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Estimation of salt thickness and restoration of cross-sections with diapiric structures: a few critical comments on two powerful methods

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Abstract—Estimation of the initial thickness of a salt layer that has produced diapirs in a sedimentary basin provides information about basin history and evolution of the resulting salt structures. In many cases quantifying sedimentation and deformation history assists the understanding of hydrocarbon entrapment by salt structures. Limitations of the methods that are used to estimate salt thickness and restoration of profiles with salt structures may cause great error in thickness calculation or interpretation of deformation history. These limitations also cause confusion if they are not explained clearly during presentation of results.

Restoration of profiles of extension areas where salt structures are present could give erroneous results when the regional extension and the flow of salt in and out of the profile along strike and within the profile are not incorporated in the restoration. Scaled analogues demonstrate that restored profiles of diapiric structures may show incorrect evolution history of salt structure and initial salt thickness.

INTRODUCTION

Two major methods have been used to quantify the initial salt thickness in a sedimentary basin with mature salt structures (Seni & Jackson 1983, Sørensen 1986, Bergendahl 1989, Jensen & Sørensen 1992). These two methods are: (1) direct calculation of salt volume in salt structures through the estimation of total volume of salt in diapirs, determining the amount of dissolved salt, and estimating the volume of the remnant salt at depth; and (2) indirect calculation of salt volume by calculating the excess volume of sediments in the rim synclines associated with the salt structures (Seni & Jackson 1983, Sørensen 1986, Jensen & Sørensen 1992). Restoring cross-sections of natural examples or physical analogues through computer modelling has also been used to study the evolution of diapiric structures (Lin 1992, Schultz-Ela 1992). Commercial software packages are used for restoration of geologic cross-sections in areas where salt movement has taken place. In general, these approaches are effective tools to quantify salt thickness and associated deformation. But we should be aware of their limitations when they are applied to natural examples. If not constrained by geological and geophysical data (such as two- and three-dimensional seismic and well data, and sedimentation history) restoration programmes have limitations that could cause significant error in determining salt thickness and/or evolution of the salt structures. There exists much room for error in restoring deformation history of salt structures or in calculating the volume of the initial salt. Therefore, these methods should not be used as straightforward applications without strong geological input.

Our knowledge of salt tectonics has greatly improved in the recent years by studying analogue models and three-dimensional reflection seismic data (Hale *et al.* 1992, Koyi *et al.* 1992a, Ratcliff 1992, Vendeville & Jackson 1992a,b). Physical analogues can be used as a checking tool since both their initial and final stages are known and are directly compared. Some of the approaches that are applied to natural examples may be tested on scaled-analogue models in order to obtain a general idea about their limitations. This paper points out some of the shortcomings in the application of these approaches and the errors that may result from them when they are applied independently.

VOLUME CALCULATION

Jensen & Sørensen (1992) presented a comprehensive study of the evolution of the salt structures and estimated an initial thickness of the salt layer in the Nordkapp Basin offshore northern Norway. By calculating the volume of salt in the salt structures and the excess sediments in the rim synclines, Jensen & Sørensen (1992) estimated an original maximum salt thickness in the northeast Nordkapp subbasin to be 4000–5000 m (Fig. 1). However, this estimated large salt thickness is probably due to over-simplification in the analytical methods.

There are some difficulties associated with direct calculation of salt volume, because the volume of salt depends on the geometry and size of the salt diapirs, the amount of dissolved salt and the amount of remnant salt at depth. Additional uncertainties arise from inadequate description of the methods used to calculate the salt volume. Error in calculating the initial thickness of salt may occur if the following aspects are not carefully analysed: geometry of the salt structures, estimation of the volume of the dissolved salt, the volume of the excess

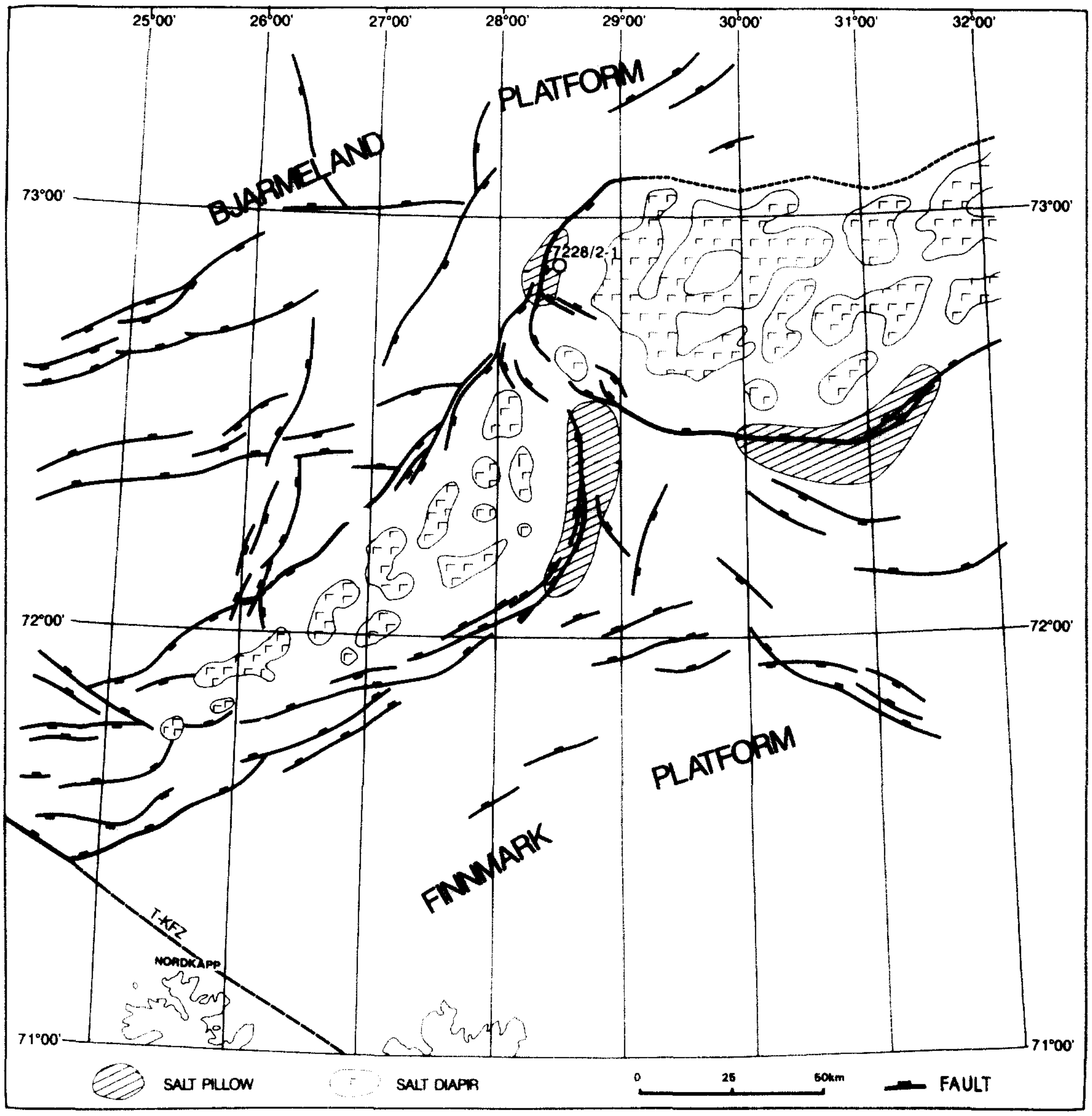

Fig. 1. Structural map of the northeastern and southwestern Nordkapp subbasins (after Jensen & Sørensen 1992).

sediments in rim synclines and non-axisymmetry of diapirs.

Geometry of the salt structures and basin area

Accurate knowledge of the geometry of a salt diapir is the first step in calculating the salt volume correctly. In general, the steep dips of the flanks of salt structures do not allow for accurate imaging of the geometry of salt structures on conventional seismic profiles; it is difficult to calculate how much salt they contain. Diapir overhangs are commonly wider than their feeding stems and obscure underlying reflectors on seismic data. Therefore, in many cases, salt diapirs are interpreted as columnar structures on seismic data. But salt diapirs develop different geometries according to their evolution and sedimentation history (Vendeville & Jackson 1991). Detailed study of many seismic profiles that cross the salt structures at different directions, combined with study of the basin history, give a better idea of the geometry of the structures. Koyi *et al.* (1992a) showed that seismic velocity pull-up of pre-salt reflectors on reflection seismic data could be used to determine the geometry of salt diapirs. Using physical analogs, Vendeville & Jackson (1991) demonstrated that diapirs developed broad overhangs when sedimentation ceased or when sedimentation rate was lower than the rate of diapiric rise.

In their calculation of the salt volume, Jensen & Sørensen (1992) admitted that "some diapirs have spherical tops and some are clearly mushroom shaped". Nevertheless, they assumed vertical sides for all the salt diapirs in the Nordkapp Basin (i.e. the stems of the diapirs are as wide as their crests). However, in the Nordkapp Basin, many of the salt diapirs formed broad overhangs during the slow sedimentation of the Late Triassic through Jurassic that obscure underlying reflectors on seismic data (Gabrielsen *et al.* 1992, Koyi *et al.* 1992b). Therefore, assuming columnar geometry for the diapirs would result in incorrect calculation of the amount of salt in them and the initial salt thickness. To clarify the variation in the calculated salt volume due to

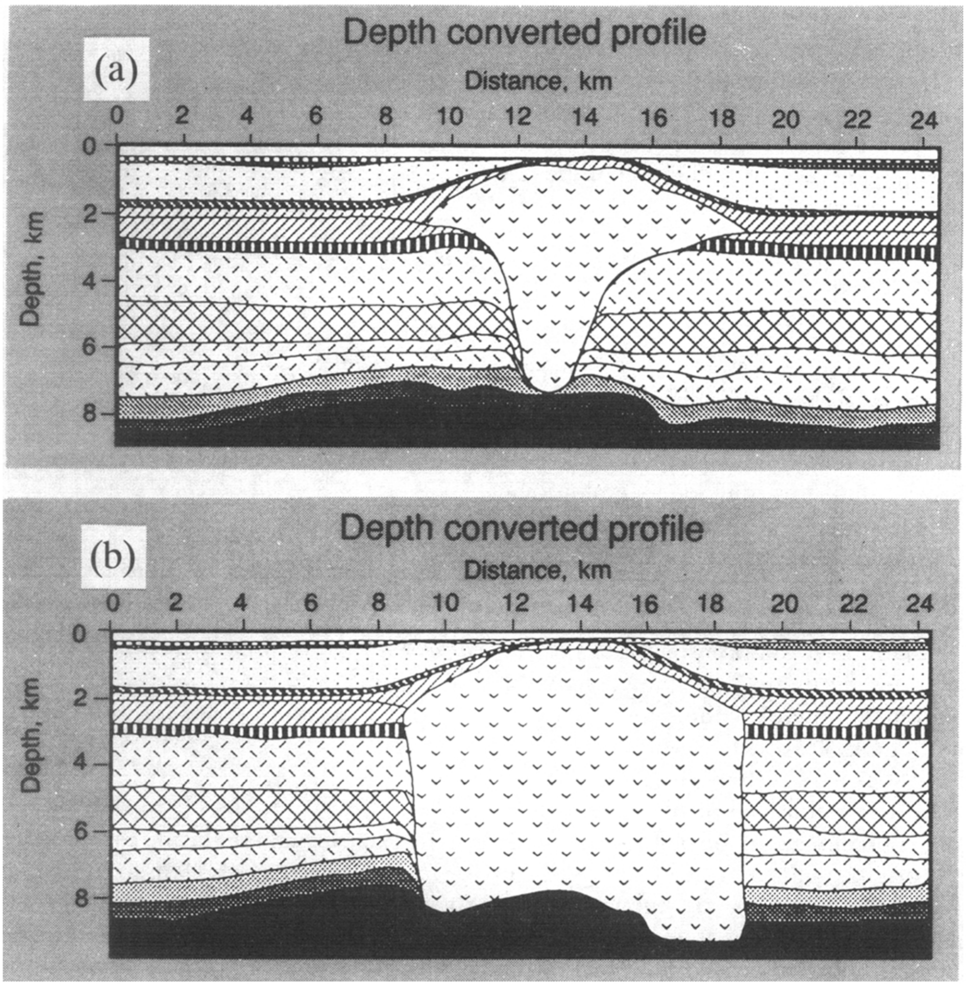

Fig. 2. Two possible interpretations of a salt diapir in the Nordkapp Basin (after Koyi *et al.* 1992b). (a) Narrow stem with broader overhang and (b) columnar geometry. The diapir (b) shows 45.5 km^2 more area of salt than the diapir (a).

the uncertainty in the geometry of salt diapirs, the cross-sectional area of the salt from two different interpretations of a salt diapir in the Nordkapp Basin was calculated (Fig. 2). In profile, a columnar interpretation of the diapir suggests 171% (45.4 km^2) more salt than does the interpretation of a diapir with overhang (Fig. 2). Let us make the unrealistic assumption that the diapir is axisymmetric and possesses similar geometry in different profiles. Then, the columnar interpretation of diapir geometry gives a volume of 243 km^3 of salt, which is 390% (193 km^3) more salt than that calculated for the interpretation of diapir with overhang (Fig. 2). The latter interpretation of the geometry of the salt diapir is consistent with the geometry of the velocity pull-up of the sub-salt horizons (Koyi *et al.* 1992a). Distributing these two volumes of salt over an area of 400 km^2 yields an original salt thickness of 600 and 120 m, respectively. Although these figures are not directly applicable to the Nordkapp Basin, they show that large differences in the estimated salt volume and initial thickness occur when the geometry of salt structures is obscure.

Another source of error is in the estimation of the height of the structures. If diapirs are assumed to be cylindrical, then the volume of the salt in a diapir would be equal to the area of the diapir multiplied by its height. However, it is difficult to image the base of salt structures at depth on the seismic data. Further, in a basin with active basement faulting, the base of the salt beneath different diapirs may be located at different depths, which means that the diapirs would have different heights. Jensen & Sørensen (1992) used three different depth estimates in their calculation to account for the uncertainties in the depth to the base of the diapirs in the Nordkapp Basin. Their calculation showed that assuming different depth to the base of the salt diapirs resulted in a difference of 3400–7500 km^3 in salt volume. Distributed over the Nordkapp Basin (simplified area of the basin that is 30–80 km wide and 350 km long (Jensen & Sørensen 1992)), this volume gives differences of 121–323 or 267–714 m in the initial salt thickness, respectively.

To determine salt thickness, the calculated salt volume must be divided by a unit area where salt was initially precipitated. Determining this unit area is a difficult task because salt withdraws from areas of initial precipitation and forms a salt weld that may be too thin to be resolved in reflection seismic profiles (Jackson & Talbot 1992). However, the salt remaining in the salt weld is also ignored. Consequently, the unit area may be smaller than the actual area of salt deposition. Distributing the salt volume over this smaller unit area results in an incorrectly thicker salt layer.

It may not be correct to assume an initially constant thickness for a salt unit. A salt unit that is precipitated in a faulted basin would be expected to have a variable thickness. Further, in general, more thinning of the salt unit toward the basin margin is likely.

Estimation of the volume of the dissolved and remnant salt at depth

Salt may dissolve or erode when diapirs rise close to the surface (Talbot & Rogers 1980, Talbot & Jarvis 1984) or to the seafloor (Jensen & Sørensen 1992). It is typically difficult to estimate the amount of salt lost by dissolution or erosion and this may lead to additional errors of the original salt volume. The salt structures in the Nordkapp Basin have undergone at least two major phases of erosion and dissolution during Late Triassic and late Tertiary times (Nardin & Røssland 1990, Nyland *et al.* 1992). Jensen & Sørensen (1992) stated that their calculations accounted for the loss of salt caused by dissolution without explaining how they estimated the amount of dissolved salt.

Thick domal cap rocks are further evidence of large-scale dissolution. The amount of salt dissolved can be determined if the percentage of insoluble (primarily anhydrite) in the original salt, and the volume of cap rock composed of insoluble residue are known.

Salt may remain at depth as a relatively undeformed wedge or tabular salt body. Recently, Seni & Jackson (1992) reported remnant salt from the Gulf of Mexico. Calculation of remnant salt may not be easy especially if there are not enough data. If it is not possible to calculate the amount of salt at depth, a gross estimation could be made from those available seismic profiles that cross the area. But it is important to clarify how the estimate was made.

The volume of the excess sediments in a rim syncline

An indirect calculation of salt volume is often obtained by calculating the excess volume in the secondary rim synclines (Seni & Jackson 1983, Sørensen 1986). However, it may not be correct to assume that the volume of excess sediments in a rim syncline of a salt diapir is always equal to the amount of withdrawn salt. The excess volume of sediments in the rim syncline is not always due to salt withdrawal alone. Some of the volume may also be due to local subsidence by movement along basement faults that underlie a salt structure or due to differential loading caused by basement slope. If rooted to a basement fault, in a profile perpendicular to the strike of the fault, the sediments in the rim syncline would be thicker on the subsiding side than on the footwall side of the diapir (Fig. 3). If diapirs are triggered by differential loading due to basement slope, the excess volume of sediments that accumulate on the downdip side would be larger than the volume that accumulates on the up-dip side of the diapir.

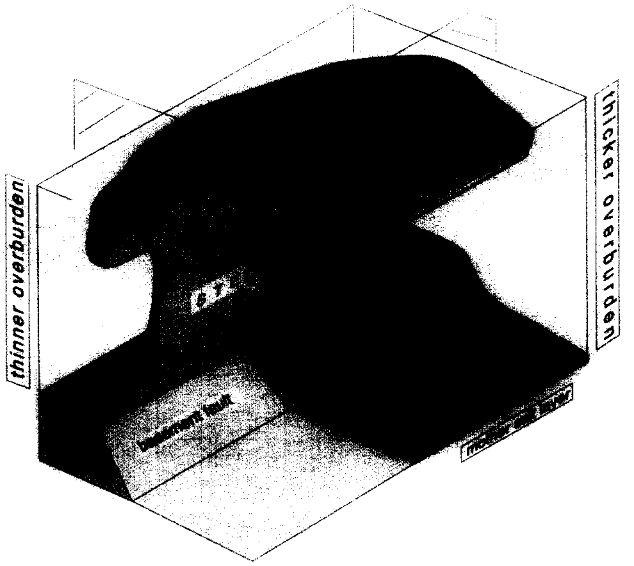

Fig. 3. Schematic diagram of a diapir that has a broad overhang and roots to a basement fault. Note that the overburden units are thicker on the hangingwall side of the diapir than on the footwall side; also that the geometry, and hence the amount of salt, varies according to the direction of the plane of section relative to the diapir. On seismic reflection data, it would be difficult to image the true geometry of this diapir because its steep flanks may be obscured beneath the broad overhang.

In the Nordkapp Basin, the base of salt is faulted (Gabrielsen *et al.* 1992, Jensen & Sørensen 1992, Koyi *et al.* 1992a). On seismic profiles, many of the salt diapirs in the Nordkapp Basin show asymmetric rim synclines with thicker sediments on the basin side of the diapir. Although many of the sub-salt reflectors are poorly imaged or obscured in seismic data, some of the seismic lines that do not cut the salt structures show basement faults cutting the pre-salt reflectors. Therefore, the excess volume of sediments in the rim synclines around the salt structures in the Nordkapp Basin could be caused partly by salt withdrawal and partly by local subsidence of the basement faults underlying some of the diapirs (Fig. 3). The subsiding hangingwalls of these faults produce half grabens that accumulate greater amounts of sediments than do the footwalls (Fig. 3). Therefore, the basement faults in the Nordkapp Basin should account for part of volume of sediments that accumulate around the salt diapirs associated with the basement faults. The amount of the sediments in these areas is the sum of the amount of sediments that displaced the withdrawn salt plus the amount of sediments that accumulated because of subsidence of the hangingwall. Neglecting the latter would result in an overestimation of initial salt volume and thickness.

Rock salt does not compact after precipitation, whereas most non-evaporitic sediments compact with burial. The thicker sediments on the hangingwall side of a diapir that roots to a basement fault undergo more compaction than their thinner equivalents on the footwall side of the diapir that are located at shallower depths. Some volume loss of the sediments may occur due to differential compaction and could lead to underestimation of the withdrawn salt.

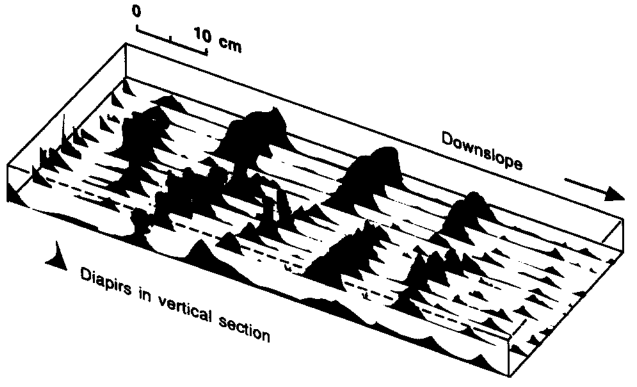

Fig. 4. Serial vertical profiles after deformation of an analog model (produced by Lin Shing-Tzong). Initially, the model consisted of a 2-cm-thick layer of silbione (Rhodorsil gomme) that was buried under layers of loose sand (Lin 1992). The model was allowed to spread towards the right. Note that the diapirs are two-dimensional structures at depth and that their geometry changes along strike. This model shows the importance of the three-dimensional aspect in calculating the 'salt' volume and restoration of deformation history.

Non-axisymmetry of diapirs

Salt diapirs are not necessarily axisymmetrical structures, although they appear to be so at shallow levels. At depth, diapirs may be linear structures that change geometry along their strike (Fig. 4) (Lin 1992, Seni & Jackson 1992, Vendeville & Jackson 1992b). Estimating the three-dimensional geometry of salt structures depends strongly on the resolution of the data. The denser the seismic grid that is used to estimate the geometry of the salt structures and to calculate the volume of salt, the better the resolution. But volume calculation in areas with poor seismic coverage (especially over the diapiric structures) or limited well data, is usually based on maps that are prepared by making assumptions about and simplification of the geometry of the salt diapirs. Consequently, this leads to error in calculating the volume and thickness of salt.

RESTORED PROFILES

Restoration of cross-sections (mainly seismic profiles) is an important tool in describing the deformation history of an area. Balanced sections and palinspastic reconstruction have been used to study salt tectonics in the Gulf of Mexico (Worrall & Snelsen 1989, Hossak & McGuinness 1990, Wu *et al.* 1990). But all restoration methods have their limitations because they require simplifications that may cause incorrect results if they are not checked with detailed geologic data. However, salt structures vary dramatically along strike due to the extreme mobility of rock salt and its interrelationship with sedimentation. Salt diapirs are also fed by source material from surrounding areas that are highly loaded as well as by source material below them. As illustrated by experiments (Lin 1992), this causes variation in the geometry of the diapirs in serial sections (Fig. 4). Similarly, rock salt material in nature is expected to flow in and out of the analysed profile as well; this is likely to cause errors in calculating the original salt thickness and the deformation history of the salt structures by restoration of single profiles.

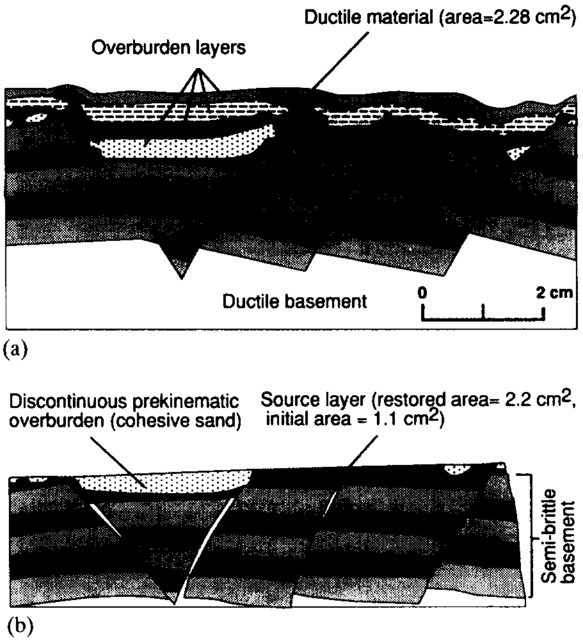

Fig. 5. Profile of a scaled analog model simulating the salt diapirs in the Danish Basin (a) after deformation. (b) Restored version of the profile in (a) using the LOCACE restoration program. The ductile areas in both the deformed and the restored profiles are similar, suggesting that area was conserved during restoration. Compared to the initial parameters of the model, the restored area is twice the size of the initial area of the ductile layer which simulated salt in the Danish Basin. This difference is attributed to the fact that during restoration the three-dimensional flow of ductile material is not taken into account. Note also that unlike the initial stage of the model, in the restored profile (b) the prekinematic layer is not continuous. Courtesy of Dr Jake Hossack.

Figure 5(a) shows a section of a late state of an experimental model that investigates the influence of basement faults on salt diapirs in the Danish Basin (Koyi & Petersen 1993). The area of the ductile salt analogue in the restored section was 2.2 cm^2 (Fig. 5b). However, in the actual model before deformation, the ductile material had a known initial area of 1.1 cm^2 (the initial thickness of the layer was 0.1 cm and its length was 11 cm). This two-fold increase in the area of the ductile layer is due to flow of the ductile material into the section during the evolution of the diapirs, which the restoration software could not account for and restore. However, the ductile material occupied an almost equal area in the deformed and the restored profiles, which may suggest that plane strain and/or area conservation was assumed during restoration (Figs. 5a & b).

Lin (1992) used a commercially available computer restoration software (RESTORE) to analyse the evolution of analog models. In Lin's analogue models, the ductile material flowed along strike due to differential loading. The geometry of the diapirs in vertical section changed along strike (Fig. 4). RESTORE (Schultz-Ela & Duncan 1991, Schultz-Ela 1992) does not require that the area of a ductile substratum remains constant corresponding to flow in or out of the section. However, the estimated amount of flow of the ductile substratum is

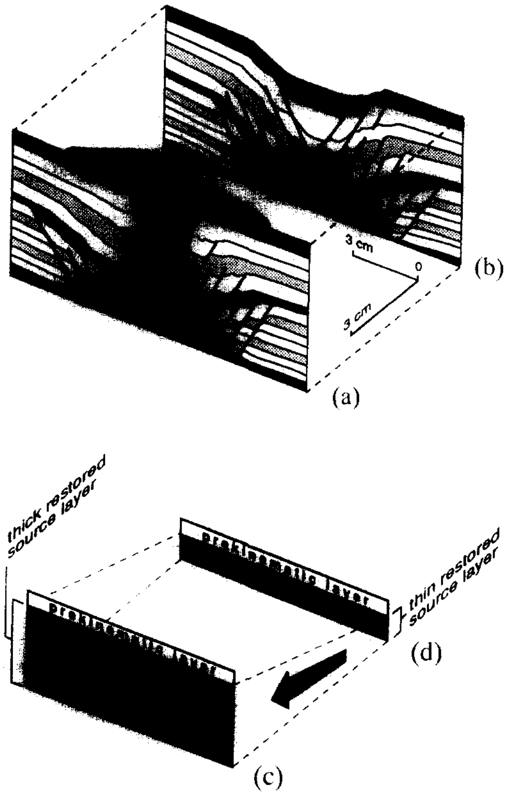

Fig. 6. (a) & (b) Two parallel sections through an analogue model produced by regional extension (modified after Vendeville & Jackson 1990a). (c) & (d) Schematically restored profiles of the model sections (a) and (b), respectively. The restored profile (c) results in thicker source layer than (d) when flow into the section is not accounted for in the restoration. Arrow shows direction of flow of the source material to feed the passive diapir in (a).

constrained by voids or overlaps that appear during restoration of the overburden blocks relative to the rigid basement underlying the ductile substratum. The rigid basement can deform only by translation and rotation and can be moved vertically to result in a desired substratum area or to satisfy some other criterion such as estimated isostatic response (Schultz-Ela 1992). In other words, unlike what commonly happens in nature and experiments, the flow of the ductile substratum in and out of the restored section does not depend on the differential loading across the section.

Applied to scaled analogues with known sedimentation and deformation histories, RESTORE performs a successful restoration of the profiles (Lin 1992, Schultz-Ela 1992). If the initial thickness of the ductile substratum is known (as in models), the rigid basement can be shifted vertically until the initial thickness of the ductile substratum is restored to its true value after restoration of the overburden blocks. In nature where the initial parameters are not (or poorly) known, restoration of the thickness of the ductile substratum and its three-dimensional flow is more difficult (Fig. 6). Restoring the salt thickness incorrectly leads to errors in the evolution history of the studied area because flow of the ductile material in and out of the studied sections influences the deformation and sedimentation histories (Fig. 6).

It may be possible to restore the flow of the ductile material in and out of restored profiles to a certain extent if serial profiles are restored interactively. Interactive restoration of serial profiles could be incorporated in the restoration softwares. Serial profiles give an idea of the relative thickness change of overburden units and the resulting differential loading across the profiles. By including the effect of differential loading across the serial profiles during the restoration procedure, at least part of the flow of the ductile material could be restored.

Errors occur in restoring profiles of areas that have been extended if the regional extension was not accounted for during restoration. Vendeville & Jackson (1992a) showed that restoration of their model profile resulted in incorrect initial stage when the amount of extension was not included in the restoration. In Vendeville & Jackson's (1992a) model, the amounts of incremental and total extension were documented by planview photographs and measurements during experiments. In nature, however, these parameters are not always known. Therefore, Vendeville & Jackson (1992a) suggested that: "extension can only be constrained within a range by any of three additional data: (1) the salt budget of all the salt structures; (2) the overall length of a regional section at different times deduced independently of diapir width; and (3) along-strike variations where an emergent diapir passes into a buried one, whose width is constrained by restoring its roof; such along-strike variations are common".

Some of the mismatches between initial and restored profiles may be the result of assuming area conservation during restoration or restoration of only a part of a profile. Plane strain may not be a realistic assumption for areas with extensive salt movement and may result in an incorrectly restored thickness of the buoyant layer (Fig. 6). A restoration software scenario that assumes plane strain and relies on conservation of material in the restored section would fail to give a correct picture of the deformation history of the salt structures and the initial thickness of the salt layer.

Restoring only a small segment of a profile where salt movement has taken place may not give consistent results (Fig. 7): it can neither restore flow in and out of the profile along strike (as discussed earlier) nor correctly restore flow of the ductile material within the section itself. This is because, within the profile, the ductile material may flow in and out of the restored segment of the profile from and to the unrestored segment of the profile (Fig. 7). Recently, Gabrielsen *et al.* (1992) used the program ECHO/PAL to restore two depth-converted sections of a salt pillow located on the margin of the Nordkapp Basin. Their restored profiles showed that in some places the salt was up to 1500 m thick on the margin of the basin (Gabrielsen *et al.* 1992, fig. 8). Their restored profiles failed to restore the salt pillow and kept the same wedge-shaped geometry of the salt mass. All the salt amount that is present in the salt pillow might have not been there from the start. Some of the salt might have come from the basin where the salt layer was under a higher pressure. Restoration of these

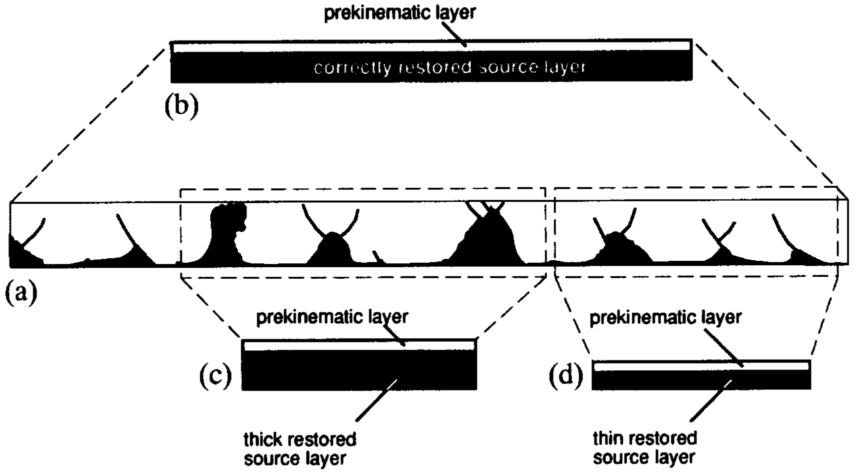

Fig. 7. Schematically restored profiles illustrating that restoration of only segments of a cross-section may result in incorrect thickness of a ductile layer (black). (a) Simplified cross-section of an analogue model showing only diapirs of a ductile material that have risen through an overburden of loose sand (after Lin 1992). (b) Schematic diagram of a restored profile of the entire cross-section in (a). (c) & (d) Schematic diagrams showing restored profiles of segments of the cross-section in (a). Note that, due to variation in size and geometry of the diapirs, in the schematically restored profiles (c & d), the ductile layer is restored to be thicker (c) or thinner (d) than the initial ductile layer (b). In these schematic restoration profiles, an unrealistic assumption is made that no flow of the ductile material occurred in and out of the cross-section.

sections cannot account for this lateral flow of salt into the section, and it may give inaccurate results.

CONCLUSIONS

Calculations of salt volume depends on aspects that could be very subjective. Therefore, it is important to explain clearly how the salt volume in the salt structures is calculated, how much of the volume is attributed to dissolution and why, and finally, to show geologic evidence that supports the calculation. If these data are available, readers could at least draw their own conclusions independently.

In order to estimate salt thickness and the deformation history of salt structures, it is essential to keep the three-dimensional aspect of salt flow in mind. Testing restorations using analogue models where the initial and final stages are known and checking them with the geological history of the restored sections would clarify the limitation of these methods and may help avoid error. Restoration of serial profiles decreases the error significantly.

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