Foreland basin stratigraphic control on thrust belt evolution

James B. Chapman and Peter G. DeCelles
Department of Geosciences, University of Arizona, 1040 E. 4th Street, Tucson, Arizona 85721, USA

ABSTRACT

The link between orogenic activity and foreland basin stratigraphy is well established; however, potential controls by foreland basin stratigraphy on thrust belt architecture have not been fully evaluated. Mechanical properties of typical foreland basin stratigraphic successions influence the structural development of fold-thrust belts in predictable ways. Fundamental features of foreland basins include the onset of rapid subsidence and deposition of a coarsening-upward sedimentary succession. In the lower part of this succession are fine-grained, distal foreland basin deposits. Enlargement of the orogenic wedge through frontal accretion incorporates the foreland basin strata into the thrust belt, and distal foreland basin depositional units may be preferentially exploited as a thrust detachment zone, resulting in multiple detachment levels. We propose that foreland basin stratigraphic architecture has significant influence on the structural development of thrust belts and that, by extension, processes that influence foreland basin sedimentation may ultimately influence orogenic evolution far removed in time and space.

INTRODUCTION

Frontal parts of most fold-thrust belts consist of structurally cannibalized foreland basin successions. Whereas robust explanations for patterns of foreland basin sedimentation and stratigraphy have been developed (e.g., Quinlan and Beaumont, 1984; Allen et. al., 1991; Sinclair, 1997; Liu et. al., 2005), and numerous structural studies demonstrate the importance of mechanical properties of the stratigraphic column in controlling deformation within a fold-thrust belt (e.g., Woodward and Rutherford, 1989; Pfiffner, 1993), the connection between foreland stratigraphy and structural architecture has not been systematically explored. In this study we synthesize data from several foreland basins and fold-thrust belts to demonstrate the relationship between stratigraphic architecture of the basin and structural style of the adjacent fold-thrust belt, highlighting the formation of intermediate-level detachments (i.e., regional detachments that are at a higher structural level than the basal décollement). We find that detachments preferentially form in fine-grained, distal foreland basin deposits. The presence of multiple detachments within thrust belts affects structural development, including partially decoupled shortening and crustal thickening without deep exhumation (Ruh et. al., 2012). The implication of this relationship is that characteristic patterns of foreland basin sedimentation that are products of orogenic evolution may in turn have significant control over orogenic evolution.

FORELAND BASIN STRATIGRAPHIC ARCHITECTURE

Foreland basins include wedge-top, foredeep, forebulge, and back-bulge depozones that develop as a result of isostatic adjustment of the lithosphere during loading by the adjacent fold-thrust belt (DeCelles and Giles, 1996). Synthetic stratigraphic sequences have been generated based on the horizontal migration of these depozones during orogenic growth (e.g., Quinlan and Beaumont, 1984; Flemings and Jordan, 1989). At the cratonward edge of a uniformly advancing foreland basin system, limited subsidence and sedimentation initially occur in the back-bulge depozone, which typically consists of fine-grained shallow-marine to nonmarine sediment (Flemings and Jordan, 1989; DeCelles and Giles, 1996). Although net sediment accumulation in a back-bulge depozone is at least an order of magnitude less than that of the foredeep, back-bulge depozones are roughly twice the width of the foredeep (DeCelles and Giles, 1996). In some instances, the record of sedimentation in the back-bulge depozone is eroded by passage of the forebulge (Crampton and Allen, 1995). The transition from forebulge to distal foredeep deposition is characterized by accelerating subsidence and limited sediment supply (Flemings and Jordan, 1989). Distal foredeep sedimentation often represents maximum water depths and comprises fine-grained clastic material or carbonate pelagic sediments (Sinclair, 1997). Following deposition of the distal foredeep unit, sediment supply and caliber increase and water depth decreases as the proximal foredeep migrates toward the craton.

DETACHMENT FORMATION AND DEFORMATION MECHANISMS

The observed structural geometry in fold-thrust belts is often used to divide the stratigraphic succession into structural lithic units that tend to deform as a mechanically coherent package (Currie et. al., 1962; Woodward and Rutherford, 1989). Separating these structural lithic units are mechanically incompetent (low shear strength) stratigraphic layers that contain detachments. The central premise of this study is that fine-grained, distal foreland basin deposits (back-bulge to distal foredeep depozone) frequently contain detachments and tend to separate structural lithic units in fold-thrust belts. In addition to their mechanical incompetence, fine-grained, low-permeability, distal foreland units are commonly overpressured as a result of disequilibrium compaction following rapid burial by synorogenic units (Swarbrick and Osborne, 1998).

Effective stresses are thought to approach yield stress several tens of kilometers into the foreland ahead of the leading thrust ramp (van der Pluijm et. al., 1997). Rocks ahead of the deformation front undergo internal strain before bulk failure, manifested as plastic hardening and then plastic softening for Coulomb materials (Mitra et. al., 1984). For incompetent layers, this plastic softening extends significantly farther into the foreland and can include small amounts of layer-parallel displacement, which accommodates plastic deformation and pressure solution in the competent layers (Mitra et. al., 1984; Yonkee and Weil, 2010). The formation of a new thrust sheet in the foreland basin depends on the initial shear failure of a relatively competent layer within the foreland basin succession. Once the competent layer fails, the shear propagates until it intersects an incompetent layer already near or at yield stress to form a new detachment and thrust sheet (Eisenstadt and De Paor, 1987; Davis and Engelder, 1985). In thrust belts with rheological layering, intermediate-level detachments may develop within these incompetent layers in addition to the basal décollement. This phenomenon is often revealed at the front of a thrust belt where the basal décollement ramps up to an intermediate-level detachment at a higher stratigraphic level (time, T, = 1; Fig. 1). With continued shortening, the basal décollement will return to a lower structural position and a duplex system may form at depth, isolating the intermediate-level detachment as a roof thrust in a classic duplex system (Mitra, 1986) (T = 2; Fig. 1). In the following we show that these intermediate-level detachments are commonly initiated in distal foreland deposits.

CASE STUDIES

The first stage (T = 1) in the kinematic sequence described here and illustrated in Figure 1 is exemplified by the Main Frontal thrust in the Himalayan thrust belt, which ramps up to the base of Subhimalayan synorogenic sedimentary rocks that represent distal foreland basin sedimentation (DeCelles et. al., 1998; Mugnier et. al., 1999). The Ouachita orogenic system (southern United States) provides an example of the second stage in the kinematic sequence (T = 2; Fig. 1), where an intermediate-level detachment in the distal foreland basin units, the Tesnus

GEOLOGY, Data Repository item 0000000 | doi:10.1130/G36597.1

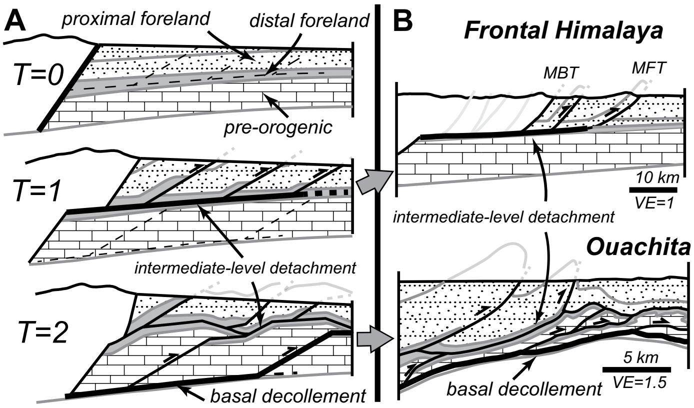

Figure 1. A: Schematic forward model for shortening in a thrust belt with an intermediate-level detachment. During orogenic loading, an undeformed, rheologically layered foreland basin develops (time, T, = 0). As the foreland is caught up in thrust belt deformation, shortening steps up from the basal décollement to an intermediate-level detachment that is located in fine-grained, distal foreland depositional units (T = 1). With continued shortening, the stratigraphic succession below the intermediate-level detachment is also deformed resulting in a duplex and a folded fault surface (T = 2). B: Examples of thrust belts that display the geometry and detachment positions described in A. The frontal Himalaya (modified from DeCelles et. al., 1998) corresponds to stage T = 1 and the Marathon segment of the Ouachita (southern United States) (modified from Chapman and McCarty, 2013) corresponds to stage T = 2. MBT—Main Boundary thrust; MFT—Main Frontal thrust; VE—vertical exaggeration.

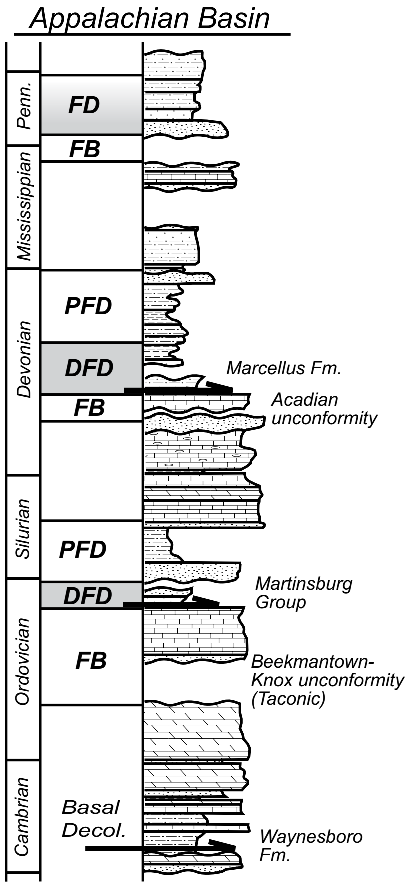

Figure 2. Generalized stratigraphic column for the central Appalachian Basin (eastern United States; modified from Swezey, 2002) that shows the relationship between depozone and detachment position. FB—forebulge, DFD—distal foredeep, PFD—proximal foredeep, FD—foredeep, Decol—décollement, Penn—Pennsylvanian, Fm.—formation.

Formation and Stanley Group, was folded by later deformation resulting from slip along the basal décollement and duplex formation (Chapman and McCarty, 2013).

In both the Himalayan and Ouachita examples, the formation of an intermediate-level detachment in a fold-thrust belt and the deposition of foreland basin sediments are temporally related to the same orogenic event. However, some foreland basins contain several stratigraphic units vertically and along strike that represent distal foreland sedimentation at different times and locations associated with multiple orogenic events. For example, the central Appalachians (eastern United States) underwent at least three major orogenic events during the Paleozoic, including the Taconic, Acadian, and Alleghanian orogenies (Hatcher et. al., 1989), each of which produced clastic wedges with the characteristic stratigraphic architecture of foreland basin systems (Ettensohn, 1994) (Fig. 2). This is a complication to the simple model described here, wherein a single foreland depozone is exploited as an intermediate-level detachment in the same orogenic event, but it presents an opportunity to test the correlation between foreland basin depozone and fold-thrust belt architecture. We predict that the distal foreland units will be preferentially exploited as intermediate-level detachments in composite foreland basins.

Three regional detachments exist in the central Appalachian fold-thrust belt: a basal décollement in the Cambrian Waynesboro Formation and two detachments at intermediate structural levels in the middle Ordovician Martinsburg Group and lower Devonian shale including the Marcellus Formation (Perry, 1978) (Fig. 2). Detachments in the Martinsburg Group and lower Devonian shale were active during the Alleghanian orogeny, and occur within shale-rich, distal foredeep units deposited during the older Taconic and Acadian orogenies, respectively (Ettensohn, 1994). In some places in the central Appalachians, both the Devonian and Ordovician distal foredeep detachments are present, resulting in multiple stacked duplexes (Mitra, 1986).

Similar multidetachment patterns are observed in the Canadian Rocky Mountains and the central Andes. Numerous bedding-parallel detachments are present within the Alberta thrust belt, the most prominent of which are located within the Mississippian Banff Formation, the Jurassic Fernie Group, the middle Cretaceous Alberta Group, and the upper Cretaceous Bearpaw Formation (Spratt and Lawton, 1996). Except for the detachment in the Banff Formation, all of these detachments correspond to shale intervals at the base of a foreland basin sequence (Cant and Stockmal, 1989). In the Andes, an intermediate-level detachment is present in the Devonian Los Monos and Icla Formations (McQuarrie, 2002), which are distal foreland deposits related to Paleozoic terrane accretion events (Isaacson and Díaz-Martínez, 1995).

DISCUSSION AND CONCLUSIONS

To demonstrate the relationship between distal foreland depozones and intermediate-level detachments, we plot major detachment positions and depozones for several well-known thrust belts (Fig. 3). There is a correlation between the position of intermediate-level detachments and distal foreland depozones (distal foredeep to backbulge) (Fig. 3). The range of possible detachment positions in fold-thrust belts is not limited to distal foreland deposits. Prominent exceptions to this relationship are the Pyrenees (Spain) and Zagros (Iran) thrust belts, which are dominated by multiple detachments in evaporites that predate their respective foreland basin systems (Vergés et. al., 1992; Sherkati et. al., 2006). The presence of evaporite alone, however, is not inconsistent with the model described. For example, a regional intermediate-level detachment occurs within evaporites of the Arapien Formation in the western U.S. Cordillera (DeCelles and Coogan, 2006), possibly deposited in a back-bulge depozone. Similarly, the structurally highest regional detachment in the Zagros occurs in Miocene evaporites (O'Brien, 1957; Sherkati et. al., 2006), which were deposited in the distal foreland basin system (Fakhari et. al., 2008).

Accepting the premise that thrust belt architecture is in many instances linked to a characteristic foreland stratigraphy, we can begin to explore potential new relationships between foreland basins and orogenic growth.

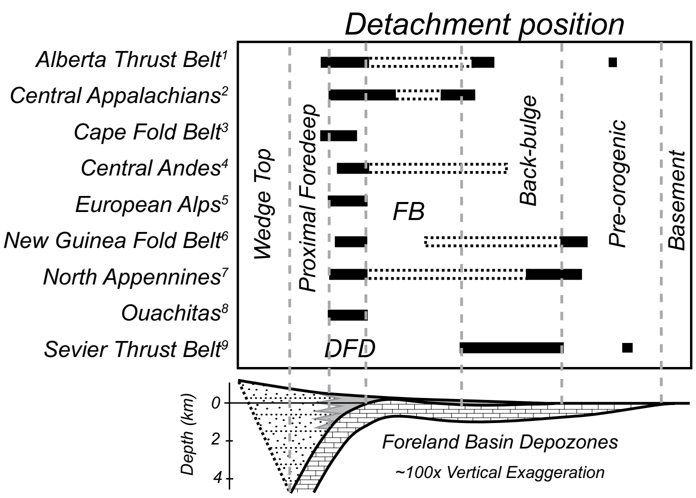

Figure 3. Chart of intermediate-level detachment position and depozone for selected thrust belts. Basal décollements are not shown. Detachment positions commonly occur in distal foredeep to back-bulge depozones. Schematic foreland basin depozones are shown in cross-sectional view below the chart. DFD—distal foredeep, FB—forebulge. Data are from: 1—Fermor and Moffat (1992); 2—Perry (1978); 3—Tankard et. al. (2009); 4—McQuarrie (2002); 5—Homewood et. al. (1986); 6—Hill et. al. (2004); 7—Barchi et. al. (2001); 8—Chapman and McCarty (2013); 9—DeCelles and Coogan (2006). Lithology symbols as in Figure 1.

One such link arises from the well-documented connection between multiple detachment levels and structural style. Numerical (Stockmal et. al., 2007) and analog (Ruh et. al., 2012) modeling suggests that multiple detachments are conducive to enhanced basal underplating, which limits exhumation of deeper structural levels. This relationship may help explain areas of crustal thickening with limited exhumation. For example, Late Cretaceous structural thickening in the Lhasa terrane in the Tibetan Plateau was decoupled between the upper and middle crust by a detachment in the basal Takena Formation, which was deposited in a distal foredeep depozone (Leier et. al., 2007; Volkmer et. al., 2007). Volkmer et. al. (2007) proposed that the process of decoupled shortening in the upper crust may be common throughout the Tibetan Plateau; if true, this suggests that characteristic foreland stratigraphy may have played a role in the mode of thickening of Tibetan crust.

The link between thrust belt structure and foreland basin stratigraphic architecture can also provide a bridge to evaluate additional geodynamic parameters and processes. The influences on foreland sedimentation are myriad, but two key parameters are lithospheric flexural rigidity and climate. High-rigidity lithosphere produces wide, shallow foreland basins, whereas low-rigidity lithosphere results in narrow and deep foredeeps (Molnar and Lyon-Caen, 1988). Watts (1992) proposed that flexure of lithosphere with initial low rigidity could result in rapid subsidence that outpaces sediment availability during early foreland basin sedimentation. In turn, thrust belts developed on low-rigidity lithosphere may be prone to multiple levels of detachment in relatively thick but localized distal foreland basin deposits, whereas thrust belts formed on more rigid lithosphere may be prone to a single, regional, intermediate-level detachment associated with widespread but thin back-bulge and distal foredeep deposits.

Climatic changes are often invoked to explain structural adjustment in thrust belt orogens (e.g., Whipple, 2009). However, if climate affected foreland basin depozones at the time of deposition, then it is possible that the subsequent structural development may reflect these older climatic signals. The prevailing wind direction and amount of orographic precipitation can have a pronounced effect on erosion, sediment transport, and patterns of foreland deposition (Willett, 1999). Windward-facing orogens may have reduced topographic loads and increased sediment supply, resulting in poorly developed distal foreland depozones, whereas leeward-facing orogens may have well-developed, fine-grained, distal foreland sediments (Hoffman and Grotzinger, 1993).

The implications for the examples briefly discussed above are that leeward-facing orogens and orogens built upon low-strength lithosphere should have more well-developed distal foreland depozones that are conducive to a specific thrust belt geometry involving intermediate-level detachments, in turn favorable to partially decoupled shortening in the upper crust, basal underplating, duplex formation, and potentially limited deep exhumation. Though generally untested, these relationships raise the prospect of other potential correlations that may be inferred by examining the cascading links among the stratigraphic architecture of foreland basins, the structural style of fold-thrust belts, and their ultimate influence on orogenic evolution.

ACKNOWLEDGMENTS

Constructive reviews and suggestions by editor Rónadh Cox, Mary Beth Gray, Sanjeev Gupta, and an anonymous reviewer helped us to improve the manuscript. Support for components of this work was provided by National Science Foundation grant 1140068.

REFERENCES CITED

Allen, P.A., Crampton, S.L., and Sinclair, H.D., 1991, The inception and early evolution of the North Alpine foreland basin, Switzerland: Basin Research, v. 3, p. 143–163, doi:10.1111/j.1365-2117.1991.tb00124.x.

Barchi, M., Landuzzi, A., Minelli, G., and Pialli, G., 2001, Outer Northern Apennines, *in* Vai, G.B., and Martini, I.P., eds., Anatomy of an orogen: The Apennines and adjacent Mediterranean Basin: London, Kluwer Publishers, p. 215–254.

Cant, D.J., and Stockmal, G.S., 1989, The Alberta foreland basin: Relationship between stratigraphy and Cordilleran terrane-accretion events: Canadian Journal of Earth Sciences, v. 26, p. 1964–1975, doi:10.1139/e89-166.

Chapman, J.B., and McCarty, R.S., 2013, Detachment levels in the Marathon fold and thrust belt, west Texas: Journal of Structural Geology, v. 49, p. 23–34, doi:10.1016/j.jsg.2013.01.007.

Crampton, S.L., and Allen, P.A., 1995, Recognition of forebulge unconformities associated with early stage foreland basin development: Example from north Alpine foreland basin: American Association of Petroleum Geologists Bulletin, v. 79, p. 1495–1514.

Currie, J.B., Patnode, H.W., and Trump, R.P., 1962, Development of folds in sedimentary strata: Geological Society of America Bulletin, v. 73, p. 655–674, doi:10.1130/0016-7606(1962)73[655:DOFISS]2.0.CO;2.

Davis, D.M., and Engelder, T., 1985, The role of salt in fold-and-thrust belts: Tectonophysics, v. 119, p. 67–88, doi:10.1016/0040-1951(85)90033-2.

DeCelles, P.G., and Coogan, J.C., 2006, Regional structure and kinematic history of the Sevier fold-thrust belt, central Utah: Implications for the Cordilleran magmatic arc and foreland basin system: Geological Society of America Bulletin, v. 118, p. 841–864, doi:10.1130/B25759.1.

DeCelles, P.G., and Giles, K.A., 1996, Foreland basin systems: Basin Research, v. 8, p. 105–123, doi:10.1046/j.1365-2117.1996.01491.x.

DeCelles, P.G., Gehrels, G.E., Quade, J., Ojha, T.P., Kapp, P.A., and Upreti, B.N., 1998, Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold-thrust belt, western Nepal: Geological Society of America Bulletin, v. 110, p. 2–21, doi:10.1130/0016-7606(1998)110<0002:NFBDEU>2.3.CO;2.

Eisenstadt, G., and De Paor, D.G., 1987, Alternative model of thrust-fault propagation: Geology, v. 15, p. 630–633, doi:10.1130/0091-7613(1987)15<630:AMOTP>2.0.CO;2.

Ettensohn, F.R., 1994, Tectonic control on the formation and cyclicity of major Appalachian unconformities and associated stratigraphic sequences, *in* Dennison, J.M., and Ettensohn, F.R., eds., Tectonic and eustatic controls on sedimentary cycles: Society for Sedimentary Geology (SEPM) Concepts in Sedimentology and Paleontology Volume 4, p. 217–242, doi:10.2110/csp.94.04.0217.

Fakhari, M.D., Axen, G.J., Horton, B.K., Hassanzadeh, J., and Amini, A., 2008, Revised age of proximal deposits in the Zagros foreland basin and implications for Cenozoic evolution of the High Zagros: Tectonophysics, v. 451, p. 170–185, doi:10.1016/j.tecto.2007.11.064.

Fermor, P.R., and Moffat, I.W., 1992, Tectonics and structure of the Western Canada foreland basin, *in* Macqueen, R.W., and Leckie, D.A., eds., Foreland basins and fold belts: American Association of Petroleum Geologists Memoir 55, p. 81–105.

Flemings, P.B., and Jordan, T.E., 1989, A synthetic stratigraphic model of foreland basin development: Journal of Geophysical Research, v. 94, p. 3851–3866, doi:10.1029/JB094iB04p03851.

Hatcher, R.D., Jr., Thomas, W.A., Geiser, P.A., Snoke, A.W., Mosher, S., and Wiltschko, D.V., 1989, Alleghanian orogen, *in* Hatcher, R.D., Jr., et. al., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 233–318.

Hill, K.C., Keetley, J.T., Kendrick, R.D., and Sutriyono, E., 2004, Structure and hydrocarbon potential of the New Guinea Fold Belt, *in* McClay, K.R., ed., Thrust tectonics and hydrocarbon systems: American Association of Petroleum Geologists Memoir 82, p. 494–514.

Hoffman, P.F., and Grotzinger, J.P., 1993, Orographic precipitation, erosional unloading, and tectonic style: Geology, v. 21, p. 195–198, doi:10.1130/0091-7613(1993)021<0195:OPEUAT>2.3.CO;2.

Homewood, P., Allen, P.A., and Williams, G.D., 1986, Dynamics of the Molasse Basin of western Switzerland, *in* Allen, P.A., and Homewood, P., eds., Foreland basins: International Association of Sedimentologists Special Publication 8: Oxford, Blackwell Scientific Publications, p. 199–219, doi:10.1002/9781444303810.ch10.

Isaacson, P.E., and Díaz-Martínez, E., 1995, Evidence for a middle-late Paleozoic foreland basin and significant paleolatitudinal shift, Central Andes, *in* Tankard, A.J., et. al., eds., Petroleum basins of South America: American Association of Petroleum Geologists Memoir 62, p. 231–249.

Leier, A.L., DeCelles, P.G., Kapp, P., and Ding, L., 2007, The Takena Formation of the Lhasa terrane, southern Tibet: The record of a retro-arc foreland basin: Geological Society of America Bulletin, v. 119, p. 31–48, doi:10.1130/B25974.1.

Liu, S.-F., Nummedal, D., Yin, P.-G., and Luo, H.-J., 2005, Linkage of Sevier thrusting episodes and Late Cretaceous foreland basin megasequences across southern Wyoming (USA): Basin Research, v. 17, p. 487–506, doi:10.1111/j.1365-2117.2005.00277.x.

McQuarrie, N., 2002, The kinematic history of the central Andean fold-thrust belt, Bolivia: Implications for building a high plateau: Geological Society of America Bulletin, v. 114, p. 950–963, doi:10.1130/0016-7606(2002)114<0950:TKHOTC>2.0.CO;2.

Mitra, G., Yonkee, W.A., and Gentry, D., 1984, Solution cleavage and its relationship to major structures in the Idaho-Utah-Wyoming thrust belt: Geology, v. 12, p. 354–358, doi:10.1130/0091-7613(1984)12<354:SCAIRT>2.0.CO;2.

Mitra, S., 1986, Duplex structures and imbricate thrust systems: Geometry, structural position and hydrocarbon potential: American Association of Petroleum Geologists Bulletin, v. 70, p. 1087–1112.

Molnar, P., and Lyon-Caen, H., 1988, Some simple physical aspects of the support, structure, and evolution of mountain belts, *in* Clark, Jr., S.P., et. al., eds., Processes in continental lithospheric deformation: Geological Society of America Special Paper 218, p. 179–208, doi:10.1130/SPE218-p179.

Mugnier, J.L., Leturmy, P., Mascle, G., Huyghe, P., Chalaron, E., Vidal, G., Husson, L., and Delcaillau, B., 1999, The Siwaliks of western Nepal: Geometry and kinematics: Journal of Asian Earth Sciences, v. 17, p. 629–642, doi:10.1016/S1367-9120(99)00038-3.

O'Brien, C.A.E., 1957, Salt diapirism in south Persia: Geologie en Mijnbouw, v. 19, p. 357–376.

Perry, W.J., Jr., 1978, Sequential deformation in the central Appalachians: American Journal of Science, v. 278, p. 518–542, doi:10.2475/ajs.278.4.518.

Pfiffner, O.A., 1993, The structure of the Helvetic nappes and its relation to the mechanical stratigraphy: Journal of Structural Geology, v. 15, p. 511–521, doi:10.1016/0191-8141(93)90145-Z.

Quinlan, G.M., and Beaumont, C., 1984, Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the eastern interior of North-America: Canadian Journal of Earth Sciences, v. 21, p. 973–996, doi:10.1139/e84-103.

Ruh, J.B., Kaus, B.J.P., and Burg, J.P., 2012, Numerical investigation of deformation mechanics in fold-and-thrust belts: Influence of rheology of single and multiple décollements: Tectonics, v. 31, TC3005, doi:10.1029/2011TC003047.

Sherkati, S., Letouzey, J., and Frizon de Lamotte, D., 2006, Central Zagros fold-thrust belt (Iran): New insights from seismic data, field observation, and sandbox modeling: Tectonics, v. 25, TC4007, doi:10.1029/2004TC001766.

Sinclair, H.D., 1997, Tectonostratigraphic model for underfilled peripheral foreland basins: An Alpine perspective: Geological Society of America Bulletin, v. 109, p. 324–346, doi:10.1130/0016-7606(1997)109<0324:TMFUPF>2.3.CO;2.

Spratt, D.A., and Lawton, D.C., 1996, Variations in detachment levels, ramp angles and wedge geometries along the Alberta thrust front: Bulletin of Canadian Petroleum Geology, v. 44, p. 313–323.

Stockmal, G.S., Beaumont, C., Nguyen, M., and Lee, B., 2007, Mechanics of thin-skinned fold-and-thrust belts: Insights from numerical models, *in* Sears, J.W., et. al., eds., Whence the mountains? Inquiries into the evolution of orogenic systems: A volume in honor of Raymond A. Price: Geological Society of America Special Paper 433, p. 63–98, doi:10.1130/2007.2433(04).

Swarbrick, R.E., and Osborne, M.J., 1998, Mechanisms that generate abnormal pressures: An overview, *in* Law, B.E., et. al., eds., Abnormal pressures in hydrocarbon environments: American Association of Petroleum Geologists Memoir 70, p. 13–34, doi:10.1306/M70615C2.

Swezey, C., 2002, Regional stratigraphy and petroleum systems of the Appalachian Basin, North America: U.S. Geological Survey Scientific Investigations Map I-2978.

Tankard, A., Welsink, H., Aukes, P., Newton, R., and Stettler, E., 2009, Tectonic evolution of the Cape and Karoo basins of South Africa: Marine and Petroleum Geology, v. 26, p. 1379–1412, doi:10.1016/j.marpetgeo.2009.01.022.

van der Pluijm, B.A., Craddock, J.P., Graham, B.R., and Harris, J.H., 1997, Paleostress in cratonic North America: Implications for deformation of continental interiors: Science, v. 277, p. 794–796, doi:10.1126/science.277.5327.794.

Vergés, J., Muñoz, J.A., and Martínez, A., 1992, South Pyrenean fold-and-thrust belt: Role of foreland evaporitic levels in thrust geometry, *in* McClay, K.R., ed., Thrust tectonics: London, Chapman and Hall, p. 255–264, doi:10.1007/978-94-011-3066-0_23.

Volkmer, J.E., Kapp, P., Guynn, J.H., and Lai, Q., 2007, Cretaceous–Tertiary structural evolution of the north central Lhasa terrane, Tibet: Tectonics, v. 26, TC6007, doi:10.1029/2005TC001832.

Watts, A.B., 1992, The effective elastic thickness of the lithosphere and the evolution of foreland basins: Basin Research, v. 4, p. 169–178, doi:10.1111/j.1365-2117.1992.tb00043.x.

Whipple, K.X, 2009, The influence of climate on the tectonic evolution of mountain belts: Nature Geoscience, v. 2, p. 97–104, doi:10.1038/ngeo413.

Willett, S.D., 1999, Orogeny and orography: The effects of erosion on the structure of mountain belts: Journal of Geophysical Research, v. 104, p. 28,957–28,981, doi:10.1029/1999JB900248.

Woodward, N.B., and Rutherford, E., Jr., 1989, Structural lithic units in external orogenic zones: Tectonophysics, v. 158, p. 247–267, doi:10.1016/0040-1951(89)90327-2.

Yonkee, W.A., and Weil, A.B., 2010, Reconstructing the kinematics of curved mountain belts: Internal strain patterns in the Wyoming salient, Sevier thrust belt, U.S: Geological Society of America Bulletin, v. 122, p. 24–49, doi:10.1130/B26484.1.

Manuscript received 9 January 2015
Revised manuscript received 16 April 2015
Manuscript accepted 17 April 2015

Printed in USA