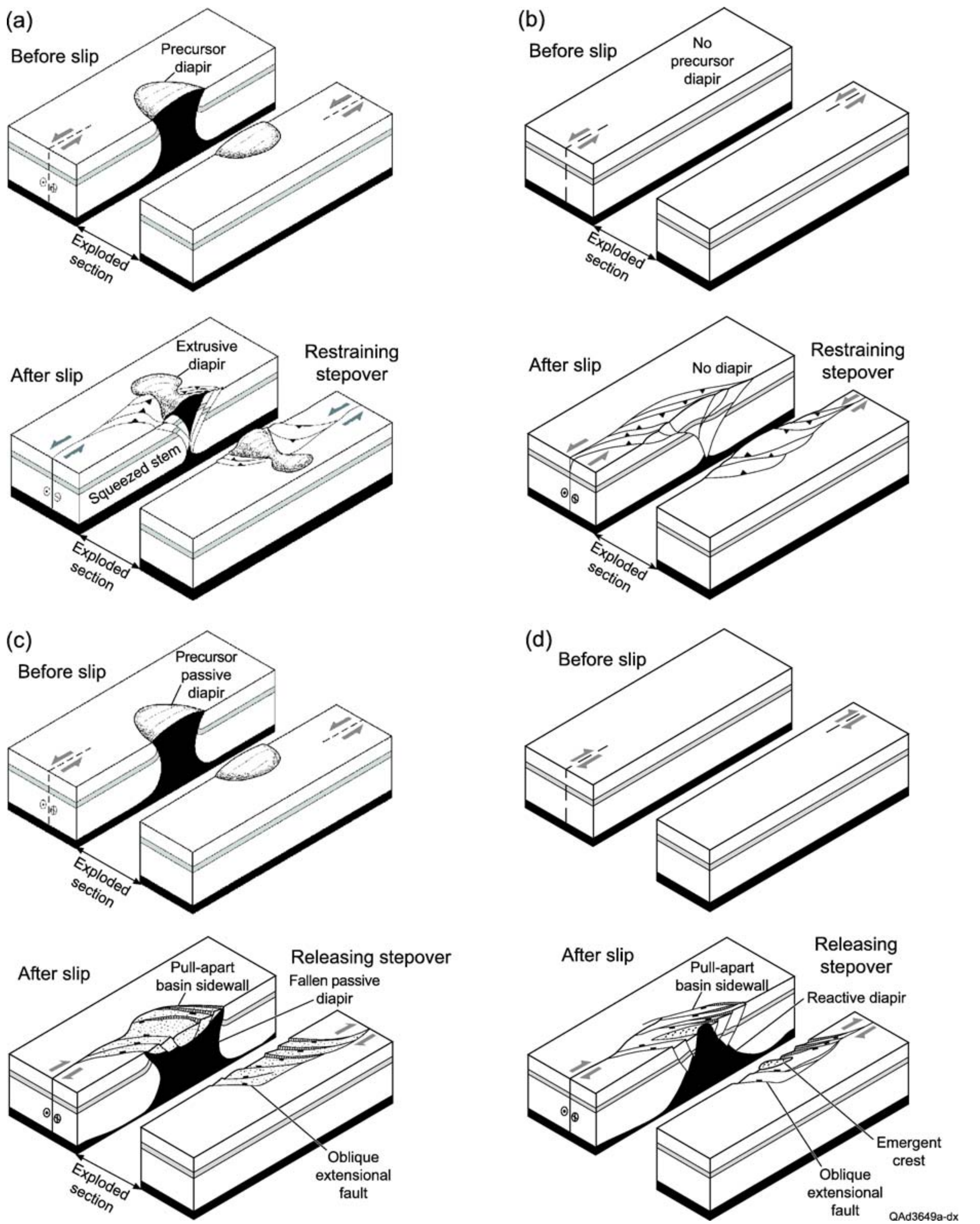

Fig. 30. Schematic illustrations of salt tectonics in strike slip. (a) Restraining stepover and precursor diapir. (b) Restraining stepover and no precursor diapir. (c) Releasing stepover and precursor diapir. (d) Releasing stepover and no precursor diapir.

source-fed thrusts require regional compression to form, they are found exclusively in orogenic belts and at the toe of passive margins. Plug-fed extrusions can in principle form in extensional, compressional, or tectonically neutral settings. However, most known examples appear to have formed during shortening (Hudec and Jackson, 2006). This is because salt is displaced up and out of feeders during shortening, favoring the extrusion of salt.

4.4. Salt in strike slip

Pure strike slip has little effect on a salt layer, but salt may flow if wrenching creates a component of tensional or compressive stress. Most salt-involved structures therefore occur at bends or stepovers in strike-slip fault systems (Figs. 29 and 30). In these localized strain zones, salt behaves much as in the regional extensional and contractional provinces described earlier.

Thrust systems form in restraining bends and stepovers, shortening any preexisting diapirs. In the example in Fig. 15a, salt extrudes out the top of the pinched-off stem to flow over the sediment surface. In the absence of precursor structures, the salt acts as a décollement layer for thrusts (Fig. 15b).

Extensional stepovers or releasing bends form pull-apart basins. Any preexisting diapir in one of these basins will widen and rise or fall depending on the rate of supply of new salt (Fig. 15c). If no precursor structure exists, a reactive diapir may form in an extensional stepover (e.g., Talbot and Alavi, 1996; Talbot and Aftabi, 2004).

5. Conclusions

Despite the bewildering variety of salt structures in nature, the basic mechanics of salt tectonics is reasonably simple. Salt flows laterally from areas of high load to areas of lower load, inhibited only by frictional resistance in the boundary layers along the edges of the salt body and by the strength of the encasing sediments. Load gradients affecting salt can be generated by top-salt salt topography or lateral variations in the weight of the overburden (gravitational loading), regional extension or shortening (displacement loading), or temperature gradients in the salt (thermal loading).

For salt to pierce its overburden, a differential load typically must be generated, simultaneously weakening or removing the overburden. This combination is most easily accomplished during regional deformation. Most salt diapirs in the world pierced during extensional events, suggesting a genetic relationship. Piercement is also possible during shortening and concomitant uplift and erosion of anticlines, especially if some salt structures were present before deformation.

Salt structures can be economically important. They can also help refine tectonic models for the basin containing them. Salt's mechanical weakness makes it a very sensitive barometer of strain, so salt structures may reveal a much more detailed chronology of basin deformation than might otherwise be possible. Because salt layers form extremely efficient regional décollements, they strongly control the style of deformation. A basic understanding of salt tectonics is thus useful to any geologist working on sedimentary basins.

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