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Review

# Cross-section restoration of salt-related deformation: Best practices and potential pitfalls

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ABSTRACT

Cross-section restoration typically assumes plane-strain deformation and area conservation, constraints that are usually invalid for salt because of its characteristic three-dimensional flow and possible dissolution. Thus, restoration of salt-related deformation provides added challenges and uncertainty. In this review paper, we summarize the historical development of ideas, methods, and applications of restoration in salt basins. While most published restorations do not maintain salt area, constraints on its variation range from arbitrary assumptions to quantitatively incorporating isostatic calculations.

We illustrate several scenarios in which the presence of salt adds ambiguity to restoration, primarily because it can hide deformation: diapirs can widen during extension and narrow during shortening; translating overburden can move into salt and drive allochthonous advance; secondary minibasin subsidence can be accommodated at both shallow and deep salt levels; and allochthonous salt can record evacuation of deeper salt.

Although we caution against using restoration to test and validate small-scale details of interpretations, we emphasize that sequential restoration remains an essential tool in structural and basin analyses. However, because of the uncertainties, a regional three-dimensional approach and sound geological reasoning are critical for deriving meaningful and useful results from cross-section restoration of salt structures.



## 1. Introduction

Restoration of cross sections is a well-established technique employed by geoscientists since pioneering work in the Canadian Rockies during the 1960s (Bally et al., 1966; Dahlstrom, 1969), though its roots go back to depth-to-detachment calculations (Chamberlin, 1910; Laubscher, 1961) and schematic evolutionary models such as those of Buxtorf (1916) for the Jura Mountains. Restoration is the process of reversing deformation, whether in one step to the undeformed state or in multiple increments to show the progressive evolution of structures. Its original purpose was to test and validate cross sections and interpreted seismic profiles, i.e., to show that a given interpretation is geometrically possible, through the concept of balancing (e.g., Dahlstrom, 1969; Hossack, 1979; Elliott, 1983; Gibbs, 1983), and this remains a common application. But the strength of cross-section restoration is much broader, especially when growth strata are present. Sequential restoration can be used, for example, to analyze and illustrate structural evolution, determine deformation rates, constrain models of thermal maturation and hydrocarbon migration, and evaluate the interplay between deformation and sedimentation.

Restoration typically relies on several fundamental assumptions (see Woodward et al., 1985). Among these is that the deformation is plane strain, i.e., that there is no movement of material into or out of the plane of the cross section. Thus, the section must be oriented parallel to the overall transport direction. A second assumption is that the cross-sectional areas of individual stratigraphic intervals do not change during deformation. This is typically accomplished using various graphical restoration algorithms (see Rowan and Kligfield, 1989; Nunns, 1991; Schultz-Ela, 1992): bed-length restoration preserves the line lengths of horizons; vertical-simple shear and inclined simple shear maintain the lengths of vertical or inclined lines, respectively; fault-parallel slip keeps imaginary lines parallel to a given fault at a constant length; rigid-body rotation maintains the exact shape and size of fault blocks; and area restoration relaxes the other constraints while still preserving unit

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area. Alternatively, various geomechanical approaches employ finite-element modeling and similar techniques (e.g., Maerten and Maerten, 2006; King and Backé, 2010; Smart et al., 2010). Note that all these methods also involve a component of rigid-body translation when restoring normal- or thrust-fault offsets.

It has long been recognized that restoration of cross sections that include one or more layers or bodies of salt is problematic because the fundamental assumptions cited above are usually invalid. First, salt flow is typically three-dimensional (e.g., Rowan, 1993; Hossack, 1995; Diegel et al., 1995); even when a section is oriented properly for plane-strain deformation of supra- and subsalt units, salt may flow laterally into nearby diapirs, from beneath adjacent minibasins, or within the cores of anticlines. Second, even if salt flow were two-dimensional, it can flow into or off the ends of all but the most regional sections (e.g., Worrall and Snelson, 1989). Third, salt can be dissolved by fluids such that even the volume, let alone cross-sectional area, is not maintained over time (e.g., Lohmann, 1972; Jenyon, 1984; Hossack, 1995). Fourth, the plane-strain assumption may not apply even to the overburden in some cases: movement directions above salt canopies with significant base-salt relief can be locally variable (Rowan, 1996); and minibasins can rotate about vertical axes during lateral translation above salt (Rowan and Vendeville, 2006).

In this review paper, we first summarize a survey of some eighty papers (found through a search of the literature) to illustrate the development and application of techniques that tackle the special problems inherent in restoration of salt-related deformation. We then address a number of specific scenarios in which the presence of salt provides added uncertainty in restoration, emphasizing the potential pitfalls and suggesting best practices for successful application of the method. Most of these scenarios revolve around the simple idea that salt can hide deformation, whether laterally as in the case of squeezed diapirs or vertically as when one salt layer records deformation in a deeper salt layer. Our intent is not to discourage geoscientists from applying cross-section restoration to salt structures; despite the challenges, restoration remains an essential structural tool in salt basins of all types. Instead, our goal is to help practitioners of restoration derive meaningful and useful results. Consequently, we offer some general guidelines for choosing and restoring cross sections through salt basins.

## 2. Historical review

In the following sections, we review the evolution of the theory and application of cross-section restoration in salt basins. The literature cited is not intended as an exhaustive list but as a selection of representative papers. We neither include restorations of experimental-model results, nor do we cite examples of schematic evolutionary models or interpretation of seismic profiles employing horizon-flattening techniques. Instead, we focus on quantitative restorations of cross sections derived from field exposures and/or seismic data. The vast majority of such restorations has been carried out using commercial software such as Geosec, Locace, 2DMove, and LithoTect. Of course, we are limited to those that have been published — many more restorations of salt structures have been constructed within the petroleum industry, only a few of which have been presented and fewer published.

### 2.1. Early developments

The earliest published restorations of salt-related deformation were of foreland fold-and-thrust belts with basal or intermediate salt detachments, for example the Sulaiman foldbelt of Pakistan (Banks and Warburton, 1986), the Jura Mountains of northwestern Switzerland (Bitterli, 1990), and the southern Alps (Schönborn, 1992). Thrust-related folding was restored using bed-length techniques while maintaining the thickness and cross-sectional area of salt; effectively, salt was treated no differently than any other stratigraphic unit.

Cross sections through extensional and diapiric terranes proved to be more difficult to restore due to the mobility and changing thickness of the salt. Early attempts at showing the evolution of such structures were purely schematic (e.g., Masson, 1972; Heybroek, 1975; Stude, 1978). In a pioneering paper, Worrall and Snelson (1989) used a combination of vertical-simple shear and rigid-body rotation to restore both the growth of diapirs and flanking minibasins and the evolution of normal faults soling into allochthonous salt in the northern Gulf of Mexico (Fig. 1). They were the first to acknowledge the special characteristics of salt and allowed the cross-sectional area of salt to vary over time, speculating that much of the salt moved basinward off the ends of the cross sections. In the same year, Rowan and Kligfield (1989) used flexural-slip and vertical-simple shear to restore a cross section with extensional diapirism, but kept the salt-area constant in an attempt to emphasize interpretation validation rather than structural evolution.

Applications of cross-section restoration increased during the following years, with most efforts directed at the extensional portions of passive margins such as the northern Gulf of Mexico

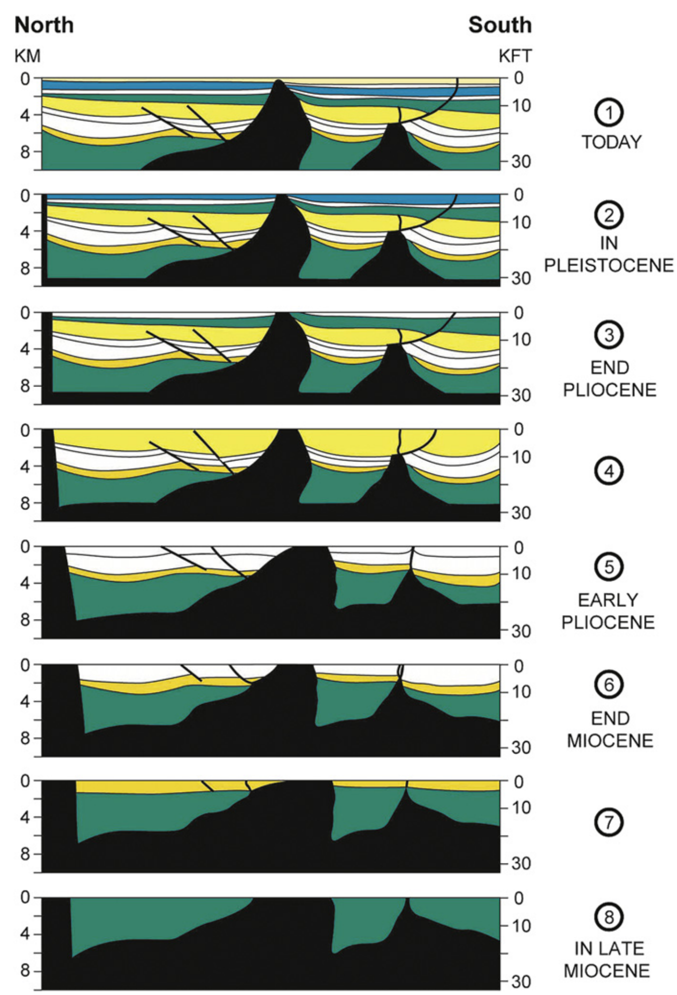


**Fig. 1.** Early sequential restoration showing the development of a passive diapir and flanking minibasins from the Louisiana shelf, northern Gulf of Mexico (modified from Worrall and Snelson, 1989). Base of salt (in black) is unspecified. No vertical exaggeration.