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Introduction to special section: Active Fault-Related Folding: Structural Evolution, Geomorphologic Expression, Paleoseismology, and Seismic Hazards

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[1] Folds are one of the obvious and common manifestations of deformation of the continental crust, and attempts to understand the origins of these structures extend back to the very beginnings of geology as a discipline within the Earth Sciences. In particular, the relationship between faults and folds, and the manner in which fault-related folds grow and evolve through time, has been the subject of intense interest within the structural geology and tectonics communities for more than a century. Indeed, it did not take long after geologists understood the basic principles of stratigraphy and geological mapping [*Lyell*, 1830] to realize that subsurface structures could be delineated with some accuracy from surface observations, through the use of simple geometric rules [e.g., *Rogers*, 1856]. The fact that folding is associated with thrust faulting and mountain building was also recognized in the early days of structural geology, together with the necessity for large tangential displacements at the Earth's surface across fold-thrust belts [*Rogers*, 1856; *Moesch*, 1867; *Heim*, 1878; *Muller*, 1878; *Willis*, 1891; *Chamberlin*, 1910; *Argand*, 1924; *Rich*, 1934]. Moreover, geologists quickly realized how to relate quantitatively folding and horizontal shortening by assuming conservation of mass [*Chamberlin*, 1910], and soon began investigating the mechanics of folding and the relationships between fold growth and detachment faulting and thrusting through the use of analogue experiments [e.g., *Willis*, 1891] (Figure 1). The necessity of low friction along the basal detachments of fold-thrust systems was also noticed early on [*Hubbert and Rubey*, 1959].

[2] Over the past several decades, the ever increasing availability of observations from natural exposures and geophysical exploration (much of the latter conducted by the petroleum industry) has led to tremendous progress in our understanding of the kinematics and mechanics of fault-related folding, and the relationship between fault slip and fold growth, at scales ranging from individual structures to entire orogens [e.g., *Price*, 1981; *Boyer and Elliott*, 1982; *Suppe*, 1983; *Davis et al.*, 1983; *Dahlstrom*, 1990; *Suppe and Medwedeff*, 1990; *Erslev*, 1991; *Allmendinger*, 1998; *Allmendinger and Shaw*, 2000]. Collectively, these advances have facilitated modeling and quantitative analysis of the origin and evolution of fault-related folds and have fostered an understanding of fold-thrust belts as integrated mechanical systems. That understanding how fold-and-thrust systems evolve is not only of academic and economic significance has been amply demonstrated by the recent occurrence of a number of highly destructive thrust earthquakes (e.g., 1980 M_s 7.3 El Asnam, M_w 6.5 Coalinga, 1994 M_w 6.7 Northridge, 1999 M_w 7.6 Chi-Chi, and 2005 M_w 7.6 Kashmir) [*King and Vita-Finzi*, 1981; *Yielding et al.*, 1981; *Philip and Meghraoui*, 1983; *Stein and King*, 1984; *Stein and Ekstrom*, 1992; *Scientists of the USGS and SCEC*, 1994; *Yu et al.*, 2001; *Avouac et al.*, 2006]. These events have led to the growing recognition of the hazards posed by such structures to numerous urban centers around the world and highlight the need to understand the relationship between seismic slip on thrust faults and the resulting fold growth. These issues have also been the focus of much recent research by structural geologists, particularly those interested in understanding the mechanisms and rates of fold growth at timescales shorter than those provided by most exhumed examples of fold-thrust belts.

[3] Motivated by all of these issues, there has been a dramatic increase in recent research focused on active fold growth and associated fault slip. Many of these recent studies take advantage of technical advances in a number of disciplines, including (1) development of new methods to unravel the history of folding from analysis of growth strata (i.e., strata deposited above and adjacent to growing folds) [e.g., *Suppe et al.*, 1992, 1997; *Shaw and Suppe*, 1994, 1996; *Hardy et al.*, 1995; *Storti and Poblet*, 1997; *Novoa et al.*, 2000; *Shaw et al.*, 2005], (2) recognition that the kinematics of active folding and thrusting is recorded by alluvial, fluvial, and marine geomorphologic markers [e.g., *Rockwell et al.*, 1984, 1988; *Stein and King*, 1984; *Atwater et al.*, 1990; *DeCelles et al.*, 1991; *Dolan and Sieh*, 1992; *Avouac et al.*, 1993; *Bullard and Lettis*, 1993; *Molnar et al.*, 1994; *Burbank et al.*, 1996; *Jackson et al.*, 1996; *Benedetti et al.*, 2000; *Van der Woerd et al.*, 2001; *Ishiyama et al.*, 2004; *Bennett et al.*, 2005], (3) advances in our general understanding of how tectonic uplift and climatic factors influence geomorphologic processes such as alluvial deposition and river entrenchment [e.g., *Weldon*, 1986; *Bull*, 1991; *Schumm et al.*, 2000; *Burbank and Anderson*, 2001; *Poisson and Avouac*, 2004], and development of new

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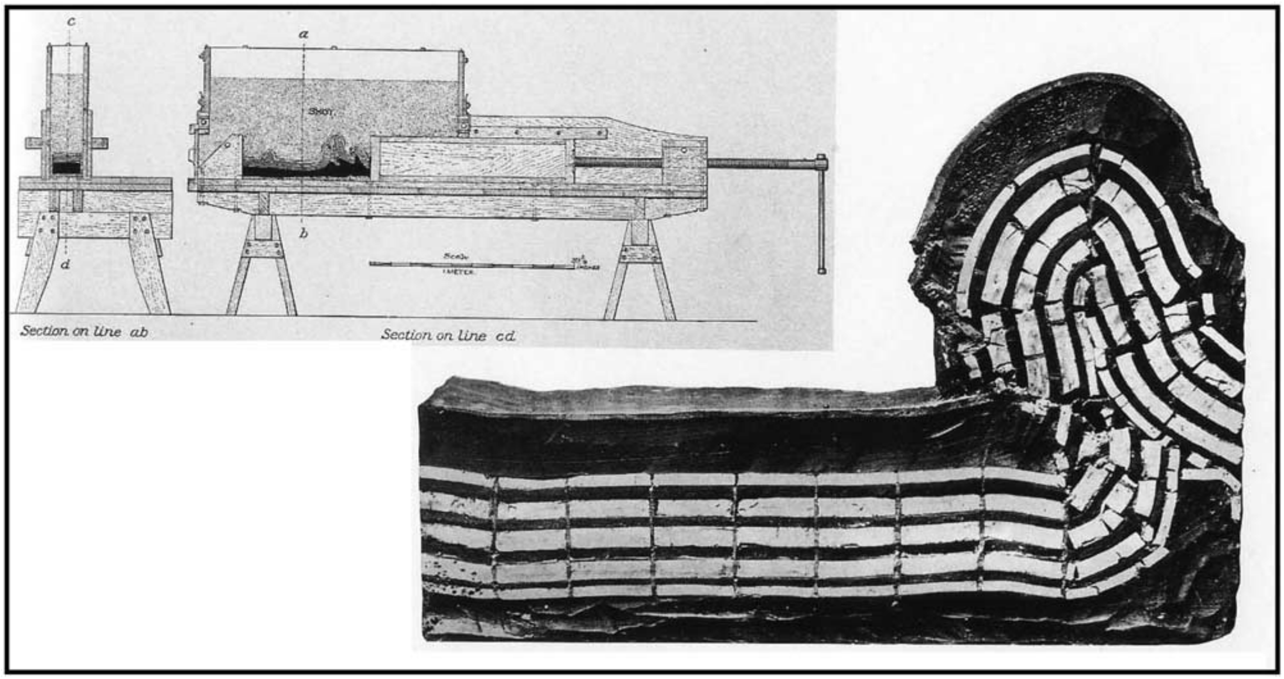

Figure 1. Sketch of the apparatus constructed by *Willis* [1891] to investigate folding mechanisms. The layers, representing geological strata, are made out of wax, and the model is overlain with lead sheets to qualitatively take into account the effect of gravity.

methods to extract quantitative tectonic signals from the geomorphologic record of folding and thrusting [*Lavé and Avouac*, 2000; *Kirby and Whipple*, 2001; *Thompson et al.*, 2002; *Lague and Davy*, 2003], (4) the use of both well-established and emerging geochronologic techniques (e.g., radiocarbon, cosmogenic radionuclide, optically stimulated luminescence dating, and magnetostratigraphy) to date growth strata and geomorphologic surfaces [*Aitken*, 1985; 1998; *Noller et al.*, 2000; *Gosse and Phillips*, 2001], (5) analysis of high-resolution seismic reflection data collected across zones of active folding above thrust faults [e.g., *Pratt et al.*, 1997, 2002; *Shaw et al.*, 2002; *Ishiyama et al.*, 2004], (6) development of new techniques to determine the paleoearthquake history of thrust faults through the recognition of ancient fold scarps [e.g., *Dolan et al.*, 2003; *Ishiyama et al.*, 2004], and (7) use of geodetic data, satellite imagery, seismic waveform modeling and precisely relocated seismicity to delineate coseismic and postseismic fault slip and associated fold growth, as well as the geometry of the causative fault [e.g., *Shaw and Shearer*, 1999; *Ji et al.*, 2001; *Johnson et al.*, 2001; *Hsu et al.*, 2002; *Dominguez et al.*, 2003; *Avouac et al.*, 2006].

[4] This special section comprises 15 articles that address these issues using active examples of fault-related folding. These studies span a wide spectrum of study, from analyses of fold growth during individual earthquakes to kinematic models of the long-term development of entire fault fold systems to mechanical studies of deformation mechanisms. The papers here are all highly multidisciplinary in nature. In particular, their focus on the behavior and evolution of active structures allows the use of geodetic, seismologic, and geomorphologic data, which are not available for ancient examples. Such data facilitate the analysis of the detailed rates, geometries, and styles of folding, which are typically much more difficult to discern in exhumed fold-thrust belts. Several of the papers focus on blind thrust faults, which are a common component of many fold-thrust systems but have generally proved to be difficult to investigate. Because these faults do not extend to the surface, analysis of their seismic behavior, and the degree to which folding above them is accommodated within discrete structural domains, as opposed to distributed deformation, has proved both problematic and controversial.

[5] Some of the specific questions that are addressed by the recent research described in this special section include the following:

[6] 1. How does the near-surface expression of folding relate to the deeper fold structure and the history of thrusting and folding?

[7] 2. Can we use data from active structures to test the validity of existing models, or are new models of fold growth required?

[8] 3. How can mechanical and analog models improve our understanding of the detailed mechanisms of fold growth?

[9] 4. How do fault-related folds grow in relation to the earthquake cycles on underlying faults? Do fault-related folds grow primarily during earthquakes, or is fold growth typically a more gradual process?

[10] 5. How do fold growth and fault slip rates vary over different timescales, ranging from seismic cycles to millions of years? How fast do folds (and by extension their causative faults) grow laterally?

[11] Many of the papers in this special section take advantage of the recent advances described above to determine the kinematics of folding and thrusting through

multidisciplinary approaches that combine subsurface imaging from geophysical techniques or well logs, geomorphologic investigations, dating of geomorphologic markers and growth strata, and structural modeling [*Amos et al.*, 2007; *Y.-G. Chen et al.*, 2007; *J. Chen et al.*, 2007; *Daëron et al.*, 2007; *Guzofski et al.*, 2007; *Hubert-Ferrari et al.*, 2007; *Okamura et al.*, 2007; *Simoes et al.*, 2007a, 2007b; *Vergés et al.*, 2007]. A number of these studies document the important result that near-surface folding associated with changes in thrust fault dip at depth (fault bend folds in the terminology of *Suppe* [1983]) is typically confined to narrow, structurally discrete zones, rather than distributed over the width of the fold, consistent with the idea that folding occurs within relatively narrow hinge zones [*Y.-G. Chen et al.*, 2007; *Guzofski et al.*, 2007; *Hubert-Ferrari et al.*, 2007; *Ishiyama et al.*, 2007; *Leon et al.*, 2007]. In particular, the geometries of growth and pregrowth strata in a number of these folds (e.g., Hubert-Ferrari et al., Leon et al.) are consistent with kinematic models of kink band migration, yet show consistent steepening of limb dips in growth strata. Perhaps most spectacularly, Y.-G. Chen et al., in their study of the thrust faults and folds that were active during the 1999 M_w 7.6 Chi-Chi, Taiwan, earthquake, document coseismic development of a discrete fold scarp formed due to deformation within a kink band associated with a deeply buried change in fault dip. This observation demonstrates that the history of coseismic deformation might be deciphered through geomorphologic observations of surface scarps and deformed fluvial and alluvial landforms, as well as through excavations of young growth strata that record the detailed history of recent folding, as described in papers by Leon et al., Ishiyama et al., and *Streig et al.* [2007]. These studies document stratigraphically and geomorphically discrete uplift, as would be expected in temporally discrete, and likely coseismic, folding events.

[12] Interpreting the geometry and deformation history of folded strata, whether at the hundred-meter scale of paleoseismic investigations, or the multiple-kilometer scale of entire folds, is not an easy task, and generally requires some sort of kinematic modeling. For example, a number of studies included in this special section describe the successful application of the trishear kinematic model [*Erslev*, 1991; *Allmendinger*, 1998] to the analysis of coseismic fold scarps (Y.-G. Chen et al., Streig et al.). When it comes to using such kinematic models to understand the long-term development of large-scale fault tip folds (i.e., folds formed at the tip of detachments or thrust faults that do not reach the surface) [*Dahlstrom*, 1990; *Poblet and McClay*, 1996; *Mitra*, 2003], the applicability of both the trishear fold model and more conventional flexural slip and kink band migration models, which has proved to be so effective in modeling fault bend folds, is limited. This is because fault tip folds generally grow as a result of heterogeneously distributed pure shear, rather than by bed-parallel simple shear, in a way that cannot be easily reproduced from the trishear model. In this regard, parameterization of the analogue model of *Bernard et al.* [2007] to allow adjustment in response to surface structural observations, geomorphologic measurements, and subsurface data (Daëron et al., Simoes et al.(b)) represents a significant step forward. The manner in which these folds grow in detail, however, and most especially the degree to which fold growth is coseismic or interseismic, remains poorly resolved. Moreover, these techniques work best in relatively young, structurally simple folds. Analysis of the kinematic and seismic behavior of more complicated examples, however, is extremely challenging. For example, Guzofski et al., as part of their analysis of the blind thrusts faults and associated folds of the western San Joaquin fold-thrust belt, show that despite the simplicity of the fold structure near the surface, the deep structure observed on seismic reflection profiles is a relatively complex wedge system. They additionally show that multiplying the uplift signature of the 1983 M_w 6.5 Coalinga earthquake by thousands of such events does not yield fold geometries that are consistent with the actual geometry of the Coalinga anticlinorium. Similarly, complex wedge geometries are also observed below the Cerro Salinas anticline, which produced M7 earthquakes along the Andean front in Argentina (Vergés et al.), and below the Quilitag anticline near Kuqa (western China) (Hubert-Ferrari et al.).

[13] Despite the past success of kinematic fold models in interpreting both geomorphologic and subsurface data, this area of research would benefit from the further development of mechanical fold models (i.e., those that take into account how the kinematics of deformation relates to stress and rock rheology). This is an important issue because a model that might seem admissible from a kinematic point of view might be unrealistic from a mechanical point of view. In practice, this is an extremely difficult issue to address from both a theoretical and a numerical standpoint [e.g., *Mandl*, 1988; *Maillot and Leroy*, 2003]. New methods, however, such as the discrete element technique described here by *Benesh et al.* [2007], offer significant promise. In their study, Benesh et al. show that the record of near-surface folding recorded by growth strata depends strongly on rock rheology, in a way that kinematic modeling might not capture correctly. This is an area where much can also be learned from the detailed analysis of analogue experiments, such as those described in the special section by Bernard et al., and earlier studies by *Davis et al.* [1983], *Malavieille* [1984], *Adam et al.* [2005], and *Maillot and Koyi* [2006]. The origin of the low basal friction suggested by the low taper angle of many thrust wedges is another issue that might benefit from insights provided by the analysis of the mechanics of active fold-thrust belts. Evidence of extremely high pore pressure within basal shear zones of subaerial thrust systems is, in fact, scarce, suggesting that the theory of *Hubbert and Rubey* [1959] may not be generally applicable in such settings. Given that the basal detachment mainly slips during recurring large earthquakes, one possibility would be that the apparent low friction would reflect a low dynamic friction, rather than a low effective friction [e.g., *Avouac*, 2003]. Low dynamic friction is a problem that has received significant recent attention, but that is not covered in this special section. It might be a specific property of thrust faults of geometric origin [e.g., *Brune et al.*, 1993; *Oglesby et al.*, 2000], or a more general property due to mechanisms that may not necessarily involve fluids [e.g., *Kanamori and Brodsky*, 2004].

[14] Collectively, the studies gathered in this special section highlight the benefits of the multidisciplinary study of active, fault-related folding, as well as the tremendous

advances made during the past several years in our understanding of the origins, evolution, mechanics, and seismic potential of fault-related folds. These studies also point to limitations of our current understanding of the mechanics of fault-related folding, providing direction for future research.

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