Introduction to special section: Balancing, restoration, and palinspastic reconstruction

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Methods to quantify deformation and reverse the process of strain as a mode to illustrate geologic evolution through time have been previously used for a number of decades. Early efforts on the quantification of bed reconstruction were completed either by manually weighing the sections on delicate balances and obtaining the average height and thickness of strata to be reconstructed by applying a scale factor (Chamberlin, 1910), or by hand-drafting sections with conserved bed length between the folded and faulted sedimentary layers, mainly in a 2D cross section (Bally et al., 1966; Dahlstrom, 1969) or map framework (Dennison and Woodward, 1963). Cross-section techniques initially applied to contractional thrust and fold belts and have proven useful in other structural settings, such as extensional and inverted domains. Development of 3D techniques enabled the analysis of strike-slip and salt tectonics where out-of-plane changes of rock volume could be addressed. Through the years, the widespread application of these techniques to predict fault and horizon geometry at depth has generated newer approaches and more sophisticated algorithms, and it has also demonstrated the potential of structural modeling techniques (e.g., construction of balanced sections, palinspastic reconstruction, kinematic and geomechanical restoration, and forward modeling) in reducing the risk and uncertainty associated with the interpretation of geophysical/geological data.

In this special section of *Interpretation*, a journal emphasizing the mutual contributions of geology and geophysics, we pay special attention to the concepts and applications of classic and recent advances in structural modeling techniques. More specifically, we focus on the commonly grouped methods of balancing, restoration, and palinspastic reconstruction. These are, generally speaking, methods that enable the geometric transformation of a deformed rock mass back to a predeformed state (single-step restoration) or to multiple intermediate steps (sequential restoration). Although balancing, restoration, and palinspastic reconstruction are terms often (and incorrectly) used as synonyms, there are important differences to bear in mind when referring to them.

Balancing a cross section (or, likewise, a 3D model) necessitates mass conservation before and after deformation. When compaction is not considered, this implies conservation of a cross-sectional area, or volume in three dimensions, whereas if decompaction is performed then surface area or volume in three dimensions generally change. A further common constraint in contractional settings is conservation of bed length and thickness of stratigraphic units before and after deformation. There are four principles that a geologic model must meet to be considered as *balanced* (Dahlstrom, 1969; Elliott, 1983; Groshong et al., 2012): (1) accuracy (i.e., it must fit the available data constraints), (2) admissibility (i.e., it must conform to structural geometries recognized in local or analogous areas, usually natural, but sometimes experimental or theoretical), (3) restorability (i.e., it can be returned to a predeformational geometry, in a single step or in multiple steps), and (4) balance (i.e., the restoration must display balanced bed lengths and/or areas, among others).

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Restoration is the concept of reversing deformation through time and usually, but not necessarily, encompasses bed or area conservation principle. As Groshong et al. (2012) points out: "… in most methodologies restoration is required for balancing, but a restored section is not necessarily balanced." Restoration can also be referred to by a longer but more descriptive term, *inverse strain transformation*.

Palinspastic reconstruction (sometimes referred as *palinspastic restoration*) can be considered in a cross-sectional case and thus is analogous to structural balancing. However, rules governing palinspastic reconstruction more commonly refer to map-view or surface restoration over time in three dimensions (Dunbar and Cook, 2003). Because of this spatial consideration, other geological and environmental factors in relation to the evolution of deformation are generally considered at each time step (e.g., palaeogeology, palaeotopography, palaeoclimatology, and palaeohydrography of the area, depositional environments, sediment source area, and provenance, etc). Palinspastic reconstruction, therefore, can be understood as a restoration integrating the geological, geomorphological, and environmental conditions at the considered time of deformation.

The eleven papers comprising this special section present a wide variety of examples, case-studies, new methods, and state-of-the-art reviews of the available techniques in which structural modeling is used as a powerful tool to guide and reduce the uncertainty in the interpretation of geophysical and geological data. We hope that readers will find a valuable selection of articles in this special section that can be applied to in their own work.

Maerten and Maerten present a methodology for automatically reducing uncertainty in the interpretation of faulted seismic horizons. The technique is based on mechanically based restoration, including unfolding and unfaulting.

Groshong defines three basic styles of compressional structures based on their area-depth-strain (ADS) relationships. In seismic-profile interpretation, mismatches between observed and ADS-predicted values for detachment locations, displacements, and layer-parallel strain provide quality control and a measure of the risk associated with the interpretation.

Based on the sequential restoration of a regional transect, **Parravano et al.** propose a new model involving salt tectonics for the foothills of the Eastern Cordillera of Colombia. The present-day thrust-fold structure is interpreted to result from the shortening of a diapiric structure formed during an earlier extensional episode.

Malz et al. demonstrate how cross-section balancing helps to constrain the structural interpretation in poorly imaged parts of a reprocessed 2D seismic line across the Jura fold-and-thrust belt of northern Switzerland. Geometric and kinematic section validation leads to a consistent interpretation of dominant thin-skinned structures and reveals older, subtle deformation features.

Pace et al. present and discuss examples of inversion structures that exhibit different structural styles by interpreting newly reprocessed 2D seismic data from the Italian sector of the Adriatic Sea. Inversion folds within the Adriatic foreland hydrocarbon province are consistent with an intraplate compressional deformation, which has important implications for hydrocarbon prospectivity.

Zamora-Valcarce and Zapata provide a clear example of how exploration opportunities can be hidden due to poorly defined structural interpretations. Presenting alternative interpretations of an existing unrestorable cross section ended with a new structural model and, most importantly, gave rise to a new exploration opportunity; the new model was restored and validated by drilling a new exploration well in the area.

Spikings et al. present a palinspastic restoration of a well-studied exhumed deep-water system where slope channels have been mapped to genetically related basin-floor fans in the Laingsburg depocenter, Karoo Basin, South Africa. The restoration of postdepositional folds and faults allows for more accurate palaeogeographic reconstructions and sedimentary volumes, and the authors present a workflow that can be applied to other analogue systems.

Eichelberger et al. discuss how combining structural forward modeling, restoration, and area-depth strain analysis provides independent validation and quantitative insight into 2D geologic interpretations. Interactive structural geologic software makes it possible to perform these analyses quickly, guiding interpreters toward optimal solutions that are quantitatively robust.

Dalton et al. find there to be a constant shortfall in the amount of contraction relative to extension in a deep-water fold thrust belt, allowing them to quantify the lateral compaction of the margin as 5%. The authors also establish a temporal model for the development and growth of thin shale detachment gravity collapse structures on passive margins.

As a warning message, **Hardy** states that nondeterminism in numerical codes has important implications for the interpretation of model results in structural geology. The authors present some examples and suggests a methodology for attaining deterministic model results.

Lingrey and Vidal-Royo review the different strain transformation (restoration) methods available and their implications for bed length and area conservation; the assessment of the restoration methods is illustrated by examining two examples and by providing tables listing and confirming the deformed/restored state line-lengths and areas. It is discussed that such tables should be provided for any strain transformation exercise to prevent over- and underestimations that deviate more than 5% from the initial interpretation.

Although unfortunately not included in this Special Section due to time constraints, **Carrillo et al.** presents a new method in which overburden accumulation, sedimentation, erosion and thermal behavior in the Eastern Cordillera of Colombia are calibrated with the evolution of deformation through time. We encourage the readers to check the next issue of *Interpretation* (February 2016) in which the article will be published.

A content-rich and informative special section like this one does not just appear from nowhere. Instead, it requires the effort, hard work, time, and devotion of many people. First, we would like to thank the authors of the aforementioned articles, who put their valuable time and knowledge at the service of the community. O. Vidal-Royo, as the organizer and assistant editor of this special section, would also like to thank the eleven geoscientists coauthoring this introduction who served as associate editors and invested significant time to ensure a smooth and timely review process. Manuscript reviews were completed by the editors along with S. Abbe, A. Argnani, R. Bell, J. P. Brandenburg, H. Broichhausen, G. Caumon, D. Dajczgewand, O. Fernández, E. Finch, R. González-Mieres, R. Hinsch, S. Homke, P. Kraemer, S. Lingrey, P. Lovely, D. Medwedeff, C. Nussbaum, F. Peel, J. Poblet, M. Rowan, and several anonymous reviewers. Finally, but not least, we would like to thank Y. Sun, editor-in-chief of *Interpretation*, for his continuous supervision and support, as well as the editorial staff of the journal who provided the essential backbone to put together this special section.

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