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Preface

Fault-Related Folds: The Transition from 2-D to 3-D

The idea for this Special Issue developed from a Geological Society of America theme session that was convened in Denver, Colorado in October 1999. That session provided a forum where researchers, independent of the tectonic setting in which they worked, could meet and discuss recent advances in the depiction, restoration, and modeling of fault-related folds in three dimensions. Shortly afterwards, a general call for papers for a special issue on the topic appeared in the *Journal of Structural Geology*, and 29 papers were submitted from around the world.

This Special Issue consists of 17 papers that (1) describe new techniques for the 3-D representation, reconstruction and/or forward-modeling of fault-related folds, (2) carefully document natural examples or experimental models of fault-related folds, or (3) describe 3-D growth of fault-related folds, including the effects or geometry of lateral fold terminations, displacement-transfer zones, and cross-strike discontinuities. This collection of papers represents an intentionally broad sampling of state-of-the-art approaches for better understanding the 3-D geometric, kinematic, and/or dynamic properties of fault-related folds; either through the use of 2-D/3-D reflection seismic data, detailed field mapping, physical modeling, and/or computer modeling. We have sequenced the papers to focus on process and not tectonic setting. In doing so, we hope to blur the distinction between approaches that have originated in various tectonic settings such that common relationships/characteristics from the different perspectives might become more apparent.

The first papers consider the nature of fault-related fold terminations based on geometric and numerical models. Wilkerson et al. use pseudo-3-D geometric models to show that criteria commonly cited as evidence for lateral ramps at contractional fault-related fold terminations are not necessarily unique. They also suggest ways to help constrain interpretations of the mechanism (lateral/oblique ramps versus displacement gradients) that causes such fold terminations in natural structures. Bernal and Hardy investigate the 3-D geometry of growth strata that are deposited above a contractional fault-bend fold termination that forms due to along-strike slip variation on the underlying fault. Cross sections through their 3-D models reveal elements of kink-band migration and limb rotation in the growth strata as well as erosion and regional/local sedimentation on the fold crest. Strayer and Suppe explore the nature and magnitude of out-of-plane motion during along-strike propagation of a simple thrust ramp and its genetically related fold using a 3-D distinct-element approach. They induce along-strike fault growth by varying friction along a seeded zone of weakness and show that finite-displacement vectors do exhibit an out-of-plane component of motion, which they attribute to a topographically induced shear stress produced by the plunging fault-related fold.

The next three papers focus on characteristics of natural fault-related fold terminations using numerical models, fieldwork, and seismic reflection/well data. Willsey et al. infer the 3-D evolution of extensional monoclines in Baja California, Mexico using both numerical models and field data associated with the upward and lateral terminations of these structures. From these data and elastic dislocation models, they predict the listric geometry of the causative normal faults and suggest a kinematics history for their development. Aportria and Wilkerson use seismic reflection data to image the southern fault-related fold termination of the Rosario structure in the Maracaibo Basin, Venezuela, and to propose a model for its lateral development that relaxes previous assumptions regarding along-strike self-similarity. Specifically, they suggest that the Rosario structure may have developed and laterally propagated as an isolated fault ramp that, with increased shortening, grew to link with upper and lower detachments to create a hybridized fault-related fold. Begin and Spratt use 2-D reflection seismic and well data to constrain the 3-D geometry of the southern termination of the Limestone Mountain Culmination in Alberta, Canada. They interpret that the abrupt termination of the structure is a result of a NE-striking transverse fault that changes along its length from a lateral ramp to a steep tear fault.

A third group of papers extend their analyses beyond the terminations of fault-related folds to include relay zones between faults. Nicol et al. examine the geometry, formation, and destruction of relay zones associated with mesoscale thrust faults from various field areas. Using slip distributions on thrusts in relay zones, they develop a conceptual model for the 3-D growth of thrust faults and suggest that relay-zone deformation is different from deformation at an isolated thrust tip line. Peacock and Parfitt note three distinct relay ramp geometries in igneous rocks

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on Kilauea Volcano in Hawaii, USA that they infer to represent evolutionary stages of extensional relay ramps. Moreover, they suggest that monoclinal folds form at the lateral tips of active normal faults and that subsequent cracks form faults that cut across the relay ramp as throw increases on the underlying master fault. Khalil and McClay describe extensional fault-related folds related to the relay zone between the Nakheil and Hamadat faults along the NW Red Sea, Egypt. Their fieldwork and trishear numerical modeling suggest that folding developed due to along-strike displacement variations on laterally propagating and interacting faults.

The next group of papers focuses on the kinematics and geometries associated with forward-modeling and restoration of fault-related folds, both locally and regionally. Medwedeff and Krantz use physical and kinematic models to simulate extensional deformation over a 3-D oblique ramp. In both types of models, they observe non-parallel displacements that bend towards the strike of the oblique ramp segment, which they quantitatively describe using an 'oblique-inclined shear' model. In their paper, Griffiths et al. illustrate a new 3-D, flexural-slip restoration technique that preserves volume in 3-D and line length in the unfolding direction. They demonstrate this technique on an evaporite-cored contractional fold in the NW German Basin. Using a different approach, Rouby et al. perform a 3-D restoration of a listric growth fault system on the West African margin, which has experienced gravity-induced extension. They palinspastically reconstruct the 3-D geometry of the system in six incremental steps in its history as two 'rafts' progressively separate from each other. Thomas and Bayona present regional palinspastic-map and cross-section restorations through the Anniston transverse zone in Alabama, USA. Their approach allows them to recognize the origin of regional cross-strike discontinuities in thrust belt displacement patterns, and they propose that this particular transverse zone formed in response to variations in basement depth in thicknesses of the weak rocks that host the decollement.

The final group of papers provides detailed 3-D analysis of fault-related folding from a variety of tectonic settings. Bulnes and Aller describe the 3-D geometry of fault-propagation folds in the western part of the Cantabrian Zone, NW Iberian Peninsula. They propose that the along-strike variation from dominantly thrust faulting in the south to dominantly folding in the north reflects the northern plunge of a large-scale fault-propagation fold complex. Hooper et al. use 3-D reflection seismic data to interpret the regional interactions between extensional, contractional, and shale diapir provinces in the Niger Delta, West Africa. Growth strata distributions in the area are intimately linked with the 3-D evolution of the structures in each tectonic province and a detailed analysis of the sedimentary and tectonic records demonstrates the sequential development of each tectonic province and the relationships between them. Faulds et al. integrate detailed field mapping, age relationships, and paleomagnetic data to demonstrate the 3-D relationship of extensional fault-related folds in an opposed-dip accommodation zone in the Highland Range, Nevada, USA. And lastly, Carena and Suppe integrate focal mechanisms, surface geology, reflection seismic and well data, and fault-related fold modeling to generate 3-D structural models of the source regions of the 1994 Northridge and 1971 San Fernando earthquakes in California, USA. Their approach improves on existing methods for incorporating earthquake data to image active faults and helps detail previously unrecognized mega-corrugations in the Northridge fault surface.

As editors of this Special Issue, it was exciting to read and to discuss the various approaches that different researchers were employing to 'transition' from 2-D to 3-D. While occasionally we (and/or the reviewers) may have disagreed with the specifics of a particular interpretation, the techniques and methodologies presented in these 17 papers clearly provide a broad snapshot of how researchers are presently approaching the characterization of the 3-D geometries, kinematics, and dynamics of fault-related folds. Hopefully, these approaches will serve as a foundation for future work that, with improving subsurface data and visualization/modeling technologies, will help future geoscientists better understand the 3-D and 4-D development of fault-related folds.

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