Structural and clumped-isotope constraints on the mechanisms of displacement along low-angle detachments

Thesis by

Erika Swanson

In Partial Fulfillment of the Requirements for the Degree

of

Doctor of Philosophy

CALIFORNIA INSTITUTE OF TECHNOLOGY

Pasadena, California

2015

(Defended August 4, 2014)

ACKNOWLEDGEMENTS

The thesis has been made possible by a large number of people, who have helped in a variety of ways. I am very grateful for the help and advice provided by my advisers, Brian Wernicke and John Eiler, for providing the opportunity to work on cutting-edge new techniques, and their applications to the field of structural geology. Brian Wernicke has been enormously helpful in providing geologic context for the studies here, has provided great insights in the field, and helped promote my work in the broader geologic community. I am very grateful for John Eiler and his work on clumped isotope thermometry, without which half this thesis would not be possible.

I would also like to thank Jean-Philippe Avouac, in particular for teaching about the relative contributions of seismic and aseismic slip on faults. Readings and discussions for that class impressed on me that slip along faults occurs in a wide variety of ways, not just from brittle failure during earthquakes. Jason Saleeby showed me what ductile deformation looks like in the field, and discussions with him in Hawaii drastically improved my understanding of volcanic processes.

I would also like to thank Tom Hauge, who was an incredible resource for finding the best outcrops within the Heart Mountain area for both clumped-isotope thermometry sampling and structural observations. In addition, he was a great person to discuss ideas with, and helped me understand the historical context of the Heart Mountain problem.

Field work is often logistically difficult, and a number of field assistants took time out of their own work to help me in the field. Tom Hauge, Hamik Mukelyan, Adam Subhas, Jason Price, Luca Malatesta, Frank Sousa, and Steven Losh all helped trips run well. For the times that didn’t run so smoothly, I am grateful for the assistance of Terry Gennaro, Mark Garcia, and the Clark County search and rescue for getting all people and trucks home safely. Work within the Meadow Valley Mountains would not have been possible without help from Union Pacific for use of their roads, and their employees for unlocking gates, and jump starting our truck.

Nami Kitchen provided amazing analytical support for obtaining isotopic data. Her ability to figure out what’s broken and fix it quickly is incredible. Chi Ma provided a great deal of support for use of the SEM. Steve Skinner, Kristel Chanard, Jason Price, and Daven Quinn have all been fantastic officemates, providing support for tough days, and celebrating successes with me. In addition, an enormous number of other faculty, staff, and colleagues provided support and insightful conversations that have contributed to my development as a geologist, numbering too many to list here.

Last but certainly not least, I would like to thank my friends and family for their support in everything I do.

ABSTRACT

Despite years of research on low-angle detachments, much about them remains enigmatic. This thesis addresses some of the uncertainty regarding two particular detachments, the Mormon Peak detachment in Nevada and the Heart Mountain detachment in Wyoming and Montana.

Constraints on the geometry and kinematics of emplacement of the Mormon Peak detachment are provided by detailed geologic mapping of the Meadow Valley Mountains, along with an analysis of structural data within the allochthon in the Mormon Mountains. Identifiable structures well suited to constrain the kinematics of the detachment include a newly mapped, Sevier-age monoclinal flexure in the hanging wall of the detachment. This flexure, including the syncline at its base and the anticline at its top, can be readily matched to the base and top of the frontal Sevier thrust ramp, which is exposed in the footwall of the detachment to the east in the Mormon Mountains and Tule Springs Hills. The ~12 km of offset of these structural markers precludes the radial sliding hypothesis for emplacement of the allochthon.

The role of fluids in the slip along faults is a widely investigated topic, but the use of carbonate clumped-isotope thermometry to investigate these fluids is new. Faults rocks from within ~1 m of the Mormon Peak detachment, including veins, breccias, gouges, and host rocks, were analyzed for carbon, oxygen, and clumped-isotope measurements. The data indicate that much of the carbonate breccia and gouge material along the detachment is comminuted host rock, as expected. Measurements in vein material indicate that the fluid system is dominated by meteoric water, whose temperature indicates circulation to substantial depths (c. 4 km) in the upper crust near the fault zone.

Slip along the subhorizontal Heart Mountain detachment is particularly enigmatic, and many different mechanisms for failure have been proposed, predominantly involving catastrophic failure. Textural evidence of multiple slip events is abundant, and include multiple brecciation events and cross-cutting clastic dikes. Footwall deformation is observed in numerous exposures of the detachment. Stylolitic surfaces and alteration textures within and around “banded grains” previously interpreted to be an indicator of high-temperature fluidization along the fault suggest their formation instead via low-temperature dissolution and alteration processes. There is abundant textural evidence of the significant role of fluids along the detachment via pressure solution. The process of pressure solution creep may be responsible for enabling multiple slip events on the low-angle detachment, via a local rotation of the stress field.

Clumped-isotope thermometry of fault rocks associated with the Heart Mountain detachment indicates that despite its location on the flanks of a volcano that was active during slip, the majority of carbonate along the Heart Mountain detachment does not record significant heating above ambient temperatures (c. 40-70°C). Instead, cold meteoric fluids infiltrated the detachment breccia, and carbonate precipitated under ambient temperatures controlled by structural depth. Locally, fault gouge does preserve hot temperatures (>200°C), as is observed in both the Mormon Peak detachment and Heart Mountain detachment areas. Samples with very hot temperatures attributable to frictional shear heating are present but rare. They appear to be best preserved in hanging wall structures related to the detachment, rather than along the main detachment.

Evidence is presented for the prevalence of relatively cold, meteoric fluids along both shallow crustal detachments studied, and for protracted histories of slip along both detachments. Frictional heating is evident from both areas, but is a minor component of the preserved fault rock record. Pressure solution is evident, and might play a role in initiating slip on the Heart Mountain fault, and possibly other low-angle detachments.

TABLE OF CONTENTS

LIST OF TABLES

Number *Page*

Chapter 2

Chapter 3

Chapter 4

Chapter 5

LIST OF ILLUSTRATIONS

Number *Page*

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 1

Introduction

Slip on shallowly dipping detachments is one of the longest-debated puzzles in structural geology. Coulombic failure laws, derived from laboratory experiments, predict failure as a function of the ratio of shear stress to normal stress. These laws also describe how the orientations of failure planes lie within a narrow range, at an angle of approximately 30° to the maximum compressional stress. Classic Andersonian theory applies these failure laws to the earth's crust, and specifies that one of the principal stress orientations be vertical, due to the negligible shear tractions along the surface of the earth. Under these conditions, extensional faults within the upper crust occur when the maximum compressive stress is vertical, and these faults would be expected to dip 60°.

Observed faults do not always obey this relationship, however: extensional detachments (nominally, low-angle normal faults with displacements of kilometers to tens of kilometers) are widely described in the literature (e.g. Armstrong, 1972; Davis and Coney, 1979; Pierce, 1980; Allmendinger et al., 1983; Wernicke et al. 1985; Hauge, 1985, 1990; Lister and Davis, 1989; Scott and Lister, 1992; Wernicke, 1995; Morley, 2014). These planes occur at angles that are some 20-40° more shallow than predicted by Andersonian mechanics.

Attempts at explaining slip on unfavorably oriented faults often invoke effects in some way related to pore fluids, as originally proposed by Hubbert and Rubey (1959) and Rubey and Hubbert (1959). They proposed that an impermeable seal above the fault traps pressurized fluid, reducing the effective normal stress and making it easier to slip. The requirement of an impermeable hanging wall was seen as problematic by, for example Wilson (1970), who observed that faults tend to have highly fractured and permeable hanging walls. He preferred an explanation invoking the presence of inherently weak material at the base of a fault, like shale or salt. Most current explanations of extensional slip on low-angle faults also invoke some form of fluid pressure and/or weak materials along the faults. Although both these mechanisms can make slip easier once a fault is formed, neither makes previously unfavorable angles more favorable at the onset of faulting (e.g. Collettini, 2011). These mechanical difficulties have led some geologists to question the very existence of low-angle normal faults, even on geological grounds (e.g. Miller et al, 1999; Anders et al, 2006; Wong and Gans 2008).

This thesis presents structural and stable isotopic data from two low-angle faults where debate is currently focused: the Mormon Peak detachment in southeastern Nevada and the Heart Mountain detachment in northwestern Wyoming (Figure 1, areas 1 and 2, respectively).

Figure 1. Overview map of the western United States, showing areas discussed in the text. Area 1 includes the Meadow Valley Mountains and Mormon Mountains, Nevada. Area 2 includes the eastern edge of the Absaroka Mountains and the Heart Mountain detachment, Wyoming and Montana.

The Miocene Mormon Peak detachment (originally recognized by Tschanz and Pampeyan , 1970 and Wernicke et al., 1985) has been variably explained as (1) a rooted detachment fault with ~20 kilometers of displacement (e.g. Axen et al, 1990; Axen, 1993), (2) a smaller fault where heavy dissolution took place (Anderson et al, 2010; Diehl et al, 2010), and (3) a series of surficial landslides transported radially away from the topographic crest of the Mormon Mountains (e.g. Carpenter et al, 1989; Anders et al. 2006; Walker et al. 2007).

The Eocene Heart Mountain detachment is also a subject of keen debate, though its rootless character is generally accepted. Given its location on the flank of a volcano that active during slip, volcanic processes are often invoked to facilitate slip on the detachment. Much of the current debate is focused on the rate of emplacement, with many recent workers preferring a single, catastrophic slip event (e.g. Beutner and Gerbi, 2005 ; Aharonov and Anders, 2006 ; Craddock et al., 2009, 2012; Anders et al., 2010, 2013), while others prefer emplacement at geologic slip rates, over 1-2 Ma (e.g. Hauge 1990, 1993; Templeton et al., 1995; Hiza, 2000; Douglas et al, 2003; Beutner and Hauge, 2009).

Here, we bring a new geochemical technique to address a problem in fault mechanics, namely carbonate clumped-isotope thermometry. Although the technique has thus far proved effective in addressing problems in paleoclimate, it is readily adaptable to structural problems, and results presented in Chapter 2 is the first to do so.

Geologic mapping in Chapter 3 provides constraints on the displacement of the Mormon Peak detachment (is it part of a crustal extensional fault system, or a landslide?), which is a critical first step in explaining its mechanics of slip. The map also exposes complexities in the interaction of Sevier-age compressional structures, with implications for slip direction and magnitude.

A study of the textures of fault rocks along and near the Heart Mountain detachment is presented in Chapter 4. Determining whether slip occurred during one catastrophic event or over time is a pre-requisite for discussions on dynamics, and Chapter 4 presents observations with implications for both slip rate and dynamics.

Further use of carbonate clumped-isotope thermometry in made in Chapter 5, where the role of volcanic or other proposed high-temperature processes in slip along the Heart Mountain detachment is explored. Volcanic or magmatic processes are commonly invoked for facilitating slip, and temperature measurements of the related faults rocks are important for evaluating that possibility. In addition, new clumped-isotope thermometry samples from the Mormon Mountains are presented, presenting and opportunity to make a detailed comparison between it and the Heart Mountain allochthon.

These observations help shed new light on the origin and evolution of low-angle faults within the upper crust, and show the utility of clumped-isotope thermometry for investigating the sources and temperatures of fluids on these faults.

References cited

Aharonov, E., and Anders, M. H., 2006, Hot water: A solution to the Heart Mountain detachment problem?: Geology, v. 34, no. 3, p. 165.

Allmendinger, R. W., Sharp, J. W., Von Tish, D., Serpa, L., Kaufman, S., Oliver, J., and Smith, R. B., 1983, Cenozoic and Mesozoic structure of the eastern Basin and Range Province, Utah, from COCORP seismic reflection data: Geology, v. 11, p. 532-536.

Anders, M. H., Christie-Blick, N., and Walker, C. D., 2006, Distinguishing between rooted and rootless detachments: A case study from the Mormon Mountains of southeastern Nevada: Journal of Geology, v. 114, no. 6, p. 645-664.

Anders, M. H., Fouke, B. W., Zerkle, A. L., Tavarnelli, E., Alvarez, W., and Harlow, G. E., 2010, The Role of Calcining and Basal Fluidization in the Long Runout of Carbonate Slides: An

Example from the Heart Mountain Slide Block, Wyoming and Montana, U.S.A: The Journal of Geology, v. 118, no. 6, p. 577-599.

Anders, M. H., Schneider, J. R., Scholz, C. H., and Losh, S., 2013, Mode I microfracturing and fluid flow in damage zones: The key to distinguishing faults from slides: Journal of Structural Geology, v. 48, p. 113-125.

Anderson, R. E., Felger, T.J., Diehl, S.F., Page, W.R., Workman, J.B., 2010, Integration of tectonic, sedimentary and geohydrologica processes leading to small-scale extension model for the Mormon mountains area north of Lake Mead, Lincoln County, Nevada, *in* Umhoefer, P. J., Beard, L.S., Lamb, M.A. (Eds.), ed., Miocene Tectonics of the Lake Mead Region, Central Basin and Range, Geological Society of America Special Paper 463, p. pp. 395-426.

Armstrong, R. L., 1972, Low-Angle (Denudation) Faults, Hinterland of the Sevier Orogenic Belt, Eastern Nevada and Western Utah: Geological Society of America Bulletin, v. 83, no. 6, p. 1729-1754.

Axen, G. J., 1993, Ramp-flat detachment faulting and low-angle normal reactivation of the Tule Springs thrust, southern Nevada: Geological Society of America Bulletin, v. 105, p. 1076-1090.

Axen, G. J., Wernicke, B. P., Skelly, M. F., and Taylor, W. J., 1990, Mesozoic and Cenozoic tectonics of the Sevier thrust belt in the Virgin River valley area, southern Nevada Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir, v. 176, p. 123-153.

Beutner, E. C., and Gerbi, G. P., 2005, Catastrophic emplacement of the Heart Mountain block slide, Wyoming and Montana, USA: Geological Society of America Bulletin, v. 117, no. 5, p. 724.

Beutner, E. C., and Hauge, T. A., 2009, Heart Mountain and South Fork fault systems: Architecture and evolution of the collapse of an Eocene volcanic system, northwest Wyoming: Rocky Mountain Geology, v. 44, no. 2, p. 147–164.

Carpenter, D. G., Carpenter, J. A., Bradley, M. D., Franz, U. A., and Reber, S. J., 1989, Comment on "On the role of isostasy in the evolution of normal fault systems": Geology, v. 17, p. 774-776.

Collettini, C., 2011, The mechanical paradox of low-angle normal faults: Current understanding and open questions: Tectonophysics, v. 510, no. 3-4, p. 253-268.

Craddock, J. P., Geary, J., and Malone, D. H., 2012, Vertical injectites of detachment carbonate ultracataclasite at White Mountain, Heart Mountain detachment, Wyoming: Geology, v. 40, no. 5, p. 463-466.

Craddock, J. P., Malone, D. H., Magloughlin, J., Cook, A. L., Rieser, M. E., and Doyle, J. R., 2009, Dynamics of the emplacement of the Heart Mountain allochthon at White Mountain: Constraints from calcite twinning strains, anisotropy of magnetic susceptibility, and thermodynamic calculations: Geological Society of America Bulletin, v. 121, no. 5-6, p. 919-938.

Davis, G. H., and Coney, P. J., 1979, Geologic development of Cordilleran metamorphic core complexes: Geology, v. 7, p. 120-124.

Diehl, S. F., Anderson, R.E., and Humprey, J.D., , 2010, Fluid flow, solution collapse, and massive dissolution at detachment faults, Mormon Mountains, Nevada, *in* Umhoefer, P. J., Beard, L.S., and Lamb, M.A. (Eds.), ed., Miocene Tectonics of the Lake Mead Region, Central Basin and Range, Geological Society of America Special Paper 463, p. 427-441.

Douglas, T. A., Chamberlain, C. P., Poage, M. A., Abruzzese, M., Schultz, S., Henneberry, J., and Layer, P., 2003, Fluid flow and the Heart Mountain fault: a stable isotopic, fluid inclusion, and geochronologic study: Geofluids, v. 3, p. 13-32.

Hauge, T. A., 1985, Gravity-Spreading origin of the Heart Mountain allochthon, northwestern Wyoming: Geological Society of America Bulletin, v. 96, p. 1440-1456.

-, 1990, Kinematic model of a continuous Heart Mountain allochthon: Geological Society of America, v. 102, p. 1174-1188.

-, 1993, The Heart Mountain detachment, northwestern Wyoming: 100 years of controversy, *in* Snoke, A. W., Steidtmann, J. R., and Roberts, S. M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir 5, p. 530–571.

Hiza, M. M., 2000, The Geochemistry and Geochronology of the Eocene Absaroka Volcanic Province, Northern Wyoming and Southwest Montana, USA [Doctor of Philosophy: Oregon State University, 240 p.

Hubbert, M. K., and Rubey, W. W., 1959, Role of Fluid Pressure in Mechanics of Overthrust Faulting: I. Mechanics of Fluid-Filled Porous Solids and its Application to Overthrust Faulting: Geological Society of America Bulletin, v. 70, p. 115-166.

Lister, G. S., and Davis, G. A., 1989, The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A: Journal of Structural Geology, v. 11, p. 65–94.

Miller, E. L., Dumitru, T. A., Brown, R. W., and Gans, P. B., 1999, Rapid Miocene slip on the Snake Range–Deep Creek Range fault system, east-central Nevada: Geological Society of America Bulletin v. 111, no. 6, p. 886–905.

Morley, C. K., 2014, The widespread occurrence of low-angle normal faults in a rift setting: Review of examples from Thailand, and implications for their origin and evolution: Earth-Science Reviews, v. 133, no. 0, p. 18-42.

Pierce, W. G., 1980, The Heart Mountain break-away fault, northwestern Wyoming: Geological Society of America Bulletin, v. 91, p. 272-281.

Rubey, W. W., and Hubbert, M. K., 1959, Role of Fluid Pressure in Mechanics of Overthrust Faulting: Geological Society of America Bulletin, v. 70, p. 167-206.

Scott, R. J., and Lister, G. S., 1992, Detachment faults: Evidence for a low-angle origin: Geology, v. 20, no. 9, p. 833-836.

Templeton, A. S., Sweeney, J. J., Manske, H., Tilghman, J. F., Calhoun , S. C., Violich, A., and Chamberlain, C. P., 1995, Fluids and the Heart Mountain fault revisited: Geology, v. 23, no. 10, p. 929-932.

Tschanz, C. M., and Pampeyan, E. H., 1970, Geology and mineral deposits of Lincoln County, Nevada, scale 1:250,000.

Walker, C. D., Anders, M. H., and Christie-Blick, N., 2007, Kinematic evidence for downdip movement on the Mormon Peak detachment: Geology, v. 35, no. 3, p. 259.

Wernicke, B., 1995, Low-angle normal faults and seismicity: A review: Journal of Geophysical Research, v. 100, no. B10, p. 20159.

Wernicke, B., Walker, J. D., and Beaufait, M. S., 1985, Structural Discordance between Neogene Detachments and Frontal Sevier Thrusts, Central Mormon Mountains, Southern Nevada: Tectonics, v. 4, no. 2, p. 213-246.

Wilson, R. C., Jr., 1970, The mechanical properties of the shear zone of the Lewis overthrust, Glacier National Park, Montana [Ph.D.: Texas A & M University, 89 p.

Wong, M. S., and Gans, P. B., 2008, Geologic, structural, and thermochronologic constraints on the tectonic evolution of the Sierra Mazatán core complex, Sonora, Mexico: New insights into metamorphic core complex formation: Tectonics, v. 27, no. 4