Sand, salt, and models: the legacy of Bruno Vendeville

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Abstract

Bruno Vendeville (1961-2022) was the foremost practitioner of analog modeling applied to the field of salt tectonics, with his work providing and promoting significant advances in our understanding of this field over more than three decades. Bruno and his collaborators contributed major works in: the mechanics of salt-related deformation; the key processes of extensional, contractional, loading-induced, and strike-slip salt tectonics; the drivers and patterns of gravity-driven, linked systems of salt-detached deformation; and the structural style and evolution of specific salt basins. In this Special Issue devoted to his legacy, we offer a series of papers that build on his foundational work and honor his critical role in advancing the theory and application of salt tectonics.

1. Introduction

The field of salt tectonics underwent a revolution in the late 1980s to mid 1990s. While advances in understanding can be attributed in part to improved seismic reflection images, a large part was provided by analog (or experimental) modeling rooted in a more realistic appreciation of the mechanical behavior of layers or bodies of halite and their surrounding sedimentary rocks. Although other researchers were involved, the foremost practitioner of sandbox modeling during this period was Bruno Vendeville (Fig. 1).

This Special Issue is devoted to the memory and legacy of Bruno, who passed away in late 2022. We have compiled an assortment of papers dedicated to him that, like so much other published research of the past 30 years, builds on the foundational work in which he was instrumental. In this introduction, we highlight his key contributions to both salt tectonics and analog modeling. We follow an approximate timeline of his research into salt tectonics driven by extension, contraction, and differential loading, and then briefly summarize other influential contributions he made during his career.

Figure 1. *Bruno Vendeville in his laboratory at the Université de Lille in 2006 (photo by O. Ferrer).*

2. Bruno Vendeville’s legacy

2.1. The beginnings – extensional salt tectonics

Bruno Vendeville undertook his doctoral studies in the mid-1980s at the University of Rennes under the direction of Peter Cobbold. There he first modeled extension above a ductile substratum using silicone putty as a décollement layer and layers of loose sand grains for the overburden. Although some of his results were applied to crustal extension above a weak mantle asthenosphere (Vendeville et al., 1987), it was the application to salt-detached extension (Vendeville and Cobbold, 1987) that became the focus of his ongoing work. After receiving his doctorate, he undertook post-doctoral studies at Texas A&M University before joining the late Martin Jackson’s Applied Geodynamics Laboratory at the Bureau of Economic Geology, The University of Texas at Austin.

It was in collaboration with Martin Jackson that Bruno made his first major contributions. Their paper on “The rise of diapirs during thin-skinned extension” (Vendeville and Jackson, 1992a) was a milestone. It was cited in fully half (42 of 85) of the papers contained in four research volumes on salt tectonics published in the following 5 years (Cobbold, 1993; Jackson et al., 1995; Travis et al., 1995; Alsop et al., 1996), was chosen as one of the top three most influential papers ever published in salt tectonics by a committee of peers in 2013 (see https://100years.aapg.org/top-100-papers-salt-tectonics), and continues to be cited widely.

Bruno’s 1992 paper was remarkable in that it revolutionized not just one, but two, aspects of salt tectonics. First, the authors argued that salt-related deformation is best viewed as a fluid mechanics problem, with a pressurized fluid (ductile halite) surrounded by more competent, brittle materials with significant shear strength. Bruno, in an effort to replicate this mechanical contrast, therefore used sandbox models with silicone polymer as the salt analog and loose sand to simulate the brittle overburden (see Weijermars et al., 1993). This was in contrast to most prior models in which the overburden was treated as a higher-density viscous fluid, and effectively inaugurated the “brittle era” of salt tectonics (see Jackson, 1995). Second, they proposed that many diapirs are triggered by, and grow during, extension detached on the salt, and they introduced the standard terminology and usage of reactive, active, and passive diapirs or diapirism (Fig. 2; see Rowan and Giles, 2021). By showing that extension generates salt structures, they upended the existing “halocentric” paradigm that salt movement is the driver that causes normal faults to form.

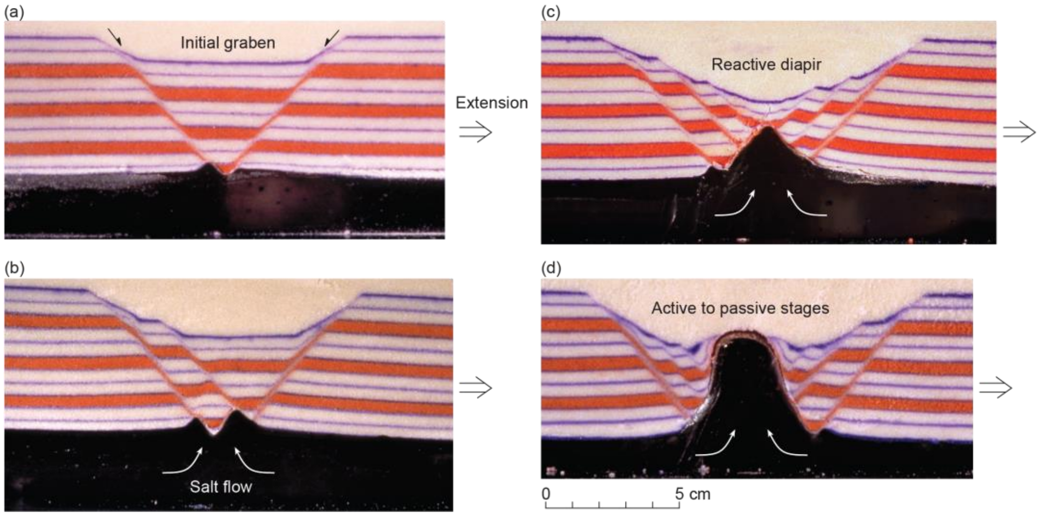

Figure 2. *Photographs of sandbox model showing diapir initiation and growth during thin-skinned extension (modified from Figs. 5 and 13 in Vendeville and Jackson, 1992a, and Fig. 3.14 of Hudec and Jackson, 2011): (a) – (c) reactive diapirism during extensional necking (boudinage) of the brittle overburden; (d) breakthrough to the surface (active stage), where the diapir will subsequently grow during the passive stage. Silicone polymer (salt) in black, sand layers in red and white. Note that the arrows indicate extension, not the order of stages in the experiment.*

Bruno's investigation of extensional salt tectonics was not confined to diapir rise during thin-skinned extension. In a companion paper (Vendeville and Jackson, 1992b), he also examined diapir fall during ongoing extension, emphasizing the role that weak bodies of salt exert in localizing strain. Furthermore, his models elucidated the concept of partial or complete decoupling during salt-involved thick-skinned extension (Jackson and Vendeville, 1994; Vendeville et al., 1995), thereby setting the foundation for other researchers and explorationists to model and interpret more accurately structures in such provinces as the Zechstein and Pyrenean rift basins of Europe.

2.2. Contractional salt tectonics

Bruno soon turned his attention and talents to the problems of shortening detached on salt. He first focused on the role of preexisting diapirs in localizing contractional strain due to their weakness (Nilsen et al., 1995; Vendeville and Nilsen, 1995), showing how shortening can drive further diapir rise (rejuvenation) even after the diapir is dead and buried (Fig. 3). He also highlighted the need to look adjacent to diapirs to determine whether they had experienced cryptic shortening (or, similarly, cryptic extension).

Again, Bruno expanded his investigation of contractional salt tectonics beyond his initial contribution. Working with Elisabetta Costa, he showed that thin-skinned contraction detached on salt results in different geometries and evolution than that detached on stronger, more frictional shales (Costa and Vendeville, 2002). Two other influential papers addressed the role of décollement dip on the geometry of accretionary wedges (Koyi and Vendeville, 2003) and the impact of having two salt layers in contractional settings (Couzens-Schultz et al., 2003). In addition, his models were the first to demonstrate the critical role of the preexisting three-dimensional diapir and minibasin distribution in controlling the subsequent development of polygonal contractional structures (Rowan and Vendeville, 2006). This proved foundational in the reinterpretation of numerous orogenic belts with unusual structural patterns due to the presence of salt and an early history of diapirism.

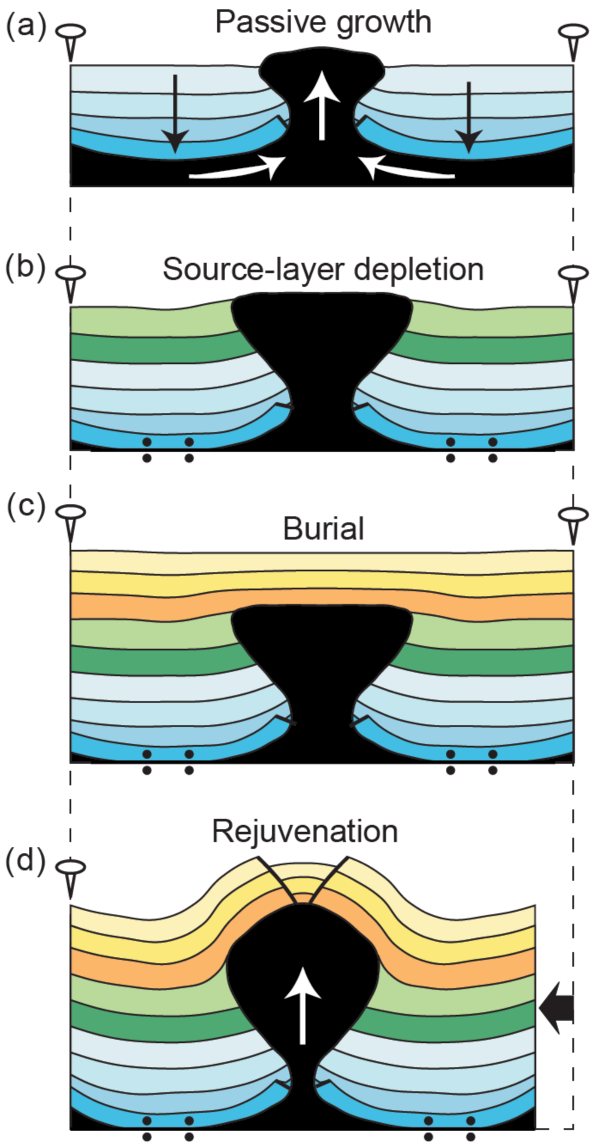

Figure 3. *Sketch of model results showing burial of a passive diapir due to source-layer depletion and then contractional rejuvenation (modified from Fig. 12 in Vendeville and Nilsen, 1995, and Fig. 2.87 in Hudec and Jackson, 2011). Silicone polymer (salt) in black, pairs of dots denote salt welds.*

2.3. Loading-driven salt tectonics

Bruno also conducted investigations of salt tectonics in the absence of either extension or contraction. In an influential paper (Ge et al., 1997), he and colleagues modeled progradational loading above salt, showing that the differential load was sufficient to drive salt basinward (Fig. 4) regardless of the density contrast between salt and its overburden, producing salt pillows, walls, and sheets. This model has subsequently been applied to many salt basins such as the Southern Permian Basin, the northern Gulf of Mexico, and the Paradox Basin.

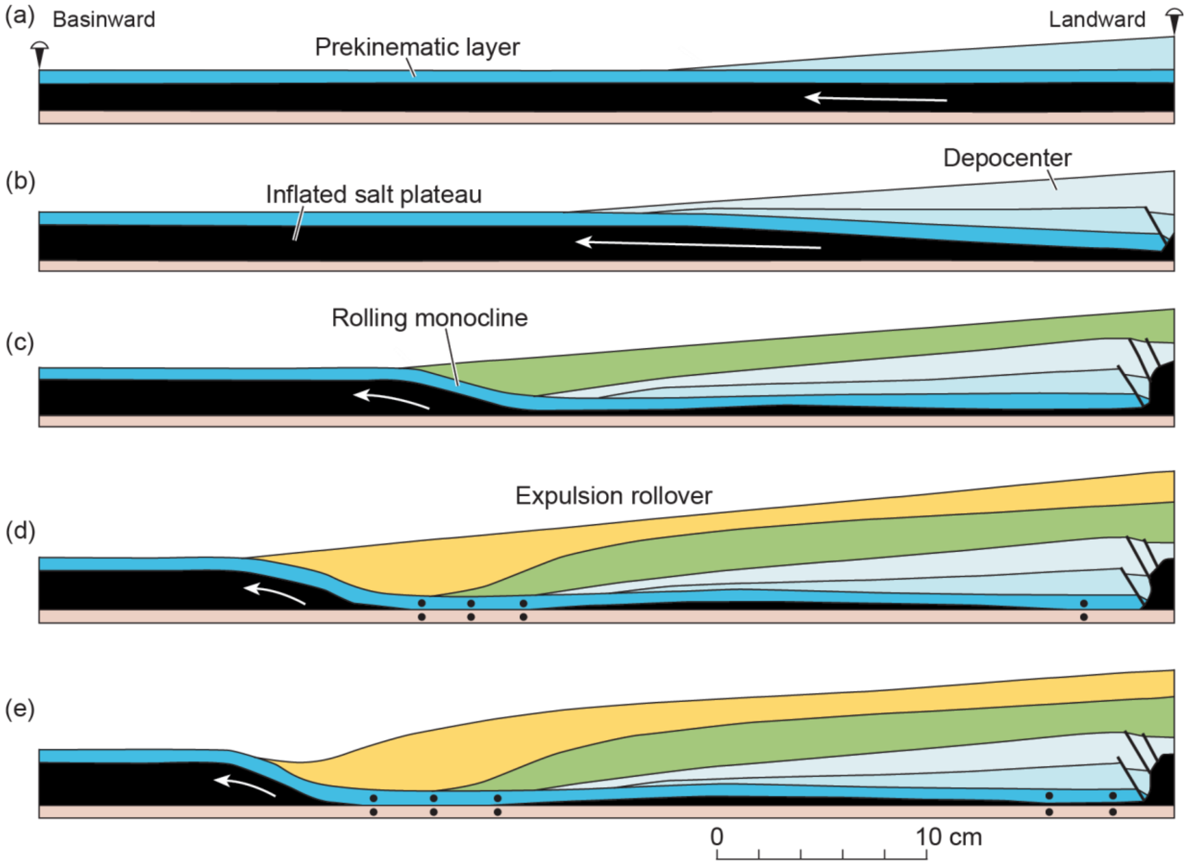

Figure 4. *Sketch of model results showing progressive expulsion of salt to produce basinward-shifting depocenters known as expulsion-rollover structures (modified from Fig. 6 in Ge et al., 1997, and Fig. 1.32 in Hudec and Jackson, 2011). Silicone polymer (salt) in black, pairs of dots denote salt welds.*

Bruno pursued these ideas in two further papers on the mechanics, kinematics, and three-dimensional geometries of linked systems of proximal extension, medial translation, and distal contraction generated by gravity spreading of depositional wedges above salt (Vendeville, 2005; Gaullier and Vendeville, 2005). This tied in to several papers on the triggers, drivers, and styles of gravity-driven deformation on rifted margins (Rowan et al., 2004, 2012). Bruno provided the mechanical reasoning and supporting analog models in arguing that gravity spreading played an important, and sometimes dominant, role in driving the deformation on several margins, in contrast to models claiming that only gravity gliding drives gravitational failure. Once again, Bruno's work proved foundational for all subsequent studies of gravity-driven deformation on rifted margins such as the Gulf of Mexico and South Atlantic salt basins.

2.4. Other significant contributions

Bruno continued publishing influential papers after his move to the Université de Lille in 2004, where he remained for the rest of his career. He conducted and published further research on extensional (e.g., Ferrer et al., 2014), contractional (e.g., Santolaria et al., 2015; Borderie et al., 2018), and loading-induced salt tectonics, but also on other aspects such as strike-slip salt tectonics (e.g., Boussarsar et al., 2022; Vendeville et al., 2024). His laboratory at Lille also contributed a series of important papers on various aspects of deformation above the Messinian salt of the Mediterranean (e.g., Gaullier et al., 2000; Loncke et al., 2006). In addition, Bruno tackled non-salty topics such as shale tectonics (e.g., Mourgues et al., 2009) and the role of overpressured fluids in deformation (e.g., Lacoste et al., 2011). In all cases, his contributions were informed by innovative analog models.

3. Papers in this volume

Bruno’s legacy lies not just in his papers and the many new ideas that were tested and refined by experimental modeling. He also stimulated and inspired others who followed in his footsteps in their own modeling labs, including, but not limited to: Tim Dooley, who took over Bruno’s position in the Applied Geodynamics Laboratory in Austin; Jean-Paul Callot, first at the IFP in Paris and then the Université de Pau; Oriol Ferrer and colleagues at the Geomodels lab in the Universitat de Barcelona; and Jürgen Adam at Dalhousie University and then Royal Holloway University of London.

In the following section, we briefly summarize the fifteen papers published in this Special Issue of the Journal of Structural Geology. These papers originate from some of the labs mentioned above, other researchers, and Bruno’s own lab at Lille. Notably, Bruno is an author of five of the contributions. In organizing the papers, we somewhat loosely follow the general progression of Bruno’s own work over the decades. We thus start with extensional salt tectonics and then move on to contractional, strike-slip, gravitational, and loading-induced salt tectonics, finishing with a paper on intrasalt deformation.

The special issue begins with Schöpfer and Lehner (2024), who take a new look at Bruno’s most famous modeling results – the rise and fall of diapirs during thin-skinned extension – but from a numerical modeling perspective. They reproduce many of the salt structures originally generated in the sandbox models of Vendeville and Jackson (1992a, 1992b), including reactive, active, passive, and collapsed diapirs, turtle and mock-turtle structures, and salt horns. Interestingly, they demonstrate that diapir fall during late-stage extension is dependent on the shape of the diapir (triangular, plug-shaped, or hourglass-shaped). Moreover, both turtle and mock-turtle structures in their models of thin-skinned extension generally have salt cores rather than underlying welds.

The paper by Evans et al. (2024) uses analog models to investigate the interplay of base-salt relief, salt thickness, and intrasalt brittle layers during gravity-driven deformation in the extensional domain. Key findings are that: (i) a first-order control is the thickness of salt relative to the magnitude of base-salt relief; (ii) thin salt promotes the development of ramp-syncline basins, lateral over vertical movement, and stronger spatial coupling between supra- and subsalt deformation; (ii) thick salt leads to reactive diapirs, extensional rollover and turtle structures, more vertical motion, and weaker coupling; and (iv) intrasalt heterogeneity increases the degree of coupling, inhibits vertical motion, and promotes distributed normal faulting.

The Special Issue includes more papers on contractional salt tectonics than on other topics. We start with the paper by Santolaria et al. (2024), who investigate the origins of oblique structures in fold-and-thrust belts. They first synthesize previously published analog models using linear backstops but laterally varying cover and/or décollement thicknesses, discussing different material properties, model setups, tested parameters, and consequent results. They then present their own analog models in which they examine gradually varying lateral thickness changes in both polymer (salt) and cover, specifically scenarios where the two thin in the same or opposite directions. They revisit two natural case studies (the South Pyrenean Central Salient and the Keping Shan fold-and-thrust belt of northwestern China) in light of the various model results, concluding that analog models are invaluable in guiding interpretations but cannot provide unique solutions.

The paper by Muñoz et al. (2024) also uses analog models to investigate the origin of oblique structures and explain the South-Central Pyrenean Thrust Salient. Their models employ trapezoid-shaped detachments of silicone polymer surrounded by frictional material and overlain by foreland-thinning wedges of sediment. The most informative models have two similarly oriented but non-parallel lateral edges of silicone, such that one side has a laterally widening frictional area between the backstop and a narrowing area of silicone, and the other has a simple laterally narrowing silicone detachment. They show that the salient is largest at early stages of deformation but becomes less prominent over time, that the viscous and frictional thrust wedges have different kinematics and styles and are separated by transition zones, and that oblique structures in these zones rarely have the same trends as the original edges of the silicone. Moreover, along-strike variations in model wedge taper and consequent topography nicely explain the asymmetric relief of the Pyrenean salient, the development of the Ainsa Basin, and the attendant routing of synorogenic sediment.

Feng et al. (2024) employ analog models to investigate the influence of mechanical stratigraphy and décollement thickness on the geometry and kinematics of salt-detached fold-and-thrust belts, with specific application to the Kuqa Basin of China. Thinner salt leads to the development of thrust faults with minimal early folding, whereas thicker salt favors the formation of break-thrust folding and eventually source-fed thrust faults. Including layers of mica flakes creates a layer anisotropy and an initially stronger overburden, but ultimately weaker and thus longer-lived, higher-displacement thrust faults. Both thicker salt and mica flakes result in more bulk movement of salt toward the foreland and the consequent growth of inflated salt massifs.

Peng et al. (2024) also use analog models to guide interpretation of structures in China, specifically the interaction between inherited basement strike-slip structures and thrust-wedge propagation in the northern Tienshan foreland basin. Although the primary sedimentary décollement is overpressured shale, the results are also applicable to salt detachments because the authors use silicone polymer as the viscous layer. They show that folding of the detachment by reactivation of the basement structure prior to contraction, especially if accompanied by erosional thinning of the overburden, leads to strain localization over the deeper structure and out-of-sequence thrusting.

Célini et al. (2024) refer to published analog models to help explain and understand structural styles in the external Western (French) Alps by invoking along-strike variations in the presence and thickness of Triassic salt. Where there was no salt (Northern Subalpine Chains), the structural style matches models with frictional detachments. Where the salt was relatively thin and in a foreland position (Jura Mountains), the style changes from a frictional wedge in the hinterland to a viscous wedge in the foreland, as seen in models. Where the salt was thick (SW Alps), the structural styles resemble those of analog models with preorogenic diapirs and minibasins, with features such as squeezed diapirs, overturned megaflaps, salt sheets, and secondary minibasins. Finally, the spatial distribution of salt controlled the development of salients and reentrants along the Western Alps wedge.

In the last paper on contractional salt tectonics, Krzywiec et al. (2024) focus on thick-skinned inversion, using both analog and numerical models to examine the genesis of seismically imaged salt pillows in central Poland. The models are mutually consistent and show that pillows form above inverted subsalt half-graben containing originally thicker salt, with the most important variables influencing the final geometry being the size and geometry of the half-graben, the viscosity of the salt, and the amount of any erosional thinning of the overburden during pillow formation. The results have significant implications for depositional thickness and facies reconstructions of the Zechstein and other synrift salt basins.

We then move to a historical paper on strike-slip salt tectonics by Vendeville et al. (2024). Bruno carried out these models in the late 1990s but never had them published. Although many more recent models on strike-slip deformation have come out in the intervening years, this methodology paper illustrates Bruno's innovative approach to analog modeling. Instead of generating strike-slip deformation in model sand by the movement of rigid underlying plates, Bruno builds two weak zones within the sand above a layer of silicone polymer before applying end-wall shortening. These are intended to represent preexisting salt structures in thin-skinned deformation or established crustal basins during basement-involved shortening. Localized contractional strain in the weak zones is linked by different styles of strike-slip structures depending on the model setup.

An example of this approach is provided by Zidi et al. (2024). They examine an area of the Tunisian Atlas Mountains where there are outcrops of Triassic salt along a fault system with two segments at about 45º to each other. They postulate the existence of an original buried salt wall with this kinked geometry and use analog models to test its reactivation during contraction. Whereas the segment oriented perpendicular to the shortening direction is squeezed orthogonally until a vertical weld forms, the oblique segment is reactivated with strike-slip movement, and areas without any preexisting diapir develop simple folds and thrust faults. Local extrusions of salt occur along both segments of the structure, matching the observations from the natural prototype.

The Special Issue includes three papers on large-scale linked systems of gravity-driven deformation. First, Anagnostoudi et al. (2024) employ complex analog models in an attempt to reproduce the salt-related geometries of the Levant Basin in the eastern Mediterranean. They model four scenarios – gravity gliding/spreading from the linear to slightly curved Levant margin, gravity spreading from the highly arcuate Nile deep sea fan, and two different combinations of both drivers –including in each the distal buttressing effects of the Eratosthenes Seamount. Although no single model fully reproduces the three-dimensional patterns of the Levant Basin, they conclude that gravity spreading of the Nile cone was the dominant driver of deformation, with relatively minor contributions of gliding/spreading from the Levant margin.

The paper by Travan et al. (2024) is the first of two that examine salt tectonics driven by a combination of tectonic shortening and gravitational failure. They use a sandbox model to evaluate the genesis and evolution of salt structures in the offshore of the central segment of the Algerian Mediterranean margin. Local uplift of the Messinian salt and its overburden was generated by underlying contractional deformation due to convergence between the African and European plates. The model suggests that this in turn led to along-strike gravity gliding down the flank of the plateau, with bulk movement of salt downdip to the west and the development of both extensional structures and a polygonal array of diapirs and minibasins due to convergent shortening.

Dooley and Hudec (2024) focus on the Sureste Basin in the southern Gulf of Mexico, progressively building complexity into analog models to address five aspects of the observed geology. They demonstrate that: (*i*) basinward narrowing of a trapezoidal salt basin results in constrictional strain and transpressional deformation along both lateral margins; (*ii*) a combination of tectonic and gravity-driven deformation is required to produce contractional structures throughout the entire basin; (*iii*) the presence of preexisting diapirs results in curvilinear and kinked fold and thrust-fault structures linking the diapirs; (*iv*) non-parallel driving forces generates strong curvature of structural trends and major transpression along the western boundary of the basin; and (*v*) an eastward-thinning salt layer explains the distribution of salt sheets and canopies in the Sureste Basin.

Ferrer et al. (2024) bring us back to more local deformation in the first of two final papers, investigating the development of halokinetic megaflaps adjacent to passive diapirs. They use analog models to investigate differential loading with either vertically-stacked depocenters or laterally-shifting expulsion rollovers. In both cases, there is earlier subsidence of one minibasin relative to another; touchdown and consequent welding of the salt beneath the first then leads to increased subsidence, stratal rotation, and megaflap formation in the later minibasin. Moreover, a more cohesive mixture of sand and clay in the prekinematic layer results in minimal bed lengthening and thinning, compatible with observations of exposed megaflaps.

In the final paper, Cofrade et al. (2024) examine the distribution, geometry, and evolution of intrasalt carbonate stringers in an allochthonous salt tongue at Les Avellanes diapir in the south-central Pyrenees. They employ an analog model to demonstrate that: (i) stringers are rotated from near-vertical in the feeder to subhorizontal in the salt sheet; (ii) intra-sheet deformation generates tight to isoclinal, inclined to recumbent folds, vergent toward the sheet toe, that become disrupted and stacked with ongoing flow; and (iii) the stringers become imbricated toward the toe of the sheet due to decelerating flow and consequent compressional stress.

4. Concluding statement

We hope and expect that this assortment of papers offers a fitting tribute to the memory of Bruno Vendeville. We stress that it is not only his scientific contributions that we honor, but also Bruno the friend, colleague, and mentor. He truly was salt of the earth.

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