Program, Abstract and Information Book

3rd Biennial Structural Geology & Tectonics Forum 2014

Colorado School of Mines
Golden, Colorado
June 16-18

National Science Foundation
WHERE DISCOVERIES BEGIN

THE GEOLOGICAL SOCIETY OF AMERICA®
STRUCTURAL GEOLOGY & TECTONICS DIVISION

COLORADOSCHOOLOFMINES.

Forum Staff and Organizational Committee

Forum Organizers:
Yvette Kuiper and Chuck Kluth (Colorado School of Mines)

Steering Committee:
Paul Karabinos (Williams College) and Basil Tikoff (University of Wisconsin)

Technical Sessions:
Katherine Boggs (Mount Royal University) and Christie Rowe (McGill University)

Field Trips:
Eric Erslev (Colorado State University)

Short Course/Workshops:
John Weber (Grand Valley State University)

Events and web:
Barbara Tewksbury (Hamilton College)

Logistics:
Wes Buchanan and Ben Frieman (Colorado School of Mines)

Registration:
Mary Carr (Colorado School of Mines)

Finance Committee:
Hal Bosbyshell (West Chester University), Emily Peterman (Bowdoin College),
and Saad Haq (Purdue University)

TABLE OF CONTENTS

GENERAL INFORMATION

Arrival and Check-in:

If you are driving to campus, you can park in any of the blue or yellow lots on the campus map. The closest lot to Forum activities is E-lot. Pay attention to signs to make sure that you don't part in a restricted space. Parking is free on the weekends. Parking in public Golden city lots is also free; however, overnight parking is prohibited in these lots. During the week, parking is $4/day if you pay at the lot, or $2/day if you buy a parking pass.

If you are staying in the dorm, you will be housed in Maple Hall (#38 on the campus map). Check-in is *between 5 pm and 11 pm in Maple Hall*. When you check in, you will receive a meal card and/or parking pass if you purchased either. If you arrive *before 5 on Sunday* you may store your belongings at the workshop locations until 5 (please do not interrupt lectures, but during classroom activities this is fine). On Friday and Saturday there is no storage option. For arrivals *after 11 pm*, please contact the person on call (this number will be posted on the Maple Hall door).

If you are not staying in the dorm, we will have your Forum packet and name tag at the first event you are registered for (field trip, workshop, or Forum opener).

Meals:

If you purchased a meal card, you will eat in the Slate Café in the Student Center (#19 on the campus map; directly north of Berthoud Hall).

Breakfast is from 7-8 am; lunch is from 12-1 pm; dinner is from 6-7 pm.

Field Trip Departures:

All field trips will depart from the D parking lot (see campus map on page v). With the exception of the Homestake Field Trip (which will depart at 7:45), all field trips will depart promptly at 8:00 am, so please arrive earlier than the departure time.

Please see the Forum information page for more information on what to bring. Remember that you must have pre-registered for a field trip in order to participate. If you have not already checked in for the Forum, the field trip leaders will have your Forum packet and name tag at the field trip departure site.

Workshop Locations:

All workshops will be held in Berthoud Hall (#7 on the campus map).

The two half day workshops on Sunday (Google Earth and Visible Geology) will be held in Berthoud Hall 222. All other workshops will be held in Berthoud Hall 201.

Remember that you must have pre-registered for a workshop in order to participate. If you have not already checked in for the Forum, your workshop leader will have your Forum packet and name tag at the workshop venue.

Oral and Poster Presentations:

All Forum sessions will be held in Berthoud Hall (#7 on the campus map).

Posters will be displayed in Berthoud Hall 243 and will be up for the duration of the Forum.

During the Forum, you will have 2 minutes to give a teaser preview of your poster. You MUST limit your preview to 2 minutes, with a maximum of 2 PowerPoint slides.

Oral presentations will be held in Berthoud Hall 242. Please adhere to the time limits set by the session conveners for your session so that there is time for questions and so that no one is short-changed in terms of presentation time.

You may upload your presentation any time before or during the Forum (at http://serc.carleton.edu/NAGTWorkshops/structure/2014_Forum_upload.html), but please be sure that your presentation is uploaded by the end of the morning or afternoon prior to your session.

Campus Emergency Contact Information:

CSM Public Safety (on duty 24/7)

Administration Office Hours:

(303) 273-3333 (Monday-Friday: 8:00 a.m. - 5:00 p.m.)

~After hours officers will answer or you will be directed to the Golden Police Department Dispatch~

Golden Dispatch PD: (303) 384-8045 (24/7)

Internet Access:

When you arrive on campus you will need to connect
to the "CSMguest" network.

The first time you bring up a web browser, you will be prompted
for a username and password.

[Note: IF THE USERNAME & PASSWORD PROMPT DO NOT APPEAR,
PLEASE ENTER '1.1.1.1' (without the quotation marks) IN THE BROWSER ADDRESS FIELD]

You will need to enter the following:

Username: *guest-structural*

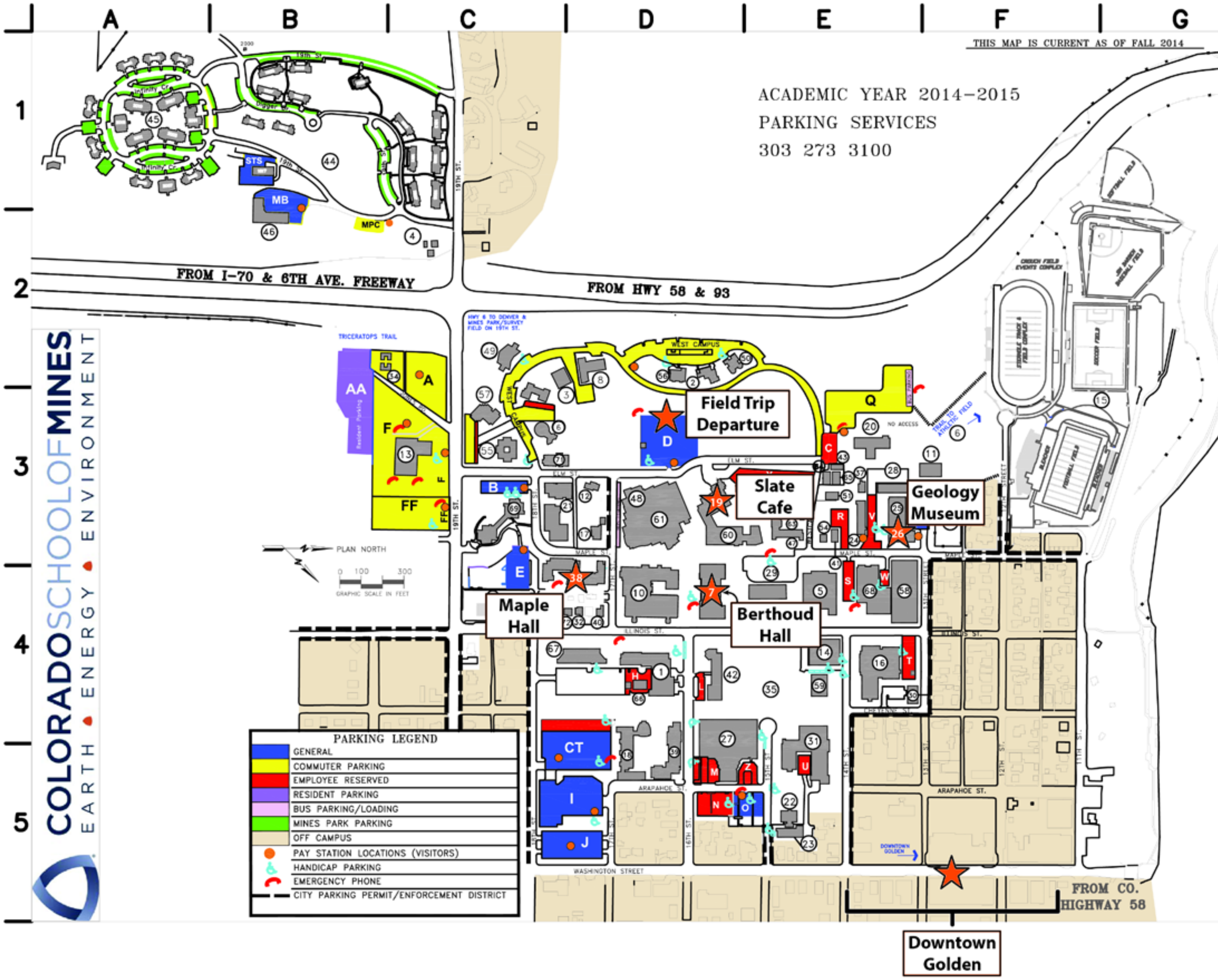
Password: *kvxu7fq6*

Once you have been authenticated, you should be able to browse the web,
check e-mail, etc. without re-entering the login information

NOTE:
If you are using Internet Explorer, and having trouble accessing the login page, please disable SSL version 2.

This can be done by going to the "Tools" menu in Internet Explorer, choosing "Internet Options" and then clicking on the "Advanced" tab.
The "Use SSL 2.0" check-box can be found near the bottom of the list.

CSM Campus Map, SG&T Forum 2014



BUILDING NAME	BLDG/SITE NO.	MAP LOCATION
ALDERSON HALL (AH)	1	D-4
ALPHA PHI SORORITY (Z4)	2	D-2
ALPHA TAU OMEGA FRATERNITY	3	C-2
ACWATEC (ZE, ZF & ZP)	4	C-2
ARTHUR LAKES LIBRARY (LB)	5	E-3
ASPEN HALL (Z2)	6	C-3
BERTHOUD HALL (BR)	7	D-4
BETA THETA PI FRATERNITY	8	D-2
BRADFORD HALL (BR)	9	E-3
BROWN HALL (BB)	10	D-4
CARPENTER/ELEC SHOP (1S)	11	F-3
CASA (ZD)	12	D-3
CENTRAL STORAGE & RECEIVING AND MUSIC PROGRAM (CR)	13	C-3
CHAUVENET HALL (CH)	14	E-4
CLEAR CREEK ATHLETIC COMPLEX	15	F/G-1/2/3
COOLBAUGH HALL (CO)	16	E-4
COOLBAUGH HOUSE (ZO)	17	D-3
CTLM (CT)	18	D-5
DINING HALL (SC)	19	D-3
EARTH MECHANICS INSTITUTE (EMI)	20	E-3
ELM RESIDENCE & DINING HALL (EL)	21	C-3
ENGINEERING HALL (EH)	22	E-5
ENGINEERING HALL ANNEX (EA)	23	E-5
FACILITIES MANAGEMENT, PARKING AND CAPITAL PLANNING & CONSTRUCTION	24	E-3
GENERAL RESEARCH LAB - GRL (RL)	25	E-3
GEOLOGY MUSUEM (RL)	26	E-3
GREEN CENTER (GC)	27	D-5
GROUNDS/TRUCK SHOP (2S)	28	E-3
GUGGENHEIM HALL (GH)	29	E-4
HEATING PLANT (HP)	30	E-4
HILL HALL (HH)	31	E-4
INTERNATIONAL PROGRAM (ZH)	32	D-4
INTRAMURAL FIELD (IM)	33	D-3
JONES ROAD COMPLEX - PUBLIC SAFETY & FOUNDATION (ZA & ZR)	34	B-2
KAFADAR COMMONS	35	E-4
KAPPA SIGMA FRATERNITY	36	C-3
LOCK SHOP (S3)	37	E-3
MAPLE HALL (MP)	38	C/D-4
MARQUEZ HALL (MZ)	39	D-5
MCBRIDE HONORS (ZS)	40	D-4
MEP (ZL)	41	E-3
MEYER HALL (MH)	42	D-4
MILITARY SCIENCE-TRAILER (5S)	43	E-3
MINES PARK I & II	44	B/C-1
MINES PARK III	45	A-1
MOLY BUILDING (MB)	46	B-2
MORGAN HALL (MO)	47	E-3
OUTDOOR RECREATION (RC)	48	D-3
PHI GAMMA DELTA FRATERNITY (Z1)	49	C-2
PI PHI SORORITY (Z3)	50	D-2
PINES TRAILER-FOUNDATION (6S)	51	E-3
PRESIDENT'S RESIDENCE (ZI)	52	C-4
RANDALL HALL (RA)	53	E-3
ROTC (ZK)	54	E-3
SIGMA ALPHA EPSILON FRATERNITY	55	C-3
SIGMA KAPPA SORORITY (Z5)	56	D-2
SIGMA PHI EPSILON FRATERNITY	57	C-3
STEINHAUER FIELD HOUSE (FH)	58	E-4
STRATTON HALL (SH)	59	E-4
STUDENT CENTER (SC)	60	D-3
STUDENT RECREATION CENTER (RC)	61	D-3
TENNIS COURTS (TC)	62	F-3
THOMAS HALL (TH)	63	E-3
TIMBERLINE TRAILER 1-UNIVERSITY ADVANCEMENTS (7S)	64	E-3
TIMBERLINE TRAILER 2-UNIVERSITY ADVANCEMENTS (8S)	65	E-3
UNIT OPERATIONS LAB (UO)	66	D-4
US GEOLOGICAL SURVEY-USGS (GS)	67	C/D-4
VOLK GYMNASIUM (GY)	68	E-4
WEAVER TOWER (WT)	69	C-3
WELCOME CENTER - FUTURE	70	C-4
W LLOYD WRIGHT STUDENT WELLNESS CENTER (WC)	71	C-3
WISEM (ZV)	72	C-4

Forum Program

Saturday, June 14

Field trip 1: Pseudotachylyte from the Homestake Shear Zone, Colorado
Leader: Joe Allen

- We will depart promptly at **7:45 am from the D parking lot.** Please eat breakfast beforehand, and please plan to arrive before 7:45 so that we can depart on time.
- This field trip involves two short but steep hikes above 9,700 feet. Bring sturdy shoes or boots for rough terrain, sun protection, and a day pack with water, rain parka, and extra warm layers. We will provide a boxed lunch. Note: you must be pre-registered for the field trip in order to participate.

6:00 Dinner on your own

Sunday, June 15

Field trip 2: Contractional linkage zones and curved faults, Garden of the Gods, with illite geochronology exposé
Leaders: Christine Siddoway and Elisa Fitz Díaz

- We will depart promptly at **8:00 am from the D parking lot.** Please eat breakfast beforehand, and please plan to arrive before 8:00 so that we can depart on time.
- Bring appropriate clothing and sun protection to suit the weather of the day and sturdy shoes for rough terrain. Compass and small map board are recommended. A boxed lunch will be provided. We will provide a boxed lunch. Note: you must be pre-registered for the field trip in order to participate.

Workshop 1 (all day): Strain programs for teaching and research (Berthoud Hall 201)
Leaders: Fred Vollmer, Matty Mookerjee, and Paul Karabinos

- The workshop will begin at **8:00 am** and conclude at **5:00 pm.** We will break for lunch from 12-1. Lunch is on your own. The dining hall accepts both meal cards and cash. Note: you must be pre-registered for the workshop in order to participate.

Workshop 2 (morning only): Structural and tectonic analysis with Google mapping technologies (Berthoud Hall 222)
Leaders: Declan De Paor and Carol Simpson.

- The workshop will begin at **8:00 am** and conclude at **noon.** Note: you must be pre-registered for the workshop in order to participate.

Workshop 3 (afternoon only): Teaching with Visible Geology, an interactive online tool for visualizing 3D geologic block models (Berthoud Hall 222)
Leaders: Rowan Cockett and Barbara Tewksbury

- The workshop will begin at **1 pm** and conclude at **5 pm.** Note: you must be pre-registered for the workshop in order to participate.

Monday, June 16

8:00-12:00 **Session 1: Lithospheric deformation - rheology and the rock record** (Berthoud Hall 241)

8:00-8:10 **Forum introduction** *Yvette Kuiper*

8:10-8:15 **Introduction** *Micah Jessup and Joe Allen, session chairs*

8:15-9:00 **Keynote talk:** Strain localization (and de-localization?) in deep continental crust: examples from an exhumed section and remote observations from still deep crust in North America *Kevin Mahan, University of Colorado, Boulder*

9:05-9:25 **Invited talk:** Initiating localized deformation in the mantle *Phil Skemer, Washington University, St. Louis*

9:25-9:45 **Invited talk:** Advances in quantifying crustal stress magnitudes *Steve Kidder, City College of New York*

9:50-10:10 **Two-minute poster pitches** (participants limited to 2 minutes each with 2 ppt slides)

- Uplift and seismicity driven by groundwater depletion in central California *Colin Amos, Western Washington University*
- Deformation-enhanced element mobility in feldspar: a strain speedometer? *Naomi Barshi, McGill University*
- Cyclicity of intra-arc deformation, crustal thickening and strain rates: implications for arc tempos in the Mesozoic Sierra Nevada, California *Wenrong Cao, University of Southern California*
- Rheology of the crust during syn-convergent extension: insights from the Cordillera Blanca Detachment, Peru *Micah Jessup, University of Tennessee, Knoxville*
- Belly of the beast: detailed mapping in the deformation core of a quartz-plastic transitional zone fault: implications for deep fault seismicity on major strike slip faults *Ben Melosh, McGill University*
- Strain-induced rutilation of quartz in mylonites and timescales of ductility in an extensional shear zone *William Nachlas, University of Minnesota*
- Stressed thrust ramps localize fault injectites on the Naukluft Thrust, Namibia *Timothy Sherry, McGill University*
- Role of dolomite in the development of weak fault zones *Rachel Wells, Texas A&M University*

10:10-12:00 Posters and coffee (Berthoud Hall 243)

12:00-1:00 Lunch Slate Café, Student Center

1:00-2:00 Group discussion (Berthoud Hall 241)

2:00-6:30 Session 2: Tectonics at the Earth's surface - geomorphic expressions and shallow deformation (Berthoud Hall 241)

2:00-2:05 Introduction *Ryan Gold and Colin Amos, session chairs*

2:05-2:50 Keynote talk: Issues in climate-tectonic interactions *Doug Burbank, UC Santa Barbara*

2:50-3:05 Coffee break

3:05-3:25 Invited talk: Determining hillslope-scale material strength from seismically-triggered landslide events *Marin Clark, University of Michigan*

3:25-3:45 Invited talk: Why should I care about your slop? Linking shallow geologic observations to deeper Earth processes *Richard Briggs, USGS*

3:45-4:05 Invited talk: Normal faulting and graben development as catalysts for Late Cenozoic landscape change, Fish Lake Plateau, Utah *Chuck Bailey, College of William and Mary*

4:05-4:30 Two-minute poster pitches
(participants limited to 2 minutes each with 2 ppt slides)

- The reactivation of the Lost Lakes Fault in Yosemite National Park (USA): when did it happen and what does it mean? *Richard Becker, University of Wisconsin, Madison*
- Finding active faults using earthquake focal mechanisms, geomorphic analysis and field work (SLAM) *Vince Cronin, Baylor University*
- Reconciling invariant topography with significant along-strike gradients in climate and tectonics in the Greater Caucasus *Adam Forte, Arizona State University*
- Anatomy of the 200 km-long, left-lateral surface rupture from the 24 September 2013 Mw 7.7 Balochistan earthquake, southern Pakistan *Ryan Gold, USGS*
- Using high-resolution basin analysis to unravel complex fault kinematics, understand tectonic events and address climate change in the central Basin and Range *Melissa Lamb, University of St. Thomas*
- Insights about polygonal faults and related structures from extensive exposures of the Cretaceous Khoman Formation, Western Desert, Egypt *Barbara Tewksbury, Hamilton College*
- Deformation bands in the Etchegoin Formation: implications for stresses on the San Andreas Fault in central California *Sarah Titus, Carleton College*
- New GPS evidence for continental transform fault creep, Central Range Fault, Trinidad, Caribbean-South American plate boundary and geological/hazard implications *John Weber, Grand Valley State University*

- Rapid uplift of the Kumkuli Basin since ~5 Ma as a consequence of large-scale transpressional faulting within the northern Tibetan Plateau *Petr Yakovlev , University of Michigan*

4:40-7:30 Posters and coffee (Berthoud Hall 243)

6:00-7:00 Dinner Slate Café, Student Center

7:30-9:00 Preparing for an academic career in the geosciences - a special evening session for grad students and post-docs (Berthoud Hall 204)
Leaders: Barbara Tewksbury and others

- Are you interested in a future faculty position? Come to this informal "speed dating" session where you will have a chance to talk with current faculty about what it's like to teach and do research at a wide variety of academic institutions and get advice on how to prepare for an academic job search.

Tuesday, June 17

8:00-12:00 Session 3: Geochronology and tectonics (Berthoud Hall 241)

8:00-8:05 Introduction *John Cottle and Emily Peterman, session chairs*

8:05-8:50 Keynote talk: Continuous thermal histories from MDD modeling of 40Ar/39Ar K-feldspar analyses and applications to extensional tectonics *Martin Wong, Colgate University*

8:55-9:15 Invited talk: Geochronology and Himalayan tectonics *Kyle Larson, University of British Columbia, Okanagan*

9:15-9:35 Invited talk: Dating brittle deformation with hematite (U-Th)/He chronometry *Alexis Ault, University of Arizona/Utah State University*

9:40-10:00 Two-minute poster pitches
(participants limited to 2 minutes each with 2 ppt slides)

- A structural and U-Pb zircon geochronology investigation of selected units in the Eastern Merrimack Belt: implications for Post-Acadian deformation, eastern Massachusetts *Robert Charnock, Colorado School of Mines*
- Geochronology of rare earth element mineralization in a high-grade metamorphic terrane, Music Valley, California *John Cottle, University of California, Santa Barbara*
- The rich isotopic memory of illite; an example of clay dating and fluid fingerprinting from the Zimapán Basin in central Mexico *Elisa Fitz-Díaz, Universidad Nacional Autónoma de México*
- Cenozoic crustal shortening and plateau uplift within the Hoh Xil Basin, north-central Tibetan Plateau: implications for causal mechanisms of plateau evolution *Lydia Staisch, University of Michigan*

10:00-12:00 Posters and coffee (Berthoud Hall 243)

12:00-1:00 Lunch Slate Café, Student Center

1:00-2:00 Group discussion (Berthoud Hall 241)

2:00-6:30 Session4: Geoscience learning and spatial cognition (Berthoud Hall 241)

2:00-2:05 Introduction *Tim Shipley and Carol Ormand, session chairs*

2:05-2:50 Keynote talk: Applying cognitive science research to improve geoscience teaching and learning *Carol Ormand, SERC, Carleton College*

2:50-3:05 Coffee break

3:05-3:30 Invited talk: Virtual geological mapping and development of geospatial analysis competencies using Google Earth and related digital technologies *Declan DePaor, Old Dominion University*

3:30-3:55 Invited talk: Visuospatial ability and geologic mapping: Experts and novices in the field *Nicole LaDue, Northern Illinois University*

4:00-4:20 Two-minute poster pitches
(participants limited to 2 minutes each with 2 ppt slides)

- A structure for mastering stereonets for structural geology *Katherine Boggs, Mount Royal University*
- Thin-skinned models for undergraduate teaching labs - flour structures *Dan Davis, Stony Brook University*
- New approaches to teaching spatial thinking in the context of structural geology *Laurel Goodwin, University of Wisconsin, Madison*
- Creating, disseminating, and testing interactive 3D models for teaching structural geology *Paul Karabinos, Williams College*
- Geological field research: an ideal course 'recipe' for advanced undergraduate and beginning graduate students *Yvette Kuiper, Colorado School of Mines*

4:40-7:30 Posters and coffee (Berthoud Hall 243)

6:00-7:00 Dinner Slate Café, Student Center

7:30-8:30 Optional visit to Colorado School of Mines Geology Museum (#24 on the map)

Wednesday, June 18

8:00-12:00 Session 5: The structural geology of natural resources and regional tectonics
(Berthoud Hall 241)

8:00-8:05 Introduction *Nils Backeberg and Mary Louise Hill, session chairs*

8:05-8:50 Keynote talk: The Central Piedmont Shear Zone of the Southern Appalachian Piedmont *Allen Dennis, University of South Carolina, Aiken*

8:55-9:15 Invited talk: SCLM rifting and regional shearing in the N. American Superior Craton – implications for deformation, mineralization, and tectonic reconstructions *Lyal Harris, INRS-ETE, Québec*

9:15-9:35 Invited talk: New thermochronologic, paleomagnetic, and fault-slip constraints on Pliocene tectonics and provenance, North Coast Marine area, Trinidad and Tobago *John Weber, Grand Valley State University*

9:40-10:00 Two-minute poster pitches
(participants limited to 2 minutes each with 2 ppt slides)

- Damaged goods in the Marmion Tonalites, Superior Province, Ontario: deformation fabrics in a gold-bearing damage zone *Nils Backeberg, McGill University*
- Siluro-Devonian assembly of the high-grade core of the Central Appalachian Piedmont *Howell Bosbyshell, West Chester University*
- Timing and style of deformation in the Nashoba Formation of the Nashoba Terrane, eastern Massachusetts *Wesley Buchanan, Colorado School of Mines*
- Mapping deformed Pennsylvanian rocks in the Dunkard Basin, southwestern Pennsylvania using GigaPan images *Patricia Campbell, Slippery Rock University*
- Southeastward propagation of thermotectonism within the Paleoproterozoic Big Sky orogeny: New Constraints from the N. Madison Range, SW Montana *Cailey Condit*
- Pre-Timiskaming folding in the Archean Southern Abitibi Greenstone Belt, Ontario and Québec, Canada: structural constraints and conundrums *Ben Frieman, Colorado School of Mines*
- Structural geology of the Nadaleen Trend, Northeastern Yukon Territory, Canada: implications for recent Au discoveries Jus*tin Palmer, Colorado School of Mines*

10:00-12:00 Posters and coffee

12:00-1:00 Lunch Slate Café, Student Center

1:00-2:00 Group discussion (Berthoud Hall 241)

2:00-6:30 Session 6: Quantitative approaches toward structural analysis
(Berthoud Hall 241)

2:00-2:05 Introduction *Saad Haq and Matty Mookerjee, session chairs*

2:05-2:25 Invited talk: Quantitative structural analysis: where does it start? *David Pollard, Stanford University*

2:25-2:45 Invited talk: Tracking Fault History in Sandbox Models *Dan Davis, Stony Brook University*

2:45-3:00 Coffee break

3:00-3:20 Invited talk: Relating lattice preferred orientation to deformational process using statistical analysis of symmetry in orientation distribution space *Christopher Thissen, Yale University*

3:20-3:40 Invited talk: Rotation statistics in structural geology *Joshua Davis, Carleton College*

3:40-4:00 Invited talk: Fault surface geometry, wear processes and evolution: implications for earthquake mechanics and fault rock rheology *James Kirkpatrick, Colorado State University*

4:00-4:20 Two-minute poster pitches
(participants limited to 2 minutes each with 2 ppt slides)

- What, if anything, should the structural geologist know about the mechanics of rock deformation? *Raymond Fletcher, Pennsylvania State University*
- Out of sequence thrusting in coulomb wedges *Saad Haq, Purdue University*
- Interactions between regional transcurrent shearing, rifting, and mantle flow on Venus: radar and gravity interpretations and Earth analogues *Lyal Harris, INRS-ETE, Québec*
- Evaluating the effectiveness of Flinn's K-value versus Lode's ratio *Matty Mookerjee, Sonoma State University*
- Paleocene paleoelevations of the Basin and Range from clumped isotope thermometry and paleosol geochemistry: a modest Nevadaplano? *Nathan Niemi, University of Michigan*
- Nucleation of ramps in fold-thrust belts: insight from quantitative analysis of sandbox models *Pragnyadipta Sen, University of Illinois at Urbana-Champaign*
- EllipseFit 3: a new computer program for integrated geological finite strain analysis *Frederick Vollmer, SUNY New Paltz*

4:40-7:30 Posters

6:00-7:00 Dinner Slate Café, Student Center

7:30-9:00 Networking time

Thursday, June 19

Field trip 3: Proterozoic metamorphism and deformation in the Northern Colorado Front Range
Leaders: Kevin Mahan, Graham Baird, and Julien Allaz

- We will depart promptly at **8:00 am from the D parking lot.** Please eat breakfast beforehand, and please plan to arrive before 8:00 so that we can depart on time.
- Field trip involves one short (less than 1,500 ft. but steep hike, so boots or sturdy shoes are recommended. All stops between 5,200 and 8,000 feet elevation. Be prepared for chilly or hot, and dry or wet weather, and bring sun protection. We will provide a boxed lunch. Note: you must be pre-registered for the field trip in order to participate.

Workshop 4 (all day): The application of shear sense indicators in shear zones (Berthoud Hall 201)
Leader: Cees Passchier

- The workshop will begin at **8:00 am** and conclude at **5:00 pm.** We will break for lunch from 12-1. Lunch is on your own. The dining hall accepts both meal cards and cash. Note: you must be pre-registered for the workshop in order to participate.

Workshop 5 (morning only): Ar-Ar datiing of illite, a method to date faults and folds formed in the upper crust (Berthoud Hall 201)
Leader: Elisa Fitz Díaz

- The workshop will begin at **8:00 am** and conclude at **noon.** Note: you must be pre-registered for the workshop in order to participate.

Workshop 6 (afternoon only): Using real geodesy data in undergraduate structural geology and geophysics courses (Berthoud Hall 201)
Leader: Vince Cronin

- The workshop will begin at **1:00 pm** and conclude at **5 pm.** Note: you must be pre-registered for the workshop in order to participate.

Friday, June 20

Field trip 4: Laramide crustal detachment and thrust tectonism, with applications to natural fracturing in Rocky Mountain resource plays
Leader: Eric Erslev

- We will depart promptly at **8:00 am from the D parking lot.** Please eat breakfast beforehand, and please plan to arrive before 8:00 so that we can depart on time.
- Field trip involves several ~1-2 mile hikes on rugged ground. Bring sturdy shoes or boots for rough terrain, sun protection, and a day pack with water, rain parka, and extra warm layers. We will provide a boxed lunch. Note: you must be pre-registered for the field trip in order to participate.

Workshop 7 (all day): Teaching structure lab with linear algebra and simple computing (spreadsheets) (Berthoud Hall 201)
Leader: Rick Allmendinger

- The workshop will begin at **8:30 am** and conclude at **5:00 pm.** We will break for lunch from 12-1. Lunch is on your own. The dining hall accepts both meal cards and cash. Note: you must be pre-registered for the workshop in order to participate.

Workshop 8 (all day): Introduction to terrestrial laser scanning (ground-based LiDAR) for Earth science research (at UNAVCO in Boulder)
Leader: Chris Crosby

- **This workshop will take place at UNAVCO in Boulder.** A bus will transport participants from Golden to UNAVCO in Boulder and will depart promptly at **7:45 am from the D parking lot.** Please eat breakfast before hand. The workshop will begin at **8:30 am** and conclude at **5:00 pm.** Note: you must be pre-registered for the workshop in order to participate.

Forum Abstracts

Abstracts appear alphabetically in order of first author's last name

Uplift and Seismicity Driven by Groundwater Depletion in Central California

Colin Amos, *Western Washington University*
Pascal Audet, *University of Ottawa*
William Hammond, *Nevada Geodetic Laboratory, Nevada Bureau of Mines and Geology, and Nevada Seismological Laboratory*
Roland Burgmann, *University of California, Berkeley*
Ingrid Johanson, *Berkeley Seismological Laboratory*

Groundwater use in California's San Joaquin Valley exceeds replenishment of the aquifer, leading to substantial diminution of this resource and rapid subsidence of the valley floor. The volume of groundwater lost over the past century-and-a-half also represents a substantial reduction in mass and a large-scale unburdening of the lithosphere, with significant but unexplored potential impacts on crustal deformation and seismicity. Here we use vertical GPS measurements to show that a broad zone of rock uplift up to 1 – 3 mm/yr surrounds the southern San Joaquin Valley. The observed uplift matches well with predicted flexure from a simple elastic model of current rates of water-storage loss, the majority of which is caused by groundwater depletion. Height of the adjacent central Coast Ranges and Sierra Nevada is strongly seasonal and peaks during the dry late summer and fall, out of phase with inflation of the valley floor during wetter months. Our results suggest that long-term and late-summer flexural uplift of the Coast Ranges reduce the effective normal stress resolved on the San Andreas Fault. This process brings the fault closer to failure, thereby providing a viable mechanism for observed seasonality in microseismicity at Parkfield and potentially affecting long-term seismicity rates for fault systems adjacent to the valley. We also infer that observed contemporary uplift of the southern Sierra Nevada previously attributed to tectonic and/or mantle derived forces is partly a consequence of human-caused groundwater depletion.

Dating Brittle Deformation with Hematite (U-Th)/He Chronometry

Alexis Ault, *University of Arizona*
Peter Reiners, *University of Arizona*

Direct, robust timing constraints on fault slip are necessary to reconstruct structural-tectonic histories, understand mountain building and landscape evolution processes, and document ancient seismicity to assess modern seismic hazards, earthquake forecasting, and fault mechanics. Fault activity is commonly indirectly deduced by dating geologic units that predate or postdate faults or a range of possible fault activity ages is inferred from variations in bedrock low- temperature thermochronology dates and/or extrapolated cooling rates. This relies on the assumption that exhumational cooling is directly tied to fault motion at a regional scale, which is often not the case. Radioisotopic methods used to place direct temporal constraints on brittle fault activity include $^{40}Ar/^{39}Ar$ dating of neo-formed fault gouge clay and U-Th dating of syntectonic carbonate and opal.

Hematite is among the most common synkinematic minerals associated with fault surfaces and is amenable to (U-Th)/He dating, presenting a new method for dating brittle deformation. (U-Th)/He dates from hematite associated with faults record brittle faulting events by constraining the timing of either synkinematic hematite formation or the rapid cooling from fault surface frictional heating during faulting. In some cases, these dates may track regional cooling, yielding a new tool to quantify tectonic exhumation or erosion linked to broader fault zone evolution. We present hematite (U-Th)/He data from faults from several case studies including the footwall damage zone of the well-characterized Wasatch fault, UT and the Gower Peninsula, Wales to demonstrate the utility and complexities in applying this technique to constrain brittle deformation. For example, hematite (U-Th)/He dates from, mirrored, metallic, locally iridescent, hematite-coated small fault surfaces in the footwall damage zone of the southern Brigham City segment of the Wasatch fault zone are interpreted as direct constraints on fault slip. Pliocene hematite He dates overlap published and new apatite (U-Th)/He and apatite fission-track data from several locations in the host rock. Texturally identical hematite from iridescent regions separated by tens of cm on a single fault surface yield significantly different hematite (U-Th)/He dates, ruling out the interpretation of the dates as conventional thermochronologic ambient cooling ages. Fault surface iridescence is associated with the high temperature conversion hematite to $Fe2^{+}$ (magnetite) from seismic slip and flash heating at geometric asperities. We suggest that these hematite (U-Th)/He dates reflect rapid cooling from this heating during localized seismic slip events, documenting evidence of ancient microseismicity in the exhuming footwall damage zone at depths of ~2-3 km.

Damaged Goods in the Marmion Tonalites, Superior Province, Ontario: Deformation Fabrics in a Gold-Bearing Damage Zone

Nils Backeberg, *McGill University*
Christie Rowe, *McGill University*

The Archean Hammond Reef gold deposit in NW Ontario, Canada, is hosted in the Mesoarchean Marmion tonalite gneisses of the south-central Wabigoon subprovince. The deposit lies on the western margin of the Marmion tonalites within a fault damage zone 2 km east of the Marmion Shear Zone, which bounds the tonalite terrane to the Finlayson Lake greenstone belt. The mineralization at Hammond Reef is structurally controlled but not vein-hosted. It is characterized by low-grade disseminations of gold-pyrite in a pervasive altered- to partially altered zone.

A kinematic study of the adjacent Finlayson Lake greenstone belt, where metamorphic conditions and structural fabrics are better preserved than in the felsic gneiss, reveals the regional deformation history. We have identified a prolonged structural, magmatic and fluid flow history of the Finlayson Lake greenstone belt and its eastern margin from peak ductile deformation at depths below 20 km to shallow reactivation. We aim to relate the deformation history to the damage zone formation in the Marmion terrane. The Marmion Shear Zone is intruded by a late felsic granodiorite, the Diversion Stock, which varies in width from 1 to 2 km along the full length of the structure. This coarser grained, younger intrusion acts as a rigid block within the shear zone. Shallow reactivation of the structure, related to the later stages of the regional deformation history, promoted the development of a brittle damage zone across the contact of the late intrusion and the Marmion tonalites. These new findings explain the 1 to 2 km distance separation of the gold deposit from the original terrane boundary and Marmion Shear Zone. An anastomosing network of brittle fractures and sericite-altered feldspars defines the foliation in the damage zone. The foliation is defined by predominantly sericite and in some cases chlorite, depending on the host rock assemblages and alteration intensity. Feldspar was preferentially fractured and altered to form the sericite matrix, which promoted further localization of the deformation and minor shearing during the development of the damage zone. This style of deformation and complete breakdown of primary feldspar in the damage zone is a possible cause for the pervasive permeability network to be developed and may have facilitated disseminated gold mineralization.

Deformation-Enhanced Element Mobility in Feldspar: A Strain Speedometer?

Naomi Barshi, *McGill University*
Christie Rowe, *McGill University*
Vincent van Hinsberg, *McGill University*

Strain rate is an important parameter for understanding rock deformation and estimating paleostress, but we cannot directly measure strain rate in the rock record. Strain rate can be inferred in specific cases when dateable events such as mineral growth or intrusions accompany deformation, but a generally applicable tool has not yet been developed.

Previous studies on tourmaline show deformation-enhanced element mobility that could, in theory, be used to calculate a duration of deformation. Unfortunately, the required diffusion parameters are lacking for tourmaline, rendering it unusable as a tool to infer bulk rock strain rate. Feldspar is a better candidate for a paleostrain-rate tool as it dominates the rheology of Earth's crust, diffusion parameters are known across a range of pressure-temperature conditions, and its compositional zoning serves as a physical, and potentially chemical, strain marker. I will combine strain measurements along a 500-meter-long strain gradient with element mobilities measured as a function of strain in zoned plagioclase phenocrysts. The strain gradient ranges from undeformed tonalite to biotitic tonalite gneiss in the marginal unit of the San José Pluton, Peninsular Ranges Batholith, Baja California, which experienced solid-state deformation during subsequent intrusions. I expect that modeling changes in element mobilities will yield an estimated duration of deformation, which can be used to infer bulk strain rate in the rock record.

The Reactivation of the Lost Lakes Fault in Yosemite National Park (USA): When Did it Happen and What Does it Mean?

Richard Becker, *University of Wisconsin, Madison*
Basil Tikoff, *University of Wisconsin, Madison*
David Greene, *Denison University*

The Lost Lakes Fault is an 8 km long NW-striking structure that parallels the Sierra Crest in Yosemite National Park. The northernmost 3 km is exposed in a pair of SW-facing cirques while the southern portion lies in a SE-draining glacial basin. In the cirques, the fault is marked by a prominent scarp that dips 80° northeast and ranges in height from 0–8 m, with 2–4 m being more typical. In the basin to the south, the topographic expression of the fault is minor.

Both sub-horizontal and sub-vertical lineations are present along the scarp and field evidence indicates multiple periods of fault activity: The presence of pseudotachylite, cataclasite, chlorite, quartz, and epidote along the fault surface suggests deformation at substantially greater pressures and temperatures than those provided by the near-surface environment. We interpret these materials to be the result of an early period of dextral strike-slip deformation, possibly Cretaceous in timing. A later period of normal faulting is indicated by the sub-vertical lineations and an offset of the Eocene erosion surface along the ridgeline between the two cirques. This displacement might have happened as recently as the last deglaciation. Efforts to further constrain the timing and nature of deformation along the Lost Lakes Fault continue.

A Structure for Mastering Stereonets for Structural Geology

Katherine Boggs, *Mount Royal University*

Student voice, exam marks and participant reported confidence levels were used here to propose a model for guiding novice student acquisition of the spatial cognition skills for conquering the stereonet while solving Structural Geology problems. This model includes: 1) an introduction to conceptual knowledge, 2) learn skills in an accretive manner, 3) use stereonet to solve different problems, 4) collaborate with peers, and 5) use stereonet to construct geoscience schematic models. While these steps are used in many Structural Geology courses, the validity of this approach is established from the student perspective.

Eleven students from an Introduction to Structural Geology course (taught in second year at Mount Royal University, a public Canadian undergraduate university) participated in this study. Exam marks over a four year period (class averages for specific questions (CA)) and participant reported confidence levels (RPL; 5.0 = high confidence to 1.0 = no confidence) on stereonet skills were used to establish basic (CA>80%; RPL 4.4 to 4.8), intermediate (CA 79.9 to 60%; RPL 3.4 to 3.9), and advanced (CA<60%; RPL 3.6) stereonet problem skill levels (model step #2). Basic skills are those that involve plotting 2-3 planar or linear features, intermediate skills involve some conceptual knowledge, and advanced skills involve rotation about non-vertical axes.

Participants ranked the usefulness of instructional techniques ((5.0) most helpful to (1.0) not helpful). "Hands-on" techniques such as class exercises (4.6), lab problems (4.7), old exam/quiz problems (4.6) and group work (4.4) were ranked above 4.0. Participants recognized the value of model steps #2, #3, and #4. Lectures (3.8) and explanations by the instructor (3.8) were ranked between 4.0 and 3.0. These responses supported model steps #2 and #3 (ranked lower than step #4). Interactions with the text were ranked below 3.0, including extra problems from the text (2.8) and reading the text (2.5). It is possible that participants reported what they perceived as being helpful for passing this challenging course (i.e. old exam/quiz problems more helpful than extra problems from the text), not recognizing the importance of step #1 (i.e. reading the textbook). Surprisingly, responses to open ended questions about participant learning experiences implied a gradual acquisition of the concepts, not the expected transformative moments (as per multiple observed experiences in the classroom).

Siluro-Devonian Assembly of the High-grade Core of the Central Appalachian Piedmont

Howell Bosbyshell, *West Chester University of Pennsylvania*
Gale Blackmer, *Pennsylvania Geological Survey*
LeeAnn Srogi, *West Chester University of Pennsylvania*
Sandy Schenck, *Delaware Geological Survey*

Amphibolite facies metamorphic rock of the West Grove Metamorphic Suite in the central Appalachian Piedmont of SE Pennsylvania and northern Delaware occurs in a stack of basement gneiss-cored nappes or thrust sheets bounded to the north by the Pleasant Grove-Huntingdon Valley shear zone (PGHV) and to the southeast by the Rosemont shear zone (RMZ); both are steeply dipping transcurrent shear zones. The granulite facies Wilmington Complex (WC) and amphibolite facies Wissahickon Fm. (WF) occupy the block east of the RMZ. From NW to SE and structurally lowest to highest, the nappes include the West Chester massif, the Woodville nappe, the Avondale massif and the Mill Creek Anticline. U-Th-total Pb monazite ages indicate that maximum temperatures in the Mill Creek were attained in the late Silurian prior to the highest temperatures in the structurally lower Avondale nappe. In turn, peak metamorphism in the structurally lowest unit, the Doe Run schist in the West Chester nappe, is even younger – maximum temperatures were not reached until 410 Ma (early Devonian). We interpret this sequence to represent successive stacking of thrust sheets from southeast to northwest with the warmer overriding sheets contributing to the thermal budget of lower sheets. This deformation and metamorphism is interpreted to be the result of the Silurian collision of Ganderia, in a sinistral transpressive tectonic regime (Hibbard et al., 2007; 2010). The geometry of thrust sheets relative to the steeply dipping PGHV shear zone is consistent with the sinistral restraining bend at the New York promontory in the Hibbard model.

The most recent ductile deformation in the PGHV is thought to reflect dextral motion; such motion could have transported the assembled nappes from a more northerly location. The middle Devonian age of monazite in the WF suggests that Barrovian metamorphism there is the result of crustal thickening during the Acadian orogeny, the accretion of Avalon in the northern Appalachians. Given the evidence for late Devonian and younger dextral transcurrent motion regionally on the PGHV and RMZ, and throughout the Appalachians, it is likely that the crustal block east of the RMZ which contains the Wissahickon Fm. and Wilmington Complex was originally located some distance to the north.

Why Should I Care About Your Slop? Linking Shallow Geologic Observations to Deeper Earth Processes

Rich Briggs, *US Geological Survey*

Geoscientists draw on many powerful tools and techniques to document surface deformation. Ideally these observations help illuminate deeper Earth processes. However, the resolution and uncertainty of geologic observations may fail to discriminate between alternative geophysical models; conversely, geophysical models can struggle to match the richness - or is it "slop"? - of surficial measurements. I will draw on work in Sumatra, Haiti, Alaska, and Pakistan to discuss examples where relatively low precision, but well-placed surficial observations are critical for differentiating geophysical models. In my own field of earthquake geology I suggest that as rapid imaging and geodetic differencing techniques become routine, the role of the field investigator will evolve away from primary observer toward opportunistic discriminator. That is, documentation of gross anatomies - such as earthquake rupture location or length - are becoming less important than discerning features that sensors may not be able to resolve, and which might prove critical for rejecting alternate hypotheses about deep processes. Relevant examples will include coastal uplift measurements for fault slip inversions; on-versus off-fault deformation measurements from large surface ruptures; and geologic versus geodetic slip rate investigations. In the best circumstances, modelers and field teams work closely before and during fieldwork. Similarly, field teams, especially in response mode, deploy with remote sensing data and preliminary geophysical models already in hand.

Timing and Style of Deformation in the Nashoba Formation of the Nashoba Terrane, Eastern Massachusetts

Wesley Buchanan, *Colorado School of Mines*
Yvette Kuiper, *Colorado School of Mines*
Robet Buchwaldt, *Massachusetts Institute of Technology*

The Nashoba terrane (NT) is a moderately northwest-dipping fault-bounded block within the New England Appalachians and is located between the Avalon terrane to the southeast and terranes of Ganderian affinity to the northwest. The NT is a multiply deformed Cambrian-Ordovician arc-backarc complex metamorphosed up to sillimanite + potassium feldspar conditions, resulting in migmatization. This package was intruded by Silurian to earliest Carboniferous granitic and calc-alkaline intermediate-composition plutons. The Nashoba Formation (NF) in the NW portion of the NT is the best exposed metasedimentary unit in the NT and preserves a complex deformational history. The NF is comprised of biotite-feldspar-quartz ± garnet ± sillimanite ± muscovite ± amphibole ± magnetite gneiss with interlayered calc-silicate, impure quartzite, marble and sillimanite-bearing pelitic schist.

Deformation in the Nashoba Formation is dominated by isoclinal folds, overprinted by top-down-to-the-NW asymmetric folds. These folds and gneissosity in the northwest portion of the formation is cut by subvertical NW-side-down ~0.5 m wide shear zones, and later local steeply NW-dipping top-down-to-the-NW ultra-cataclasites. U-Pb zircon chemical abrasion – thermal ionization mass spectrometry (CA-TIMS) geochronology was used to bracket the ages of folding within the Nashoba Formation. A ~418 Ma pegmatitic dike cross-cuts isoclinal folds. Three migmatitic dike samples were dated and contain metamorphic, igneous, and inherited zircon. All ages reported below are interpreted as crystallization ages based on zircon morphology and high Th/U ratios. A migmatitic dike folded only by top-down-to-the-NW asymmetric folds is 364.6 ± 0.6 Ma. A planar migmatitic dike that crosscuts the asymmetric folds yielded ~364-361 Ma zircon. These two samples appear to constrain the age of asymmetric folding between ~365 and ~361 Ma. However, an isoclinally folded dike, refolded by top-down-to-the-NW asymmetric folds, is 361.4 ± 0.3 Ma, suggesting that both generations of folding are younger than that. Perhaps, folding and anatexis are diachronous across the field area, or there is possible mixing of age domains within zircon grains.

The leucosome crystallization ages presented above indicate crustal melting conditions existed between ~365 and ~361 Ma. Such Late Devonian, post-Acadian migmatitic melting has not been recognized previously in this portion of the Nashoba Formation. Partial melting may have resulted from either Neo-Acadian accretion of the Meguma terrane to the composite Laurentian margin, or from post-Acadian exhumation of the Nashoba terrane.

Mapping Deformed Pennsylvanian Rocks in the Dunkard Basin, Southwestern, Pennsylvania Using GigaPan Images

Patricia Campbell, *Slippery Rock University*
Matthew Graves, *Slippery Rock University* Michael Stapleton, *Slippery Rock University*
Thomas Anderson, *University of Pittsburgh*

Panoramic images of an outcrop produced with a GigaPan robotic camera mount and Canon EOS 60D camera are used to enhance the quality of structural analysis of deformed Pennsylvanian rocks that crop out along a 250 meter-long railroad cut in southwestern PA. Clastic rocks of the lower Casselman Formation of the Conemaugh Group record tilted beds, listric normal faults, a reactivated angular unconformity and small-scale asymmetric folds. These structures are not typical of the general flat-lying rocks that characterize this region of the Appalachian Plateau and suggest at least three episodes of sliding and extension along detachment faults. The lowest exposed units, tilted 30-40° to the south, comprise decimeter scale alternating shale and lithic-quartz arenite beds. Locally developed within the tilted blocks are small-scale, tight asymmetric detachment folds that record southward transport. A prominent angular unconformity separates the tilted blocks from overlying, sub-horizontal, medium to thick-bedded cross-stratified quartz arenite. Listric normal faults that presumably underlie the tilted section do not cut the unconformity. The basal unit above the unconformity varies from 10s of centimeters to about a meter and comprises fractured siltstone and fine-sandstone, disrupted coal beds and rounded cobbles. The deformation recorded within this unit suggests reactivation of the erosional surface during detachment of the overlying sandstone. Above the unconformity, clastic dikes cut thin, discontinuous coal seams, recording the injection of fluid-rich sandstone. Conjugate shear fractures record brittle deformation of semi-lithified beds. A late north-dipping listric normal fault that records about one meter of displacement cuts both the angular unconformity and overlying quartz arenite

Although rocks of the Dunkard Basin rarely show the complex structures recorded at this outcrop, we suggest that the normal faults and detachments record transport into the Appalachian Basin penecontemporaneous with accumulation of the Casselman Formation.

Cyclicity of Intra-Arc Deformation, Crustal Thickening and Strain Rates: Implications for Arc Tempos in the Mesozoic Sierra Nevada, California

Wenrong Cao, *University of Southern California*
Scott Paterson, *University of Southern California*

The Mesozoic Sierra Nevada Arc in the North America Cordillera records magmatic cyclicity. Its causes and links to other geological processes are long-standing questions. Existing models have emphasized processes in the fore- and retro-arc regions while downplaying the deformation within the arc itself. Our integrated research has led to the recognition of cyclic intra-arc deformation involving significant crustal thickening, pulsed material transfer processes at variable rates and of a likely role in the genesis of increased magmatism.

Field mapping and geochronology reveals three regional, angular unconformities in the central Sierra that formed during the early stages of the three magmatic flare-ups. The unconformities record episodic intra-arc deformation, erosion, and renewed volcanism/sedimentation. Structures in both host rocks and plutons in central Sierra indicate co-axial to transpressive contraction during most of the Mesozoic. These events led to at least 50-75% roughly plane strain shortening of the arc crust. Based on the geology in the host rock pendants and mass balance calculations, we propose that the intensity but not the kinematics of intra-arc deformation is cyclic mimicking a similar temporal pattern to arc magmatism. We argue that two complete and one incomplete cycles existed during the Mesozoic. A complete deformational cycle consists of a ca. 20 to 30-Myr-long higher-strain rate period (HSP, bulk shortening strain rate at least at 10^{-15}/s) followed by a ca. 40 to 50-Myr-long lower-strain rate period (LSP, strain rate at 10^{-16}/s or lower). The HSPs temporally coincide with the magmatic flare-ups and features the formation of thrusts, host rocks fabrics and strata tiling. The LSPs temporally coincide with the magmatic lulls, during which erosion, and renewed volcanism/sedimentation occurred. The styles of intra-arc deformational fields decoupled from the complication along the plate boundary during the Mesozoic indicating a possible viscosity-controlled strain partitioning. Thermobarometry in plutons indicates that the maximum exhumation of the central Sierra during the Mesozoic is about 5-7 km and thus requires significant downward transfer of host rocks (DTH). The strain rates of DTH are estimated to 6×10^{-15} to 4×10^{-14}/s, close to the strain rate of the HSP, but more rapid than the strain rate of the contemporaneous fold-and thrust belt in foreland region, whose strain rate is about 4×10^{-16}/s. We propose that thickening of arc crust invoked fertilization the magma source regions by the downward-transported crustal materials, which would contribute to the productivity of magma during flare-ups.

A Structural and U-Pb Zircon Geochronology Investigation of Selected Units in the Eastern Merrimack Belt: Implications for Post-Acadian Deformation, Eastern Massachusetts

Robert Charnock, *Colorado School of Mines*
Yvette Kuiper, *Colorado School of Mines*
Andreas Möller, *University of Kansas*
Robert Buchwaldt, *Massachusetts Institute of Technology*
J. Christopher Hepburn, *Boston College*

The Silurian metasedimentary Merrimack belt of the NE Appalachians was deformed by at least two generations of isoclinal folds that were thought to be related to the Acadian orogeny. Along the eastern margin of the Merrimack belt in Massachusetts the Harvard Conglomerate (HC) lies noncomformably on top of the Ayer Granite at Pin Hill (AG). It is tightly folded and was previously thought to be Carboniferous, suggesting that significant deformation in the HC and perhaps elsewhere in the Merrimack belt occurred during the Alleghanian orogeny. We conducted (1) detailed structural analysis, (2) detrital zircon U-Pb LA-ICP-MS analysis on the HC, the Vaughn Hill Conglomerate (VHC) directly south of the HC and the possibly underlying Vaughn Hill Formation (VHF), and (3) U-Pb CA-TIMS analysis on the AG, to test this.

The youngest single grain of the VHC is 335.4 ± 4.8 Ma, 347.7 ± 4.7 Ma for the HC, and 450.6 ± 16 Ma for the VHC. The youngest graphical peak age on a probability histogram is 334.3 Ma for VHC, 431.2 Ma for HC, and 467.2 Ma for VHF.

The zircon age distributions of the VHC and HC are very similar, with major mid-Silurian peaks and minor Proterozoic (and Archean) input, suggesting Ganderian and Laurentian sources and/or recycled Merrimack belt material. The VHF has two late-Neoproterozoic peaks, and minor Archean, Proterozoic, Cambrian and Ordovician input, consistent with metasedimentary units of the Nashoba terrane. The AG has a zircon crystallization age of 420.13 ± 0.11/0.21/0.50 Ma.

Early, cm-scale, steeply plunging tight to isoclinal folds are folded by late, m-scale, open recumbent folds in the VHC and VHF. These late recumbent folds are similar in style and orientation to cm-m-scale folds in the Silurian Worcester Formation of the Merrimack terrane, suggesting that at least some of the deformation in the Merrimack belt occurred during the Alleghanian orogeny. The HC is folded by m-scale, steeply NNW-dipping, shallowly WSW-plunging tight to open folds and by localized and late cm-scale, N and S dipping, tight folds. Thus, the deformation of the HC differs from the VHC and VHF, but the zircon provenance of the HC and VHC is similar while that of the VHF is different. The different deformation styles between the HC and VHC may be a result of competency contrast between the HC and AG in the north versus the VHC and VHF in the south, not a difference in age of the units.

Normal Faulting and Graben Development as Catalysts for Late Cenozoic Landscape Change, Fish Lake Plateau, Utah

Christopher Bailey, *College of William and Mary*
Erika Wenrich, *College of William and Mary*
Hanna Bartram, *College of William and Mary*
David Marchetti, *Western Colorado State University*
Scott Harris, *College of Charleston*

Normal fault systems create accommodation space for sediment infill and, in continental settings, segment and modify existing drainage networks. The interactions between extensional structures, sedimentation, and erosion play an important role in regional landscape evolution.

In south-central Utah the Fish Lake Plateau (FLP) forms a distinct high-elevation structural block in the transition zone between the Colorado Plateau and Basin & Range provinces. The FLP is underlain by a thick sequence of Tertiary volcanic rocks that unconformably overlie Cretaceous to Paleogene strata. Multiple generations of steeply-dipping normal faults cut bedrock units and strongly influence the topographic character of the FLP. Early-formed drainage networks developed on a gently southeast-sloping landscape that resulted from progressive rotation in the hanging wall of the Thousand Lake fault system, a major structure with ~1 km of throw that juxtaposes mid-Tertiary volcanic rocks against Jurassic strata of the Colorado Plateau.

Multiple graben complexes segment the FLP. In the eastern FLP, a suite of en-echelon NNW-trending grabens becomes progressively younger towards the east. Graben-bounding faults offset Pliocene trachybasalt and basin-fill deposits are overlain by 0.5 to 0.9 Ma boulder diamicts on Fremont River strath terraces. Fish Lake, a ~10 km^2 lake at 2,700 m in elevation, occupies a wide graben produced by ~600 m of displacement on a suite of NE-striking faults. Gravity data indicates the Fish Lake basin is underlain by 100 to 225 m of sediment, including at least two sequences of Pleistocene glaciogenic sediment. The Fish Lake graben complex cuts older NNW-trending grabens and truncates the early-formed SE-trending drainage network.

Normal faulting on the FLP accommodated only modest crustal extension (~5%), yet severed older drainage networks producing internally drained basins and local sediment depocenters. The variable orientation of FLP grabens records orthogonal extension of the region during the last 5 My. Normal faults in the FLP region likely formed due to a combination of 1) far-field stresses associated with Basin & Range extension, 2) a uniaxial stress field generated by segmentation associated with uplift and topographic isolation of the FLP, and 3) fluvial erosion along the flanks of the FLP which produces a free surface that initiates gravity-driven extension in the mechanically weak Paleogene strata and dilational normal faulting in overlying volcanic units.

Determining Hillslope-Scale Material Strength from Seismically-Triggered Landslide Events

Marin Clark, *University of Michigan*
Sean Gallen, *University of Michigan*

Natural hillslope strength or slope stability, relevant for landscape evolution and hazard assessment, falls far short of laboratory measurements of rock strength on hand-sized samples. This limitation stems from the fact that laboratory shear tests are performed on intact rock, yet it is fracture density, aperture and size that set the limit on hillslope-scale (10^2–10^3 m^2) rock strength. In this study, we exploit large earthquakes in high relief settings to quantify hillslope strength because an earthquake imparts a measurable forcing (strong ground motion) and a quantifiable landscape response (landsliding). Here we apply an infinite-slope stability model developed by the hazard community from which we can assess slope stability given known topographic slope, as a function of landslide thickness and shear-strength properties (cohesion and internal angle of friction) for a particular seismic event given measured peak ground acceleration (PGA).

Using the 2008 M7.9 Wenchuan earthquake in China as a test case, we demonstrate how PGA and observed landslides can be inverted to quantify hillslope-scape rock strength. Our preliminary results suggest that tectonic history and climate factors, rather than lithology, play a more fundamental role in rock strength at large spatial scales.

Southeastward Propagation of Thermotectonism within the Paleoproterozoic Big Sky Orogeny: New Constraints from the N. Madison Range, SW Montana

Cailey Condit, *University of Colorado*
Kevin Mahan, *University of Colorado*
Alexis Ault, *University of Arizona*

Spatial and temporal patterns of deformation and metamorphism can yield insight into the kinematics, rheology, and overall tectonic significance of exhumed paleo-orogens, and allow better understanding of the processes at work in active orogens of similar scales. The Big Sky orogen in SW Montana is recognized as a late Paleoproterozoic convergent belt with a general NW-SE shortening direction. Previous work in the Highland range, the farthest NW exposure of known Big Sky affected rocks, document zircon growth and peak P-T conditions at ~1810-1780 Ma. Farther to the SE, the Tobacco Root Mountains and northwest N. Madison Range experienced conditions of ~1.0-1.2 GPa and 800°C between 1775 and 1750 Ma. These data suggest a potential pattern of younging thermotectonism from NW to SE that we have tested by analyzing basement rocks along a continued transect to the southeast.

New geochronological, petrological and structural data for the SE-central portion of the N. Madison range indicates that these rocks were also extensively reworked during the Big Sky orogeny. Multiple samples constrain peak metamorphism and deformation occurring at conditions of ~0.85 GPa and 715°C. Both SIMS U-Pb zircon and U-Th total-Pb monazite EMP geochronology constrain the timing of this metamorphism and deformation to between ~1750-1720 Ma. Thus, peak metamorphic conditions appear to progressively young from ~1810-1780 Ma in the NW to ~1750-1720 Ma in the SE. We interpret this space-time pattern to represent propagation of shortening and regional metamorphism within the Big Sky hinterland from NW to SE over 50-90 m.y., period. The high-grade metamorphic core of the Big Sky Orogen extends over a minimum length scale of ~100 km from the Highland Mountains SE to at least the central N. Madison range. This extended core encompasses half of the exposed hinterland-foreland length of ~200 km as defined by discrete Paleoproterozoic, but otherwise poorly dated, greenschist-grade structures in ranges further to the southeast. This space- time pattern of propagation and 100 km orogenic length scale provide better context for understanding the significance of Big Sky Orogen, one of North America's most recently recognized major collisional belts.

Geochronology of Rare Earth Element Mineralization in a High-Grade Metamorphic Terrane, Music Valley, California

John Cottle, *University of California, Santa Barbara*
S. Tyson McKinney, *University of California, Santa Barbara*
Graham Lederer, *University of California, Santa Barbara*
Paige Granneman, *University of California, Santa Barbara*

Monazite and xenotime occur in ore-grade concentrations within Proterozoic gneiss in the Music Valley region (MVR) of southern California. However, the age and petrogenesis of this potentially economically significant rare earth element (REE) deposit remain uncertain. A combined petrologic and geochronologic approach using SEM imaging, EPMA x-ray mapping and LA-MC-ICPMS geochronology reveals textural and temporal relationships between REE mineralization and the surrounding geology. Monazite and xenotime are restricted to biotite folia within the host Pinto Gneiss with highest concentrations occuring in close proximity to contacts between the host gneiss and diorite bodies (Gold Park Diorite), the latter of which are cut by felsic pegmatite veins that appear to have been generated by partial melting of the Pinto Gneiss. SEM imaging and EPMA x-ray mapping reveal anhedral to subhedral ore-forming monazite and subhedral to euhedral xenotime with complex internal elemental zoning. Dissolution/re-precipitation textures overprint relict oscillitory zoning with xenotime and uranothorite forming from breakdown of monazite and vice-versa (monazite and uranothorite forming from original xenotime), suggesting a later metasomatic event affected the ore body. Petrographic evidence for a reaction involving breakdown of monazite, anorthite, and biotite to form apatite and allanite also suggests later-stage metasomatism. Monazite and xenotime U-Th/Pb geochronology constrains REE mineralization to c. 1785 Ma, consistent with zircon ages obtained from the same rocks. Zircons from the Gold Park Diorite yield ages of c. 1400 Ma while those of the cross-cutting pegmatite veins yield ages of c. 166 Ma. The relatively narrow range of ages and uniform Th/U ratios of zircons from the Pinto Gneiss suggest an igneous protolith. The similarity in ages between the monazite, xenotime and zircon along with the relict igneous zoning in the phosphate minerals indicates that REE-mineralization in the Pinto Gneiss occurred during crystallization of the igneous protolith. Pegmatite genesis at c. 166 Ma post-dates the main phase of REE-mineralization but may be related to fluid-assisted alteration of the ore body.

Finding Active Faults Using Earthquake Focal Mechanisms, Geomorphic Analysis and Field Work (SLAM)

Vincent Cronin, *Baylor University*
Jordan Dickinson, *Baylor University*

The seismo-lineament analysis method (SLAM) uses an earthquake focal mechanism and a DEM or topographic map, along with geomorphic analysis, to spatially correlate the earthquake with the causative fault.

What is a seismo-lineament? Each double-couple focal mechanism has two nodal planes that are normal to each other, one of which coincides with the fault that generated the earthquake. Uncertainties in hypocenter location and nodal-plane orientation combine to form the uncertainty volume associated with each nodal plane. A seismo-lineament is the intersection of that uncertainty volume with the ground surface. Each seismo-lineament is a swath across the ground surface within which the trace of the causative fault is likely to be found if [a] the nodal plane coincides with the fault plane (i.e., it is not the auxiliary plane), [b] the earthquake occurred in the upper crust, [c] the fault is approximately planar from the hypocenter to the ground surface, and [d] the fault is emergent at the ground surface. SLAM does not require the earthquake to have actually ruptured the ground surface; however, a small earthquake must have occurred along a fault that deformed the ground surface sometime during its displacement history.

Seismo-lineament boundaries are usually mapped using an open-source code written in Mathematica, although a description of the underlying algorithm enables the boundaries to be defined manually on a topographic map. After the seismo-lineament boundaries are defined, geomorphic analysis is conducted using a DEM-based hillshade image illumined perpendicular to the nodal-plane strike, to identify any geomorphic features that might have developed due to fault displacement. Subsequent fieldwork is undertaken to locate exposures of faults or fault-related geomorphic features.

In addition to its scientific utility, SLAM provides students with a meaningful experience in the use of scientific data (earthquake focal mechanisms and DEMs), geomorphic analysis, hypothesis generation, and field work to test the hypotheses. SLAM has been used by undergraduate and graduate students to yield reasonable spatial correlations between recorded earthquakes and faults. We have spatially correlated earthquakes with known active faults, with faults that were not known to be active, and with faults that had not previously been mapped. In the future, seismo-lineament swaths might be used to design aerial LiDAR surveys conducted to identify faults through recognition of characteristic structural geomorphology. More information about SLAM is available via http://bearspace.baylor.edu/Vince_Cronin/www/SLAM/.

Thin-skinned Models for Undergraduate Teaching Labs - Flour Structures

Dan Davis, *Stony Brook University*

Analog modeling of thin-skinned tectonics can be useful in teaching as well as in research. Unfortunately, such modeling is typically not well suited for use in undergraduate teaching laboratories in structural geology. Typical 'sandbox' models take considerable time and effort to set up and are difficult to exhume in order to analyze the structures that have formed. We present here a very simple and inexpensive way for an undergraduate lab class to explore the effects of a variety of geometries and mechanical parameters in thin-skinned deformation. The experiments use only easily obtained materials: flour, sandpaper, graphite, transparency sheets, and athletic field marker chalk. In each experiment, students place flour with colored marker beds within a large shallow box (a geologic sample drawer is ideal), and they set up the model using sieves, brushes, and wooden blocks.

Although the model scaling is not perfect (scaled cohesion is about an order of magnitude high), students can easily model many aspects of thin-skinned deformation. Because the experiments are so easy to set up, a typical lab class can be split into a half dozen or more separate experiments, each with different boundary conditions and set up by separate groups of 2 or 3 students. For example, the effects of basal detachment strength on wedge taper, horizontal strain, and on thrust density and vergence can be modeled simply by placing either sandpaper or graphite on the base of the drawer. A horizontal sheet of wood or Plexiglas in front of the pushing block allows modeling a forearc with a double accretionary wedge, outer-are high, and forearc basin. Along-strike contrasts in the model can be used to generate flower structures and wrench tectonics. A block of wood glued to the base of the box in the 'foreland' and can be used to mimic the effects of basement structure.

Football field `hash marks' placed at 10 cm intervals allow for easy calculation of strain distribution at any time during or after the experiment. The model can be excavated at any angle using a plastic photocopier transparency sheet. Thin layers of colored field marker chalk between flour layers make it possible to reveal many internal details of the fold-thrust belts that have been generated, including along-strike structures.

These 'flour experiments' have proved to be a fun, inexpensive, and highly effective way to teach about thin-skinned deformation. The poster will be accompanied by suggested lesson plans.

Tracking Fault History in Sandbox Models

Dan Davis, *Stony Brook University*
Saad Haq, *Purdue University*
Christopher Grady, *Stony Brook University*

In recent years, the non-Coulomb behavior of sand has been mapped out (e.g., Lohrmann et al., 2003), with initial failure governed by a peak stress and subsequent shear taking place at a lower, stable stress. Similar behavior is observed in natural sedimentary rocks such as those found in fold and thrust belts. We have used particle image velocimetry (PIV) analysis of imaged analog modeling experiments map the strain rate field throughout a series of modeling experiments in the Haq modeling lab at Purdue. These data allow measurements of the dip angles of the series of thrust faults, including occasional out-of sequence thrusts and backthrusts.

In this poster we describe the results from one such experiment, for which we determined the orientation history of each forward thrust that formed. We find that successive forward thrusts in the experiment experience similar evolutionary cycles: initiation at a steep angle followed by shallowing with time until a new active forward thrust is generated at the front of the wedge. At that point slip ceases and the fault (shear) ceases to slip, steepens, and undergoes repeated periods of reactivation.

Prior to a distinct point in the experiment, a large portion of the nascent wedge is not near failure. During this early stage, each new thrust experiences a similar, stable evolution with a dip at the time when slip ceases within 10° of the dip at the time of fault initiation. Starting at a distinct point in the experiment, however, a critical wedge grows, with each thrust forms at a near-uniform steep dip prescribed by the internal friction before experiencing a steady decline to about 7°. This dip range appears to be defined by the nearly ideal Coulomb slip criteria of the wedge and its base. Other, related work demonstrates that the initial formation of pop-up structures at the model deformation front are consistent with the Coulomb criterion, but that the basal boundary condition becomes important only after a small but finite amount of shortening in the structure.

Preliminary results are consistent with fault evolution governed by the constraints on the stress field of simultaneous failure on the thrusts and the basal detachment. It is also consistent with mechanical behavior of the deforming sand that is not simply Mohr-Coulomb, but rather one that is initially strain-weakening.

Rotation Statistics in Structural Geology

Joshua Davis, *Carleton College*
Sarah Titus, *Carleton College*
Basil Tikoff, *University of Wisconsin, Madison*

Many geologic data are geometric in nature, consisting not just of numbers but also of directions, rotations, ellipsoids, and tensors. For example, lineations and foliation poles are both directional quantities. It is common to plot foliation and lineation data separately on stereographic projections. However, divorcing foliations from their lineations in this way results in a loss of information. Instead, we propose that each foliation-lineation pair be represented mathematically as a rotation (the rotation that takes the standard x- and y-axes to the lineation and foliation pole).

In this presentation, we summarize various tools of rotation statistics --- some new, and others borrowed from crystallography, robotics, medical imaging, and other fields --- and apply them to geologic problems such as the analysis of foliation-lineation data. We describe a novel system of displaying rotations as points in a three-dimensional plot. By depicting rotation axis and angle simultaneously, this plot can reveal outliers in rotational data, that are not apparent in other depictions. Our plot has an equal-volume property, so that it correctly represents density relationships, much as an equal-area hemispherical projection does. We adapt the concept of Kamb contouring to this setting, generating contour surfaces for density of rotational data. We also compare various conceptions of mean, variance, normal distribution, and other statistical notions in the setting of rotations. Using a simulation technique known as Markov chain Monte Carlo, we construct Bayes credible regions (analogous to confidence regions) for mean and variance of rotational data. As an example application, we consider lineation-foliation data from the western Idaho shear zone.

The Central Piedmont Shear Zone of the Southern Appalachian Piedmont

Allen Dennis, *University of South Carolina, Aiken*

The central Piedmont shear zone in western South Carolina, sometimes called the Cross Anchor fault, juxtaposes Ediacaran-Cambrian rocks of Carolinia with Silurian Cat Square (CS) paragneiss. The most recent major movement on the fault is Pennsylvanian, and is related to emplacement of a large composite crystalline thrust sheet. Lower metamorphic grade Carolina terrane rocks are in the hanging wall, and higher grade CS rocks are in the footwall. The Charlotte t of Carolinia is an exotic peri-Gondwanan arc terrane that experienced peak metamorphic conditions (upper greenschist to amphibolite facies) between 538-535 Ma. The Wenlock-Ludlow protolith of CS paragneiss included sediments derived from both Carolinia and Laurentia, and was metamorphosed to upper amphibolite facies at the Devonian-Mississippian boundary. There is no strain gradient associated with the CPSZ; generally the fault crosscuts the foliation, and the fault and foliation were subsequently folded. In central South Carolina the CPSZ is rotated to a near horizontal orientation, and footwall rocks of the CS t are exposed within the Whitmire reentrant.

The Central Piedmont shear zone is not the suture between Carolinia and Laurentia. Several lines of evidence suggest that Carolinia accreted to Laurentia in the Middle Ordovician, and subsequently rifted from the continent. Sedimentary rocks of the CS basin were deposited during this rifting event, accepting detritus from both the accreted terrane and Laurentia and covering their suture. The structure mapped as the Brindle Creek fault originally formed as the unconformity beneath the CS basin. When southern Appalachian crystalline rocks southeast of the Burnsville fault and Brevard zone are restored to their Devonian position at the New York Promontory after removing ≥ 500 km of dextral motion, it is clear that the CS basin is a southern extension of the system of Salinic basins that covers much of New England and the Canadian Maritimes. Asymmetric lithospheric thinning was coeval with CS basin deposition, and a suite of 424-414 Ma lower crustal melts (e.g., Newberry granite, Lake Murray gneiss, Clouds Creek pluton) intrudes Carolinia. These magmas were followed by a linear array of ca. 400 Ma mantle-derived alkalic-subalkalic gabbros and ring syenites. Frasnian-Fammenian collapse of the CS basin and metamorphism up to granulite facies is recorded as the Neoacadian orogeny. Subsequent dextral strike-slip motion along the Burnsville/Brevard faults during the Mississippian brought these terranes south where oblique-slip emplacement of the crystalline thrust sheet resulted in their current juxtaposition.

Virtual Geological Mapping and Development of Geospatial Analysis Competencies Using Google Earth and Related Digital Technologies

Declan De Paor, *Old Dominion University*
GEODE Team*

Field geology, especially structural and tectonic mapping, has long been a central part of geoscience education. Many programs require a residential field camp as a capstone course and many students express great enthusiasm about their structural mapping experiences. However, there is evidence that fieldwork deters underrepresented minorities and agility requirements limit access of sessile students to geoscience desk jobs. (Sessile students are those who are either unwilling or unable to go to the field in person for physical, economic, or cultural reasons). As part of a large NSF-funded collaboration called GEODE (Google Earth for Onsite and Distance Education) we are working to enable students to acquire competencies in geospatial analysis using Google mapping tools and related technologies. These include Google Maps, Google Earth, Google Maps Engine, Google Earth Engine, and associated visualization tools such as GigaPans, GigaMacros, Photospheres, and COLLADA models. These technologies allow students to take a 'grand tour,' virtually visiting a global range of tectonic settings on Earth and other planets and moons. Students can learn geospatial concepts and competencies in an engaging game-like setting and can access big geodata for authentic undergraduate research opportunities. In addition to serving the needs of sessile students, we anticipate that digital geospatial learning resources will help agile students by augmenting their physics field experiences.

**The GEODE collaboration includes: Heather Almquist, Callan Bentley, Aurthur Bern, Stephen Burgin, Meredith Butler, Cinzia Cervato, Chloe Constants, Gene Cooper, Declan De Paor, Mladen Dordevic, Andy Dunaway, Janice Gobert, Paul Karabinos, Filis McGuirk, Terry Pavlis, Jen Piatek, Cari Rand, Bill Richards, Nathan Rogers, Robin Rohrback, Jeff Ryan, Ron Schott, Kristen St John, Barb Tewksbury, Swaraj Wankhade, and Steve Whitmeyer.*

The rich isotopic memory of illite; an example of clay dating and fluid fingerprinting from the Zimapán Basin in Central Mexico

Elisa Fitz-Díaz, *Universidad Nacional Autónoma de México*
John Cottle, *University of California, Santa Barbara*
Ben van der Pluijm, *University of Michigan*

Besides vein-forming minerals such as quartz and calcite, clay minerals are one of a few species that grow during deformation in the upper crust. Among the family of clay minerals, illite contains a particularly rich isotopic memory that can be applied to a variety of geologic studies. Illite contains potassium, a radioactive element that can be used to obtain the age of deformation through Ar-Ar dating. Illite also contains structural water (OH^- ions in the octahedral layer), which, through δ^2H or $\delta^{18}O$ analyses, can provide information on the source(s) of the fluids present during deformation. Finally, illite contains boron in its structure, which provides independent information on the nature of the fluid(s) that were active during deformation and/or ambient temperature conditions.

In order to understand the mechanisms and significance of illite crystallization in syn-tectonic veins, a structural, textural and isotopic study was conducted on rocks of the well-exposed and well-preserved Zimapan Basin of Central Mexico. This now-inverted basin contains a succession of Cretaceous deep-water marine carbonates, which were strongly folded during the Late Cretaceous. Structural observations identify two shortening events in these rocks (tight folds refolded in spaced open folds and two generations of axial plane cleavage). SEM analysis of shales that were sheared parallel to bedding during flexural folding, show that illite grains grew parallel to cleavage. Based on Ar-Ar illite age analysis (IAA) of neocrystallized clays these events are constrained to have occurred at 80-84 Ma and 75-77 Ma. New in-situ U-Th/Pb ages from monazite included in calcite and quartz from syntectonic stretching veins agree within uncertainty of the Ar-Ar data, supporting the robust nature of the IAA. δ^2H analyses of both illite and fluid inclusions show that they grew in isotopic equilibrium with pore water that was a mixture of marine and meteoric sources, reflecting a combination of fluid re-cycling marine water meteoric water infiltration during basin inversion and regional deformation.

What, if Anything, Should the Structural Geologist Know about the Mechanics of Rock Deformation?

Raymond C. Fletcher, *Pennsylvania State University*

Much work in structural geology does not involve mechanics. An example is the determination of the complex structure of metamorphic rocks in New England, an area of limited outcrop, which has involved dozens of workers and 10s to 100s of structural geology person-years. Concepts of stress, strain or rheological behavior are not required. Another example is the construction of a balanced cross-section using the geometric methods of fault-bend and fault-propagation folding.

Concepts of stress, strain and rheological behavior, incompletely integrated into a complete mechanics, are of limited use in the formulation and answering of questions and problems in structural geology. Maybe they are distracting. Stress, without equations of stress equilibrium; strain, excluding kinematics; and results on deformation mechanisms, excluding specification of constitutive relations do not allow formulation of models (boundary-value problems). It seems pointless to introduce these concepts unless the development is brought to the point of modeling. Is the student motivated? I first encountered a BVP ~50 years ago, for flow of a viscous fluid between approaching, or separating, rigid plates, in Jaeger's: Elasticity, Fracture and Flow with Engineering and Geological Applications.

A question and procedure for answering it, which involves substantial knowledge of a complete mechanics, is embodied in Gilbert's study of laccoliths in the Henry Mountains. The "sketch," more a "mental construct" than an interpretative drawing, but which incorporates such drawings, starts with motivating observations: (i) the image of a laccolith lifting the super-incumbent rocks; and (ii) the increase in size of a laccolith with depth. He "sketched," in his imagination, a mechanical model that fit these observations. It is not appropriate to think of his model as "simple."

Questions concerning process, involving mechanics, often enter as after-thoughts. Gay (1968) presented a relation for the deformation of a viscous elliptical cylindrical inclusion embedded in a viscous host in plane flow. Bilby et al. (1975) showed that this result was incorrect. Treagus & Treagus (2001) used it to estimate the bulk strain of a polymict conglomerate and the relative viscosities of its components. Whatever Gay thought, his result is the exact result for a viscous sphere embedded in an incompressible viscous medium. As an example of the application of a complete mechanics, I discuss the mechanics of objects – lingula, crinoid ossicles and concretions - used to estimate strain in the central Appalachians. Several unanswered questions raised earlier by structural geologists are answered.

Reconciling Invariant Topography with Significant Along-Strike Gradients in Climate and Tectonics in the Greater Caucasus

Adam Forte, *Arizona State University*
Kelin Whipple, *Arizona State University*

The Greater Caucasus Mountains (GC) are a predominantly east-west striking orogen, that lie between the Black and Caspian Seas and represent the locus of NE-SW directed convergence in the central Arabia-Eurasia collision zone. Despite significant along-strike gradients in climate, convergence rate, structural geometries, crustal structure and exposed lithologies, the topography of the GC is remarkably invariant. In detail, the western end of the range is a predominantly singly-sided, south-directed orogen lacking a well developed fold-thrust belt, with hinterland exposures of basement rocks, may have experienced a slab-detachment event, has a low modern convergence rate of 1-4 mm/yr and a high mean annual precipitation (MAP) of 1-2 m/yr. Contrastingly, the eastern end of the range is a doubly-vergent orogen with active fold-thrust belts in both the northern and southern forelands, is devoid of basement exposures, is underlain by a subducting slab, and experiences a convergence rate of 8-12 mm/yr and MAP of only 0.1-0.5 m/yr. On their own, the gradients in climate and convergence predict a narrow and low elevation range in the high-precipitation, low- convergence west and a wide and high elevation orogen in the low-precipitation, high-convergence east. However, the actual topography of the GC is instead characterized by remarkably similar maximum elevations, 2.5 km scale relief, orogen width, and cross-sectional area along the strike of the range. This disconnect between the topography and the various forcing mechanisms could reflect either (1) a dynamic balance between competing along-strike gradients, or (2) one or more of the driving mechanisms have changed recently and the topography of the range has not yet responded.

Importantly, these two alternatives make fundamentally different predictions regarding along-strike variation in millennial- scale erosion rates. Although no published erosion rates exist for the GC to date, we can utilize established relationships between catchment scale erosion rates and topography (hillslope gradients and channel steepness) developed elsewhere to assess whether an along-strike gradient in erosion rates is likely in the GC. The relationship between channel steepness and mean hillslope gradient is invariant along strike and suggestive of a moderate erosional efficiency, implying no significant climatic control on topography and erosion rates. This finding suggests that there is no significant along-strike gradient in either erosion or rock uplift rates, implying that gradients in MAP and convergence are compensated for by other forcing mechanisms. Ultimately, measurements of catchment-scale erosion rates along-strike are essential to test these ideas.

Pre-Timiskaming Folding in the Archean Southern Abitibi Greenstone Belt, Ontario and Québec, Canada: Structural Constraints and Conundrums

Ben M. Frieman, *Colorado School of Mines*
Yvette D. Kuiper, *Colorado School of Mines*
Thomas Monecke, *Colorado School of Mines*
Nigel M. Kelly, *Colorado School of Mines*

Preliminary structural observations from the southern Abitibi subprovince (SAS) of Ontario and Quebec, Canada, suggest that tight to isoclinal folding occurred before deposition of the ~2680-2670 Timiskaming episode sedimentary rocks. Rocks affected by pre-Timiskaming structure display little to no internal deformation and the mechanism of folding is therefore unclear. The SAS is one of the largest continuous, best exposed, and well-studied Archean greenstone belts in the world. The geological history of the SAS is characterized by a relatively long phase (>2750-2695 Ma) of seafloor volcanism followed by uplift, sedimentary basin formation, and deformation. In the SAS, two major episodes of sedimentary basin formation are recognized based on temporal and stratigraphic constraints: the ~2695-2685 Ma Porcupine episode and the ~2680-2670 Ma Timiskaming episode. Porcupine episode sedimentary rocks are dominated by turbiditic facies rocks deposited in a submarine setting. Timiskaming episode sedimentary rocks contain fluvial to alluvial conglomerate and sandstone units. Throughout the study area, Timiskaming episode rocks unconformably overlie older volcanic greenstone and Porcupine episode rocks. Here we document a number of localities that expose this unconformity and define pre-Timiskaming structure throughout the SAS, including from west to east: the Kenogami, Perron, Doig, Grace, and Rouyn unconformities. At these localities, layers with opposite facing directions in the older volcanic greenstone are truncated by the Timiskaming unconformity, suggesting the existence of isoclinal folds prior to sedimentation. Some localities display back-to-back facing relationships between Timiskaming and older stratigraphic units while others display relatively high angle angular unconformities. Fold hinges are rarely observed in the field and are commonly inferred from map patterns. Based on these observations, pre-Timiskaming folds are characterized by 1-10 kilometer wavelengths and shallow plunges. Post-Timiskaming deformation resulted in the development of penetrative fabrics in all rocks of the SAS and is characterized by flattening fabrics and either a steeply plunging or subhorizontal lineation, especially along long-lived, crustal deformation zones that crosscut the SAS. Typically, no penetrative fabric is associated with the pre-Timiskaming folds away from these deformation zones. In general, formation of isoclinal folds requires substantial pure shear strain, or, more commonly, simple or general shear strain, all of which typically result in associated penetrative fabrics such as foliations, lineations, and/or shear fabrics. The absence of such fabrics in association with pre-Timiskaming isoclinal folds and the preservation of pristine primary structures such as volcanic pillows in these folded rocks remain problematic. The potential mechanisms for formation of these folds will be discussed.

Anatomy of the 200 km-Long, Left-Lateral Surface Rupture from the 24 September 2013 Mw 7.7 Balochistan Earthquake, Southern Pakistan

Ryan Gold, *U.S. Geological Survey*
Nadine Reitman, *U.S. Geological Survey*
Richard Briggs, *U.S. Geological Survey*
William Barnhart, *U.S. Geological Survey*
Gavin Hayes, *U.S. Geological Survey*

The 24 September 2013 Mw7.7 Balochistan earthquake ruptured a ~200 km-long stretch of the Hoshab fault in southern Pakistan. We mapped the extent of this left-lateral surface rupture using high-resolution (0.5 m) pre- and post-event satellite imagery. The continuous rupture passed through several stepovers ranging in width from 0.5-1.0 km. The width of the surface rupture zone ranges from <5 m to 2 km. We find that peak sinistral displacement values measured on geologic piercing points (offset streams, terrace risers, roads, etc.) approach ~12 m and that displacements are inversely correlated to the width of the surface rupture zone (e.g., largest displacements where the fault zone is narrowest). We also analyzed pre-event imagery spanning the Hoshab fault and find evidence for previous strike-slip faulting at the SW and NE extent of the rupture, though evidence is lacking for repeated, frequent, and large strike-slip events on this fault system. Through ongoing analysis of pre- and post-event imagery, we plan to assess the relative percentages of deformation that occurred on-fault as opposed to off-fault. These results will have implications for geologic fault slip-rate studies, paleoseismic studies that estimate earthquake magnitudes from geomorphic offsets, and comparisons of geodetic and geologic slip-rate data.

New Approaches to Teaching Spatial Thinking in the Context of Structural Geology

Laurel Goodwin, *University of Wisconsin, Madison*
Carol Ormand, *SERC, Carleton College*
Kristin Gagnier, *Temple University*
Kinnari Atit, *Temple University*

We all understand that spatial thinking skills are essential for student success in visualizing 3D structures or collections of structures from 2D sections (maps, outcrop or hand sample surfaces, and thin sections), and solving 3D problems. Yet our undergraduate geoscience majors bring a wide range of spatial skill levels to the classroom, and we learn from experience that even the brightest students may struggle with 3D visualization and manipulation. Recent research shows, however, that spatial thinking improves with practice, and can improve more rapidly with intentional training. We report on the results of a collaborative effort to apply lessons learned from cognitive science research to the development of teaching materials to improve structural geology students' spatial thinking skills.

Promising teaching strategies that have emerged from recent cognitive science research into spatial thinking include gesture and visual comparison. Gesture is familiar to most geoscientists as a means of communication, particularly for spatial information, but is less likely to be consciously employed as a teaching strategy. Nonetheless, recent studies have shown that using gesture can facilitate student learning, and that students who gesture learn better than those who just watch their instructors gesture. Visual comparison is exactly what it sounds like. Comparison draws students' attention to similarities and differences between familiar and unfamiliar structures or concepts.

Research into the utility of incorporating these strategies into a Structural Geology course at the University of Wisconsin - Madison began in Spring, 2012. We are using a pre- and post-test study design, with a series of tests of spatial thinking skills administered at the beginning and end of each semester. In 2012, we used a "business as usual" approach to the course to gather baseline data, measuring how much students' spatial thinking skills improved in response to more typical geological methods of developing 3D thinking skills. Pre- to post-test comparisons showed that most students' spatial skills improved over the course of an academic term, with average gains on the order of 10%. In 2013 and 2014 we incorporated curricular materials informed by cognitive science research, in an attempt to boost students' spatial learning gains.

We are currently collecting post-test data for this year, and will complete analyses before the Forum. These data will allow us to determine whether the research-based teaching materials we developed boost students' spatial thinking skills beyond the gains we would expect them to show from completing a Structural Geology course.

Out of Sequence Thrusting in Coulomb Wedges

Saad Haq, *Purdue University*

The theory of Critical Coulomb wedges in conjunction with scaled analog models has been successful in explaining the pattern of deformation in accretionary prisms and thin-skinned fold and thrust belts under a variety of mechanical conditions. In this study we use frictional analog models, along with detailed kinematic analysis of developing structures in cross-section (using image correlation and particle tracking) to investigate the mechanism for the development of out- of-sequence (OSS) thrusting in contractional systems. We examine the influence that a hinterland-ward increase in bulk mechanical strength, normal to the convergence direction, which occurs as the wedge becomes mechanically consolidated with time, has on OSS faulting. While some OSS thrusting is expected in a wedge to maintain a tapered topography and a force balance, a hinterland-ward increase in strength can lead to significant OSS slip on both older and newly formed thrust structures. In nature the observation of major OOS thrusting is frequently associated with the development of mega-splay faults in accretionary prisms. These faults frequently produce large tsunami due to their steep dip. We investigate the mechanical conditions that can enhance or decrease OOS fore and back-thrusting in frictional wedges, including the role of fault orientation, basal friction, and sedimentation. We find that significant OOS thrusting is an inevitable process in frictional wedges even under constant mechanical conditions, that small variations in wedge strength will enhance the need for OOS thrusting, and that this process is cyclical in behavior driven by ongoing frontal thrust accretion with periodic recovery of taper and followed by additional OSS faulting.

Interactions Between Regional Transcurrent Shearing, Rifting, and Mantle Flow on Venus: Radar and Gravity Interpretations and Earth Analogues

Lyal Harris, *INRS-ETE, Québec, Canada*

Venus is dominated by upwelling and downwelling mantle plumes within a stagnant lid or transitional convection regime. NASA's Magellan radar imagery does not show any evidence for single-sided subduction zones, spreading ridge-transforms, nor arcuate volcanic chains that typify present-day plate tectonics on Earth and there is consensus that plate tectonics does not occur on Venus. Radar data over part of W Ishtar Terra portrays brittle-ductile shear zones within orogenic belts on the margins of the ‘craton-like’ Lakshmi Planum. A fold-thrust-transpressional shear belt and high plateau, with structural and Bouguer gravity similarities to the Himalayan orogen and Tibetan Plateau on Earth, developed N of Lakshmi Planum. On the western N- to NE-trending planum margin, the offset of lithological layering and early structures along shear zones and fold-shear relationships indicate sinistral transpression. Dextral shearing along the NNW trending E planum margin and sinistral shearing on sub-parallel structures 500 km E of Lakshmi Planum are interpreted. Folds, shear zones, and rifts are similar in geometry to those associated with regional indentation and lateral escape during formation of the Himalayas and the Eastern Alps on Earth. Northward displacement of Lakshmi Planum refutes the conjecture that there have been no large horizontal displacements on Venus.

Bouguer gravity images and horizontal gravity gradient edges ('worms') portray hitherto unrecognized crustal structures on Venus. Belts of high Bouguer gravity and thinned crust (comparable to the Mid-Continent Rift in N America) suggest underplating of denser, mantle-derived material beneath extended crust. Rifts are partitioned by transfer faults and flank a zone of mantle upwelling between colinear upwelling mantle plumes. Gravity data support the model for northward drift and indentation of Lakshmi Planum. Reversal of transcurrent displacement senses and fold and thrust overprinting imply an orthogonal change in principal strains. The large displacements of areas of continent-like crust are interpreted to result from mantle tractions / pressure acting against their deep lithospheric mantle 'keels' commensurate with extension in adjacent rifts. Displacements of the continent-like Lakshmi Planum and Ovda and Thetis Regiones on Venus cannot be attributed to plate boundary forces (ridge push, slab pull). Continent-like 'drift' on Venus resembles the westward translation of the Americas and continued northward displacement of India which are driven by mantle flow tractions on Precambrian cratonic keels. This new perspective of Venus provides an analogue for an Archean Earth without plate tectonics.

SCLM Rifting and Regional Shearing in the North American Superior Craton: Implications for Deformation, Mineralization, and Tectonic Reconstructions

Lyal Harris, *INRS-ETE, Québec, Canada*
Jean Bédard, *Geological Survey of Canada, Québec, Canada*

3D images of S-wave seismic tomographic velocity anomalies for the Superior Province, N America, illustrate that the Abitibi Subprovince overlies a symmetrical rift in the sub-continental lithospheric mantle (SCLM) of an older 'proto-craton' (N Superior Province and Minnesota River Valley domain). Mantle plume activity led to necking, focussed thermal erosion, destruction and assimilation of ancient lithosphere, and formation of isotopically juvenile crust in a volcanic plateau-like setting. Whilst generally E-W-trending, the interpreted Archaean rift changes to a NW-SE orientation in the easternmost Abitibi and Grenville Province parautochthon. The NW-SE trending rift segment parallels the Belomorian Province separating the Kola and Karelian cratons abutting the Superior Province in tectonic reconstructions. The change in orientation by 120° suggests rifting may have occurred over a mantle plume. The NE segment of an Archaean sinistral, NE-striking shear zone (the proto-Grenville shear zone), interpreted from the offset of gravity and aeromagnetic anomalies along the SE margin of the Abitibi and Opatica subprovinces, similarly makes a 120° angle with the two rift segments and follows an aulacogen in the rifted SCLM.

Early rift structures localized ca. 2696 Ma deformation and hydrothermal fluid flow. Enhanced aeromagnetic images of the central-northern Abitibi illustrate penetrative E-W dextral ductile shearing preceded formation of discrete conjugate transcurrent and E-W reverse (± dextral) shear zones implying ca. N-S bulk shortening. The displacement history and geometry of shear zones in the Abitibi Subprovince is similar to that of structures developed during progressive lateral escape and indentation during impingement of a rigid body. We propose that southward migration of the old cratonic nucleus (N Superior Craton) in response to mantle flow acting upon its deep lithospheric keel, and not subduction-related processes, led to progressive southward accretion of crustal fragments and oceanic plateaux-like segments, shortening and inverting the initial rift. Major epigenetic gold deposits are located above rift-bounding faults in the SCLM, suggesting that early rift structures localized subsequent deformation and hydrothermal fluid flow. The 1.1 Ga Desmaraisville and 0.55 Ga Otish kimberlite clusters also coincide with interpreted SCLM rifts. Outcomes highlight the important role of ancient mantle structures on localizing deformation, hydrothermal fluid flow, emplacement of igneous bodies, and mineralization in the overlying crust.

Funding: Laurentian Goldfields, NSERC, Richmond Minerals, Fort Chimo Minerals, and DIVEX. The seismic tomographic database was provided by S. Godey.

Rheology of the Crust During Syn-Convergent Extension: Insights from the Cordillera Blanca Detachment, Peru

Micah Jessup, *University of Tennessee, Knoxville*
Colin Shaw, *Montana State University*
Cameron Hughes, *University of Tennessee, Knoxville*

Models for the rheology of the lithosphere rely on data derived from shear zones that were exhumed in various tectonic settings. The Cordillera Blanca detachment, extending for 200 km along orogenic strike, occurs in the Peruvian segment of the central Andes. It records a zone of syn-convergent extension within the highest elevations (>6,000 m) in this portion of the Andes. The footwall, dominated by leucogranodiorite of the Cordillera Blanca batholith (8 Ma), hosts a shear zone that records a range of deformation conditions that can be used to characterize the rheology of the middle crust during syn-convergent extension.

The detachment strikes northwest-southeast and exhibits a range of dip angles between 10-45° southwest. From deeper to shallower structural positions in the 100-500-m-thick mylonitic zone, solid-state fabric overprints early magmatic fabrics. Kinematic indicators such as mica fish, S-C fabrics, oblique grain shape fabrics, and sigma-clasts consistently record top-down-to-the-southwest sense of shear. The deepest structural positions contain quartz dominated by grain boundary migration recrystallization (>500°C). At intermediate structural positions, quartz recrystallization by subgrain rotation (400-500°C) begins to overprint grain boundary migration. Within the intermediate and shallowest structural positions, localized zones of ultra-mylonite are dominated by smaller grain sizes and record quartz recrystallization by bulging (280-400°C). A zone of cataclasite, including angular clasts composed of mylonitic quartz defines the top of the shear zone.

Preliminary EBSD analysis was conducted on samples representing quartz recrystallization conditions that range from grain boundary migration through bulging. LPO are dominated by prism slip in samples that preserve a range between grain boundary migration and subgrain rotation recrystallization. For samples that predominantly record subgrain rotation, the LPO begins to form a central girdle, indicating a more complex combination of slip systems (prism, rhomb, basal). Paleopiezometric calculations from samples with grain boundary migration and subgrain rotation yield estimates between 32-83 MPa.

Creating, Disseminating, and Testing Interactive 3D Models for Teaching Structural Geology

Paul Karabinos, Williams College

Many fundamental geologic concepts are rooted in 3D spatial relationships. Well-crafted 2D perspective diagrams illuminate such relationships for some students, but interactive 3D models help a much wider range of students visualize complex geometries. In particular, students commonly learn how to solve specific problems using 2D projections but many fail to link the solution to the underlying 3D geometry. SketchUp is a particularly useful program for creating 3D models because it is relatively easy to learn and a free version exists. 3D SketchUp models illustrate how the stereographic projection works and how geologic maps and cross-sections summarize the geology of an area. 3D models show how structure contours can test if a contact is planar, determine the strike and dip of planar beds, find the true thickness of stratigraphic units, solve the 3-point problem, determine the depth of a target unit, estimate displacement across faults, and create cross-sections. SketchUp Pro is required to create dynamic components, which can be used in the free version, and add another level of interactivity to SketchUp models. For example, models illustrating how the stereographic projection works can incorporate dynamic components so that the user can specify strike and dip or trend and plunge and explore how planes and lines will plot.

Creating effective 3D models is only the first step. Only motivated users will download a new program or plugin and take the time to learn how to use it. The models must, therefore, be easily accessible to instructors and students and be intuitive to use. The real challenge is to provide interactive 3D models in a familiar format. SketchUp models can be exported as COLLADA digital asset exchange (.dae) files, and incorporated into an iBook as interactive 3D models using iBooks Author for IOS devices. The .dae files can also be uploaded to Sketchfab, a web service designed to publish and display 3D models. Once uploaded to Sketchfab, the models may be embedded in a webpage where anyone with a Web GL enabled browser can view them. A third promising approach is to export SketchUp models as 3D PDFs and incorporate them in digital instructional materials.

One advantage of 3D PDFs is that it should be possible to rigorously test how much 3D models improve student understanding of concepts by creating two sets of parallel teaching materials with identical text that differ only in whether perspective images or interactive 3D models are used.

Advances in Quantifying Crustal Stress Magnitudes

Steven Kidder, *City College New York*

Recrystallized grain size has been used to quantify the magnitude of the stresses involved in the ductile deformation of rocks for nearly 40 years. While the practice has experienced a resurgence recently, it remains a subject of considerable skepticism. Oft-cited concerns relate to the accuracy of extrapolations from laboratory conditions to nature, and the applicability of the technique in rocks that may not generally have been deformed at steady state. I provide evidence challenging both these concerns. First, stress estimates based on grain size data from Taiwan are remarkably consistent with independent estimates of stress in the Taiwan orogenic wedge. Second, experiments on quartzite under non-steady state conditions demonstrate that steady state is not required. To demonstrate the potential of the technique and a new, non-genetic approach to collecting and displaying grain size data, I present a data set of quartz grain sizes using ~250 thin sections spanning the length of New Zealand's Alpine Fault. Among other things the data demonstrate that stress magnitudes at the brittle-ductile transition double towards the ends of the fault. Recrystallized grain size piezometry is viable and inexpensive. It should be more widely utilized. Geodynamic models, for example, can be developed in tandem with actual measurements of stress magnitudes in rock samples to provide an extra dimension of testability and to better reveal gaps in our understanding of rock rheology.

Fault Surface Geometry, Wear Processes and Evolution: Implications for Earthquake Mechanics and Fault Rock Rheology

James Kirkpatrick, *Colorado State University*
Kate Shervais, *Colorado State University*

To investigate how fault geometry impacts fault surface stresses, strain localization and wear during deformation, we use digital mapping techniques to collect observations of faults in two orientations. Terrestrial laser scanner (TLS) point clouds that define slickensides show that 3D fault surfaces are non-planar at all scales of observation. We use the point clouds to measure slickenline orientations, which do not vary significantly over exposed fault surfaces. Assuming the slickenlines parallel the local maximum resolved shear stress direction, the results show that the shear stress direction does not vary spatially. This suggests geometric asperities at exposure length scales (up to a few m) cause relatively minor stress perturbations. We model the scale-dependent strain of asperities during slip and show that relatively small asperities fail inelastically and support little stress, while larger ones deform elastically. Using structure-from-motion to produce rectified images of faults in cross section, we map the internal structure of the Boyd fault, CA. Our observations show that the thickness of fault rock varies along strike. Gouge-filled injections provide evidence for coseismic pressurization, and show that earthquake slip is distributed across layers of fault rock that vary in thickness from 10-3 to 10-2 m thickness over 101 m distances. Cross cutting relationships between different generations of gouge show that fault gouge formation is a non steady-state process, with multiple discrete layers forming successively. The roughness of the edges of gouge layers decreases with displacement, consistent with wear models. However, we document evidence for failure of wall rock protrusions that are entrained into the fault gouge, a process that is episodic and serves to both increase gouge volume and increase fault roughness. Together, the two data sets show that fault strength and fault rock rheology are a function of fault core and slip zone geometry.

Geological Field Research: An Ideal Course 'Recipe' for Advanced Undergraduate and Beginning Graduate Students

Yvette Kuiper, *Colorado School of Mines*

A Geological Field Research course is an excellent way for students to learn to design and carry out their own (field- based) research. The course is set up in three parts. In the first part, students write a brief research proposal including hypotheses, tests and a work plan for the next two weeks. We study appropriate literature and take an introductory field trip to the field area. The second week focuses on field work. In the third week, students prepare a geological map and appropriate cross sections, and a report presenting rock descriptions, structural analysis, a geological history, and interpretation of results in the context of the hypotheses posed in the proposal. The course can be taught in three weeks as a three-credit course, where each part described above takes one week. It can easily be modified into a longer (but not shorter) course, and/or one that is taught over several weekends and a number of weekday in-class meetings during the semester.

Students gain experience in geological mapping and field methods in general, but, perhaps more importantly, they learn how to formulate a testable hypothesis, carry out the research and write a concise and clear report. They also read each other's proposals, and give each other constructive feedback through a mock NSF panel discussion. Furthermore, they learn how to deal with field logistics and to collaborate with their field partners. The effectiveness of the course can (on top of the student deliverables and course evaluations) be assessed through course-specific questionnaires at the beginning and the end of the course to monitor students' skills, expectations, goals and confidence.

The Geological Field Research course is ideal for students who will be conducting thesis research involving a significant structural mapping component. Especially students who will be conducting (thesis) research in the area where the course is taught will be well prepared. Furthermore, the course is an excellent way for the instructor to learn more about the field area. This is in particular useful for faculty trying to start new research projects in an area they are not fully familiar with.

Thus, the course serves both students and instructors well, not only because of the learning and teaching experience, but also by possibly enhancing their research.

Visuospatial Ability and Geologic Mapping: Experts and Novices in the Field

Nicole LaDue, *Northern Illinois University*
Heather Petcovic, *Western Michigan University*
Julie Libarkin, *Michigan State University*
D. Zachary Hambrick, *Michigan State University*
Kathleen Baker, *Western Michigan University*

Bedrock geologic mapping is a complex and cognitively demanding task. Most US geology majors receive training in geologic mapping, however, we know little about the cognitive processes that underlie successful mapping and about how these processes change with education and experience. To address this gap, sixty-seven geologists (54% male, mean age = 36.4 years, 21% undergraduate students, 28% graduate students, 55% with professional work experience) completed a suite of cognitive tests and a 1 day field mapping project in the Rocky Mountains, Montana, USA. The cognitive tests included measures of domain content knowledge, visuospatial ability, perceptual ability, and working memory capacity. Geologic problem solving was assessed through a bedrock mapping task in which participant movement was tracked via GPS. The map area was 70 hectares and included a plunging syncline, one limb of which is cut by a thrust fault. Following the mapping task, participants were interviewed to gain further insight about their mental models of the map area.

We report on the observed relationships between visuospatial ability, domain content knowledge, navigation in the field, and success in the mapping task among novices and experts in order to address the general question: what role does visuospatial ability play in successful geologic mapping? Results from this study indicate: (1) a significant visuospatial ability by geological knowledge interaction, such that there was a positive correlation of visuospatial ability with map accuracy for low geology knowledge participants (novices) but not for high knowledge participants, (2) success at the mapping task (both in accuracy of the rock distribution and correct interpretation of the structures) correlated with both geological knowledge and thoroughness ($p<.05$), (3) correct structural interpretation positively correlated with speed ($p<.05$) for experience mappers only, (4) participants' mental model accuracy positively correlated with other measures of map quality (map spatial accuracy and map structural interpretation) and geologic knowledge, and (5) for participants with low mental model accuracy, visuospatial ability correlates with understanding the distribution of rocks. Overall, the data suggest that visuospatial ability may be less important in geologic mapping than previously assumed. Visuospatial ability appears to play a role in developing accurate representations of the spatial distribution of rocks in a field area, but not in developing models of the 3D structural geology. Instead, geologic knowledge appears to play a much more critical role in developing accurate 3D geologic interpretations during mapping.

Using High-Resolution Basin Analysis to Unravel Complex Fault Kinematics, Understand Tectonic Events and Address Climate Change in the Central Basin and Range

Melissa Lamb, *University of St. Thomas*
Sue Beard, *USGS*
Thomas Hickson, *University of St. Thomas*
Paul Umhoefer, *Northern Arizona University*

The Lake Mead Area is a key area to study extensional processes (e.g., Anderson (1971; Wernicke and Axen, 1988) as well as the evolution of the Colorado River and Grand Canyon (e.g., Karlstrom et al., 2014). Much work in this area focused on structural analysis and thermochronolgy (e.g., Reiners et al., 2000; Dubendorfer, 1988) but Beard (1996) recognized the need to study the complex stratigraphy as well in order to answer many remaining questions. The Horse Spring Formation (HSF) records the fill of basins that formed prior to and during the main phase of extension, ~17 and ~8 Ma. Ranging from >25 to ~12 Ma, the HSF consists of a variable mix of carbonates, siliciclastics, tuffs, and evaporites that formed in a series of large and small basins. The deposits have been subsequently beautifully exposed due to down cutting of Colorado River tributaries, possibly due to establishment of the Colorado River in the area at 5-6 Ma. We set out to define and characterize these basins in detail to reconstruct the complex faulting and tectonic evolution of the area.

Because the HSF stratigraphy is so variable in terms of lateral and vertical facies, it can be hard to map across faults but this complexity is actually advantageous: separate basins and subbasins have their own unique characteristics that can be used to unravel the deformation. Highly variable lithologies allowed us to better define these basins and understand depositional environments. Numerous tuffs allowed us to create a detailed chronostratigraphy: we probed 216 tuff samples for geochemical fingerprinting and dated 22 samples using $^{40}Ar/^{39}Ar$ geochronology. We measured numerous detailed sections and, in the highly variable areas, walked out beds to document lateral changes. We mapped at 1:5000 and 1:10,000 scales and conducted paleocurrent and provenance analyses in key areas. Finally, we ran 715 carbonate samples for stable O and C isotope analyses.

With this huge integrated dataset, we defined several large and small basins and determined many of the faults that created them and when faulting occurred. We identified growth faulting at two different times within HSF deposition and began to distinguish tectonic and climatic signals in the stratigraphic record. We are creating a step-by-step tectonic reconstruction of the entire area from 18 Ma to present. Our structural analyses have benefitted greatly from the multidisciplinary, detailed approach. It has also been a very successful tool for engaging students in research at all scales.

Geochronology and Himalayan Tectonics

Kyle Larson, *University of British Columbia, Okanagan*

Increasingly sophisticated geochronologic analytical techniques are providing the opportunity to collect data at spatial resolutions that were not achievable and in quantities not feasible previously. The advances in spatially constrained geochronologic techniques and the incorporation of simultaneously collected rare earth element data have made it possible to interpret detailed petrochronologic histories recorded in single grains. These techniques have been instrumental in providing new data and geochronologic constraints on the tectonic evolution of orogenic systems that can be tied to both the metamorphic and deformational histories through geochronometer mineral chemistry and textural setting. There are many recent examples of the unparalleled insight this type of study can provide. One such investigation, carried out in west-central Nepal, serves as particularly instructive case study on how petrochronologic data can help provide the information necessary to constrain complex tectonic histories and elucidate parts of that history that may not be readily apparent through other observational means or analyses.

New monazite U-Th/Pb geochronologic data from the Annapurna region of west-central Nepal outline a protracted growth history spanning ~ 31 myr from the Early Eocene (c. 49 Ma) to the Early Miocene (c. 18 Ma). Rare earth element data collected concomitant with the isotopic analyses is consistent with early prograde metamorphism between ~ 49 and 40 Ma, followed by continued high-grade metamorphism between ~ 38 and 30 Ma and finally large-scale anatexis between ~ 28 and 18 Ma. The timing of metamorphism recorded in these rocks is consistent with records of crustal shortening derived from ultra-high pressure terranes of the western Himalaya and related ranges and crosscutting dykes in deformed sedimentary rocks of southern Tibet. The ages extracted in this study are the first to extend the record of Early Eocene shortening, related to the initial collision of India with Asia, south into the main Himalaya. This has important implications for tectonic reconstructions and shortening rate estimates made for the Himalaya, which commonly ignore this early, poorly constrained history. Moreover, these new dates provide information on the timescale of initial continent-continent convergent margin evolution.

Strain Localization (and De-localization?) in Deep Continental Crust: Examples from an Exhumed Section and Remote Observations from still Deep Crust in North America

Kevin H. Mahan, *University of Colorado, Boulder*
Sean Regan, *University of Massachusetts, Amherst*
Omero P. Orlandini, *University of Colorado, Boulder*
Gregory Dumond, *University of Arkansas, Fayetteville*
Shannon Leslie, University of Colorado, *Boulder*
Michael L. Williams, *University of Massachusetts, Amherst*
Vera Schulte-Pelkum, *University of Colorado, Boulder*

Rock records of strain localization provide insight into changing internal and external conditions during shear zone development. They also provide a means for interpreting the evolution of complex multiphase terranes, both those now exhumed and those still deep. This presentation will 1) review examples of multi-scale interactions between deformation and metamorphism in the exposed Athabasca Granulite Terrane (AGT) in the western Canadian shield, and 2) explore seismic anisotropy as a crustal deformation mapping tool with recently published regional examples and a new image from EarthScope's full Transportable Array.

The AGT records at least 700 m.y. of tectonism, but emphasis here is on structures that developed during the peak and exhumational stages of the youngest event (1.9-1.8 Ga). The 1.88 Ga Cora Lake shear zone is a dominantly sinistral strike-slip structure characterized by multiple strands of ultramylonite superimposed on a ~5 km wide zone of mylonite. Rock types vary but all display evidence for deformation under relatively dry, high-pressure granulite-facies conditions (1.0-0.8 GPa, 850-750°C). The ultramylonite zones also host pseudotachylyte networks and associated kinematically compatible shear fracture systems. Stable granulite-facies mineral assemblages (e.g., grain-size reduced pyroxene) in the immediate vicinity of the shear fractures and local development of new garnet in the pseudotachylyte matrix suggest seismic slip under hot and deep crustal conditions.

A younger set of structures in the AGT include two several km-wide zones of 1.85 Ga amphibolite-facies mylonite. The thrust sense Legs Lake and dextral strike-slip Grease River shear zones are both distinguished from the Cora Lake structure by pervasive synkinematic hydration. Fluid infiltration, perhaps initially into brittle or semibrittle structures in deep crust, like those still preserved in the Cora Lake shear zone, allowed re-equilibration under mid-crustal P-T conditions
(0.5 GPa, 600 °C). Reaction-weakening via growth of mica and amphibole in previously drier rock facilitated a conversion back to fully plastic and more widely distributed flow. Thus, the AGT may record portions of multiple cycles of distributed and focused deformation even within already localized high strain zones via a range of plastic to brittle modes. Data obtained from terranes such as the AGT also form a basis for the use of seismic anisotropy as a detection and mapping tool for both focused and distributed deformation in modern deep crust. Particularly if augmented with available higher resolution regional data, these tools can allow greater advancement in understanding where and how deformation is focused in orogenic systems.

Belly of the Beast: Detailed Mapping in the Deformation Core of a Quartz-Plastic Transitional Zone Fault: Implications for Deep Fault Seismicity on Major Strike Slip Faults

Ben Melosh, *McGill University*
Christie Rowe, *McGill University*
Christopher Gerbi, *University of Maine*

The Pofadder Shear Zone (Namibia-South Africa) is a right lateral, strike-slip structure, exhumed from the quartz brittle-plastic transition. In respect to lithology, kinematics and scale this shear zone is an ancient analog to the modern southern San Andreas Fault. Temperatures of deformation estimated from quartz microstructures and CPO patterns in mylonites are ~350-450°C. Detailed mapping (1:100) of the deformation core provides a first look into the guts of this transpressional shear zone at deep seismogenic depths. The shear zone is filled with many brittle faults that occur parallel to the mylonitic foliation and host off-fault tensile fracture networks suggestive of dynamic earthquake ruptures. There are no gouge or wear products on these surfaces. Some breccias are plastically healed, suggesting that a strain rate pulse, rather than exhumation to cooler temperatures is the most plausible mechanism for their formation. Unlike upper-crustal brittle structures, on which repeated seismic events may occur on a single fault, we find a distribution of earthquake markers across the width of the 30 m wide shear zone. These markers, which include dynamic fracture networks and pseudotachylyte, appear to coincide with the highest strain mylonites near competency contrasts at the shear zone boundaries. Our observations provide new insight into the distribution, evolution and interaction of strain rate sensitive mechanisms in the quartz transitional zone and contain implications for deep fault seismicity or microseismicity.

Evaluating the Effectiveness of Flinn's K-Value Versus Lode's Ratio

Matty Mookerjee, *Sonoma State University*

Lode's ratio (ν) and Flinn's k-value are the most commonly used parameters for characterizing the shape of ellipsoids. Both parameters characterize this shape by utilizing ratios of the lengths of the principal axes. For oblate, plane strain, and prolate ellipsoids, there is an exact relationship between k and ν; however, this is not true for any other ellipsoid. In fact, as k approaches zero and infinity, the possible range in ν is 1.0, i.e., 50% of its total range. Correspondingly, as ν approaches zero from either the right or the left, the possible range in k is 50% of its total range.

Given the inherent differences between k and ν, we use synthetic datasets as a means of comparing the relative effectiveness of these two shape parameters in different strain regimes. Lode's ratio demonstrated a largely strain shape-independent set of standard deviations whereas the k-value datasets were significantly dependent on strain shape and magnitude. Furthermore, the geometry of the confidence regions within the Flinn diagram are very much strain regime dependent, making it difficult to compare kinimatic data with a range of k-values. In lieu of these results, we encourage investigators to more critically evaluate their choice of ellipsoid shape parameter.

Strain-Induced Rutilation of Quartz in Mylonites and Timescales of Ductility in an Extensional Shear Zone

William Nachlas, *University of Minnesota*
Donna Whitney, *University of Minnesota*
Christian Teyssier, *University of Minnesota*
Rory McFadden, *Salem State University*

We document rutile needles that have exsolved from quartz during retrograde shearing and exhumation in an extensional shear zone. The Pioneer Core Complex (PCC) of north-central Idaho, USA, is a domal exposure of gneissic basement rocks in the hinterland of the Sevier orogenic belt. Eocene exhumation of the PCC was accommodated by the brittle- ductile Wildhorse detachment system (WDS), which localized in a zone of ductilely-sheared metasediments and juxtaposes lower crustal migmatitic gneisses with upper crustal Paleozoic sediments. Deformation in the WDS was partially localized within a continuous sequence (~200 m) of quartzite mylonites, wherein quartz grains are densely rutilated with microscopic rutile needles that are strongly oriented into the axis of flow. Quantitative analysis of the Ti content of rutilated quartz using in-situ techniques (EMPA, SIMS) is hampered by the very small size and close spacing of the needles and the trace concentration levels of Ti substitution in quartz. Instead, we apply cathodoluminescence (CL) intensity as a proxy for Ti content to semi-quantitatively map the Ti concentration field surrounding rutile needles. A depletion halo in CL intensity surrounding rutile indicates an exsolution (unmixing) origin, and we use the length and geometry of the CL intensity profile as a snapshot into the kinetics of Ti diffusion during exsolution. Three samples spaced throughout the quartzite section were analyzed and reveal unique diffusion distances and profile geometries recorded at different levels of the shear zone. By constraining temperature estimates from classical thermometers in nearby rocks and from applying Ti-in-quartz thermobarometry to recrystallized quartz in the same samples, we are able to bracket the duration of ductile shearing in the WDS. Applying the experimentally-determined Arrhenius relationship for Ti diffusion in quartz, results of our diffusion analysis show that if the shear zone was deforming at T=500°C, then the predicted timescales for exsolution range from 0.63 – 3.1 Myr; if the shear zone was deforming at T=600°C, then the predicted timescales for exsolution range from 0.05 – 0.23 Myr. If we posit that crystal plastic deformation of quartz is an effective mechanism to facilitate Ti exchange in response to changing solubility conditions, then our approach introduces a new technique to constrain the duration of ductile deformation in shear zones.

Paleocene Paleoelevations of the Basin and Range from Clumped Isotope Thermometry and Paleosol Geochemistry: A Modest Nevadaplano?

Nathan Niemi, *University of Michigan*

The Basin and Range Province of the western United States is one of the premier examples of diffuse continental extension in the world. Estimates of extension across the Basin and Range during the Cenozoic range from 200% province-wide to locally as great as 400%. However, crustal thicknesses across this region, as derived from a variety of geophysical methods, are remarkably uniform and, at ~35 km thick, are similar to global averages. Reconciling large- magnitude crustal extension with observed crustal thicknesses is difficult without calling on one of three possible alternatives: (1) an Andean-plateau crustal thickness of ~60 km at the termination of the Sevier Orogeny and prior to extension; (2) substantial addition of material to the crust by syn-extensional magmatism or (3) mobilization and redistribution of fluid lower crust during extension. Quantitative paleoelevation histories can help discriminate between these competing mechanisms for widespread Cenozoic extension. New estimates of pre-extensional paleoelevations for the northern and central Basin and Range are presented using clumped isotope (Δ47) thermometry of lacustrine carbonates that suggest modest (~2-3 km) pre-extensional elevations for the northern Basin and Range and quite low (<1 km) elevations for the southern Basin and Range. These paleoelevations are incompatible with mass balance considerations based on the observed magnitude of crustal extension and modern crustal thicknesses, and imply that crustal mass was added to the Basin and Range during extension, either from magmatism or crustal flow.

Applying Cognitive Science Research to Improve Geoscience Teaching and Learning

Carol Ormand, *SERC, Carleton College*
Thomas F. Shipley, *Psychology, Temple University*
Basil Tikoff, *University of Wisconsin, Madison*

The Spatial Intelligence and Learning Center conducts research on spatial thinking in the geological sciences, with two complementary goals: to better understand how humans reason about complex spatial problems and to use that understanding to improve science education. Spatial thinking is pervasive in the geological sciences, and particularly so within structural geology and tectonics, making us an excellent study population. SILC research demonstrates that the term "spatial skills" encompasses a wide range of specific skills, that these skills improve with practice, and that particular strategies and tools can be used to move learners along the novice-expert spectrum.

Work on characterizing the spatial thinking skills utilized in the geological sciences has revealed a broad array of skills, including (but not limited to) mental rotation, perspective taking, navigation, penetrative thinking, scaling, 3D visualization (volumetric thinking), and 4D visualization (mental animation). Measuring these skills in an individual is non-trivial, and is a prerequisite to assessing the development of spatial skills or comparing spatial skills between groups, such as undergraduate majors, graduate students, and professionals. Where psychometric instruments exist, we have used them. In other cases we have begun developing new instruments to measure specific spatial thinking skills. Our geoscience-cognitive science collaboration has allowed us to develop a valid and reliable test of penetrative thinking skills.

Laboratory and classroom experiments provide guidance as to teaching tools and strategies that help learners develop spatial thinking skills. Laboratory experiments reduce the number of confounding factors, thus allowing for focused testing of specific techniques in a highly controlled environment. Techniques shown to be helpful in a laboratory setting can then be imported into the classroom. However, classroom studies also need to be carefully designed. For example, many classroom studies use a pre- and post-test design to measure student learning. But to evaluate whether student learning gains are greater than they were with the previous teaching methods, one needs to compare these gains to those of a control group.

Our laboratory and classroom research support many standard teaching practices in structural geology and tectonics, and offer a few ideas and tools for improving student learning. We will present an overview of spatial skills assessment instruments, experimental design principles, and implications for teaching from our laboratory and classroom studies.

Structural Geology of the Nadaleen Trend, Northeastern Yukon Territory, Canada: Implications for Recent Au Discoveries

Justin C. Palmer, *Colorado School of Mines*
Yvette D. Kuiper, *Colorado School of Mines*

Recent Au discoveries in the eastern Nadaleen Trend of northeastern Yukon Territory are hosted in strongly deformed, unmetamorphosed, Neoproterozoic carbonate and siliciclastic rocks and display characteristics similar to Carlin-type deposits in Nevada. The complicated structural geology primarily results from mid-Cretaceous, thin-skinned fold-thrust deformation imposed upon a mechanically heterogeneous package of sedimentary rocks. Four generations of deformation resulted in tilting of stratigraphy to the SSW (D_1), several moderately- to steeply-SSW-, SW- and E-plunging hundred-meter scale chevron folds and the E-trending dextral Osiris Fault (D_2), the N-dipping reverse Nadaleen Fault zone (D_3), and the N-trending dextral Conrad Fault (D_4). Similar combinations of structures have not been recognized regionally, perhaps because the Nadaleen Trend is located in a zone of regional stratigraphic and structural transitions. Neoproterozoic- and Paleozoic-aged platform rocks occur west and north of the Nadaleen Trend; similarly aged basinal rocks occur to the east and south. Regionally extensive east-trending thrust faults, including the Dawson Thrust and Kathleen Lakes Fault, end within 10 km of the Nadaleen Trend. The combination of S-vergent thrust faults at and north of the Nadaleen Trend, and N-vergent thrust faults elsewhere in the region have the geometry of an E-trending triangle zone across the Nadaleen Trend. We suggest that these geologic transitions reflect the influence of a previously unrecognized, south-dipping basement normal fault (the Rackla Fault) that occurs west of the Nadaleen Trend and terminates below it. This fault is interpreted to have enough offset west of the Nadaleen Trend to obstruct north-directed fold-thrust movement, resulting in a lack of significant shortening to the north. The triangle zone is interpreted as a result of north-directed motion interacting with and overriding the minor obstruction at the eastern end of the Rackla Fault. Overriding the obstruction may have led to tectonic wedging and backthrusting. East of the Nadaleen Trend, fold-thrust movement was unobstructed.

Antiformal SSW-plunging D_2 structures host the Conrad, Osiris, and Isis East Au zones within the eastern Nadaleen Trend. The folds are oriented oblique to the general easterly trend of folds and thrust faults in the region. Their oblique orientation perhaps made them act as locally favorable channels for upwelling ore fluids, while the E-trending triangle zone across the Nadaleen Trend may have acted as a more regional structural funnel.

Quantitative Structural Analysis: Where Does it Start?

David Pollard, *Stanford University*
Stephen Martel, *University of Hawaii*

We address the question: what approach should one adopt to analyze problems of structural geology from a quantitative point of view? We focus here on physical processes of deformation and flow, which are key ingredients necessary to understand the development of most geologic structures, including fractures, faults, fabrics, folds, and intrusions.

Underpinning these processes are the conservation laws for mass and momentum. These laws are an attractive starting place for quantitative structural analyses, because they address general and fundamental relationships, while avoiding the need to specify particular mechanical behaviors such as elasticity, plasticity, or viscosity. These laws should be part of the conversation as one starts to analyze structures, whether standing on an outcrop, preparing an analogue experiment, loading rock into a triaxial rig, or contemplating an FEM code. In the context of continuum mechanics, these laws become the Equation of Continuity and Cauchy's First and Second Laws of Motion. In this form, stress and the kinematic quantities (velocity, rate of deformation, strain rate) are linked clearly and inextricably, indicating that one should approach geologic structures using both to guarantee the analysis is consistent with physical reality. Furthermore, the Laws of Motion encourage one to acknowledge that deformation rarely is homogeneous, and they provide the tools for analyzing spatial variations. Because Cauchy's Laws offer too few equations for the unknowns, the next step is to choose a constitutive law. Although laboratory data guide us, in most cases the ambiguities of nature necessitate treating the constitutive laws as 'trial balloons', to see what might satisfy the geologic constraints. We offer a case study of a ductile shear zone to exemplify some benefits and shortcomings of this approach. The analysis also requires geometric data, usually taken from field measurements, and often lacking in 3D coverage. Finally, boundary conditions in the form of tractions, displacements, or velocities are required. Often these are poorly constrained, so a range of conditions must be evaluated. The resulting stress, displacement, and velocity fields then are compared to field data and the procedure is repeated with new field data and laboratory insights leading to a sequence of quantitative analyses that successively provide an improved understanding. We suggest that a first course in structural geology should employ this approach in order to integrate research and teaching. We are preparing a new textbook for undergraduate students using this methodology, and welcome new members to our beta-test team.

Nucleation of Ramps in Fold-Thrust Belts: Insight from Quantitative Analysis of Sandbox Models

Pragnyadipta Sen, *University of Illinois at Urbana-Champaign*
Stephen Marshak, *University of Illinois at Urbana-Champaign*
Saad Haq, *Purdue University*

Faults in thin-skinned fold-thrust belts typically display a stair-step geometry, consisting of flats oriented parallel to bedding, linked by ramps that cut up-section across bedding. The process of fault growth leading to the establishment of ramp-flat geometry remains unclear, and a key question remains: Do ramps initiate at the detachment tip and grow up-dip from the tip into the strata above the detachment, or do they initiate within the strata and propagate both up-dip and down- dip until they link to the detachment? To answer this question, we used particle-imaging velocimetry (PIV) to document the evolutionary relationship between detachment growth and ramp growth in a sandbox model in cross-section. In the sand box (60 cm wide by 150 cm glass walled box) the model geometry consisted of a 4 cm thick sand-pack of sub- rounded quartz sand (internal friction angle $\phi = 32^\circ$) sifted on to a mylar sheet (μbasal = 0.44). Convergence was initiated by pulling the mylar below a fixed back wall. A series of high-resolution digital images were taken recording the development of individual thrusts in the developing wedge. These images were analyzed using image correlation algorithms (i.e., PIV LAB and MATLAB) to determine the displacement field in the model. Our results show that ramps initiate within the stratigraphic layer above the ramp tip, not at the detachment tip, that they grow up-dip and down dip, and that the down-dip end of the ramp links to the detachment at a point that lies to the hinterland of the detachment's tip line. Displacement parallel to the ramp decreases from the point at which the ramp initiates to each tip of the ramp. Once the ramp intersects the detachment, displacement on the detachment to the foreland of the thrust ramp slows as the displacement gets partitioned between the ramp and the detachment. When the vertical load on the ramp becomes great enough to cause it to lock, a new ramp initiates to the foreland.

Stressed Thrust Ramps Localize Fault Injectites on the Naukluft Thrust, Namibia

Timothy J. Sherry, *McGill University*
Christie D. Rowe, *McGill University*

Thrust ramps influence static stress change fields and control the style of fault deformation and damage. However, it is not fully understood how static stress change fields influence the style of fault rock deformation and off-fault damage during coseismic slip. Previous works have calculated Coulomb stress changes associated with fault slip and related these to areas of wall rock deformation or triggered slip on neighboring faults. We build on this by focusing on fault rock injectites, which are sensitive to both on-fault and off-fault stress conditions. Fault rock injectites record strain and are filled with pseudotachylyte or clay gouge on the scale of centimeters to meters in height, respectively. Here we correlate large (50-70 m) fault rock injectites located around a thrust ramp with modeled static normal stress changes to determine the influence of fault geometry on the formation of these structures. We mapped the area of the thrust ramp with differential GPS and generated a topographic surface model of the fault. Fault surface cross sections, parallel the southeast hanging wall transport direction, were input into USGS Coulomb3 software to model the geometric influence on static stress changes. The thrust ramps influence static normal stress change during fault motions by focusing stress change gradients at ramp inflection points. Along the length of the ramp, the static stresses perpendicular to the fault are in tension as the fault dilates to move past the ramp. Injectites tend to correlate with areas of sharp static stress change gradients between compressive and tensional stresses. These stress gradients are likely controls on injectite nucleation sites. Geometrically controlled static stress changes reinforce and localize coseismic dynamic stresses where areas of compressive static normal stress squeeze fluidized material towards zones of tension and wall rock fracture. We can also use the volume of injectites to constrain aspects of coseismic pressurization on the fault surface. The volume of material filling the injectites is related to the volume of fluidizing CO2 dissociated through frictional heating from the source rock. A simplified model is applied to estimate earthquake slip patch area for mixtures of CO_2 - H_2O fluidized slurries. The compressibility factor of water does not greatly influence earthquake magnitude estimates, with Mw ~ 4.2. Thrust ramps are therefore important sites for potential injectite localization and earthquake nucleation.

Initiating Localized Deformation in the Mantle

Phil Skemer, *Washington University in Saint Louis*

Shear localization is an essential feature of mantle deformation, particularly along plate boundaries. However the physical bases for localized deformation at high temperatures and pressures are poorly understood. There are a number of plausible strain-weakening mechanisms that may contribute to the initiation and evolution of shear zones, including grain-size reduction, compositional gradients, texture development, and viscous shear heating . Geologically, mantle shear zones are often identified on the basis of fine-grained, weakly textured, mylonitic microstructures. These microstructural observations are widely interpreted as evidence that dynamic recrystallization, grain-size reduction, and the associated transition to grain-size sensitive deformation is the predominant strain-weakening process in mantle rocks. To assess these ideas about shear localization I will present results from two studies. I will first describe some recent laboratory experiments. These experiments, conducted at 1 GPa and 1200°C on coarse grained synthetic harzburgite, demonstrate that the serial processes of dynamic recrystallization, phase mixing, and grain-size sensitive deformation, do not occur at small strains. Hence, I will argue that this commonly invoked strain-weakening mechanism is a consequence of localized deformation, rather than its cause. I will then compare our laboratory results with field observations from the Josephine Peridotite (SW Oregon). In this study, field measurements are used to construct strain profiles across several mantle shear zones to determine the magnitudes and gradients in strain accumulation. Measurements of water concentration in nominally anhydrous minerals show that gradients in water concentration exist on a 10-100 m scale, giving rise to spatial variations in viscosity of up to a half order of magnitude. These water concentration measurements are also correlated with the locations of shear zones and the observed olivine CPO. Using empirical flow laws we model the formation of mantle shear zones using water concentration variation to generate perturbations in the strain field. We also include in the models the effect of viscous anisotropy due to the progressive re-orientation of olivine CPO. On the basis of the laboratory experiments, field observations, and modeling, I will attempt to show that no single process can explain shear localization in the mantle. Rather, the initiation and evolution of mantle shear zones requires several independent serial processes.

Cenozoic Crustal Shortening and Plateau Uplift within the Hoh Xil Basin, North-Central Tibetan Plateau: Implications for Causal Mechanisms of Plateau Evolution

Lydia Staisch, *University of Michigan*
Nathan Niemi, *University of Michigan*
Marin Clark, *University of Michigan*
Hong Chang, *Institute of Earth Environment*

The timing and magnitude of deformation within the Hoh Xil Basin, located in the northern Tibetan Plateau, provides important constraints on the growth and uplift of orogenic plateaux. We present new $^{40}Ar/^{39}Ar$ fault gouge ages, low-temperature thermochronologic data, and a balanced cross section from the Fenghuoshan Fold and Thrust Belt (FFTB) to constrain the shortening history of the central Hoh Xil Basin. Fault gouge for $^{40}Ar/^{39}Ar$ dating suggests that thrust fault motion initiated in the mid-Eocene. Apatite fission-track data and apatite (U-Th)/He ages were modeled using HeFTy software. The modeled cooling history of the FFTB is consistent with $^{40}Ar/^{39}Ar$ fault gouge ages and suggests that deformation of the thrust belt took place from mid-Eocene to early Oligocene time. Geochronologic constraints indicate that shortening within the Hoh Xil Basin ceased by ~27 Ma. A geologic cross section across the FFTB, based on field observations and new and existing geologic mapping, was line and area balanced and uncertainties in hanging wall cut-offs, stratigraphic thicknesses, and depth to décollement were propagated to restore the cross section to an original width of 142.77 ± 10.02 km. Given the current length of this section of 103 km, we derive a shortening estimate of 40.26 ± 10.03 km (28.0 ± 7.2%). When combined with previous constraints on the timing of crustal shortening within the northern Tibetan Plateau, our work suggests that deformation initiated throughout the northern plateau near the onset of Indo-Asian collision.

We test whether Eocene – Oligocene shortening of the Hoh Xil Basin can account for published Miocene paleoelevations (3400–4200 m) by calculating isostatic uplift in response to shortening and thickening of the lithosphere. We assume that the initial elevation of the Hoh Xil Basin was similar to modern retroarc foreland basins, and thus less than 1 km. Our results indicate that 28.0 ± 7.2% crustal shortening and associated thickening produced surface uplift between 0.6 and 1.8 km and crustal thickness values of 40.2 ± 14.8 km. These results cannot account for Miocene paleoelevations or modern crustal thicknesses (65–70 km). Attainment of high elevations and modern crustal thickness require further mechanisms of crustal thickening and surface uplift, such as lower crustal flow, distributed thickening of the lower crust, and/or removal of the mantle lithosphere. These results indicate that attainment of high elevations in the Hoh Xil Basin occurred after the Oligocene, and in the absence of upper crustal shortening.

Insights About Polygonal Faults and Related Structures from Extensive Exposures of the Cretaceous Khoman Formation, Western Desert, Egypt

Barbara Tewksbury, *Hamilton College*
John Hogan, *Missouri University of Science and Technology*
Simon Kattenhorn, *University of Idaho*
Charlotte Mehrtens, *University of Vermont*
Elhamy Tarabees, *Damanhour University, Egypt*

Seismic investigations over the last 15 years in marine basins around the world have revealed the common occurrence of sets of extensional faults that intersect to form networks of large polygons, each hundreds of meters to more than a kilometer across. Although polygonal faults been studied remotely in over 100 basins worldwide, extensive on-land exposures that lend themselves to field study have remained elusive. Our work has revealed a polygonal fault system in chalk of the Khoman Formation near Farafra Oasis, Egypt that is almost continuously exposed over an area of ~1000 km^2 by a unique combination of regional structure, topography, and climate. Polygonal faults in the Khoman are expressed as a complex network of thousands of low, narrow ridges outlining polygonal areas 500-1000 m across. The polygonal ridge network consists of normal faults that occur in clusters, with the ridges held up by multi-phase calcite veins formed along faults in the chalk, along with subsidiary iron sulfide veins now altered to iron oxides. Grooves in the host chalk have rakes of 75-90°, and offsets indicate small amounts of normal slip on faults with steep dips (70° to nearly 90°). Fault geometries indicate that mechanically interacting, multiple fault orientations were active contemporaneously and that the horizontal strain field was essentially isotropic and extensional. The absence of any evidence for silica or clay indicates that models of polygonal fault initiation proposed by others involving volume loss due to diagenesis of biogenic silica or smectite is neither applicable in the Khoman nor necessary for polygonal faulting. We interpret the very steep dips to reflect fault initiation in response to elevated pore fluid pressures.

A terrain of isolated basins overlies the polygonal fault network. The basins range from ~50-200 m in diameter and have layering with very shallow inward dips. The polygonal fault system cuts and locally offsets the basins in the oldest parts of this terrain, and basins are spatially associated both with faults and radial veins. We interpret these isolated basins as fluid escape structures formed as the polygonal fault system evolved. This interpretation is consistent with multi-phase calcite veins along the polygonal faults.

Polygonal fault systems should be common in fine-grained sedimentary sequences in the rock record. Our field observations provide new insights into features of polygonal fault systems that lie below the resolution of seismic studies and that may assist in the recognition of on-land exposures elsewhere.

Relating Lattice Preferred Orientation to Deformational Process Using Statistical Analysis of Symmetry in Orientation Distribution Space

Christopher Thissen, *Yale University*
Mark Brandon, *Yale University*

We introduce and apply a new method for analyzing the symmetry of lattice preferred orientation (LPO) fabrics in deformed rocks. At present, these fabrics are usually analyzed empirically, through comparison with experimental results and inspection for asymmetry in pole figures. The symmetry elements in the structures of LPO fabrics are related to the symmetry of the deformational processes that created the LPO and can be used to interpret the symmetry of the deformation, such as pure shear vs. simple shear, plane strain vs. flattening vs. constriction, and the sense of shear in noncoaxially deformed rocks. Our analysis focuses on finding the set of statistically significant 2-fold rotation axes in the LPO fabric. We expect a simple-shear deformation to contain only a single two-fold rotation axis, perpendicular to the shear direction and parallel to the shear plane. In contrast, a coaxial flattening deformation (Sx=Sy>Sz) would have a great circle distribution of rotation axes, with the pole of the great circle equivalent to the maximum shortening direction. To estimate the two-fold rotation symmetry elements of an LPO data set, we search a grid of rotation axis orientations in the lower hemisphere of a stereonet, and rotate the LPO distribution around this axis to create a second, rotated LPO distribution. The original and rotated distributions are compared in orientation distribution space using a Kolmogorov- Smirnov test to measure the probability that the distributions are similar, save for random variation. This analysis allows us to simultaneously consider the symmetry of all of the measured crystallographic directions. Here, we apply our technique to analyze the deformation symmetry from a suite of samples collected across the Moine Thrust, Scotland.

Deformation Bands in the Etchegoin Formation: Implications for Stresses on the San Andreas Fault in Central California

Sarah Titus, *Carleton College*
Alice Newman, *University of Vermont*
Lucy Livesay, *Carleton College*
Amanda Yourd, *Carleton College*

Deformation bands are well developed in poorly-cemented blue sandstones of the Pliocene Etchegoin Formation in central California. These tabular structures occur both as individual bands and as sets of multiple, parallel, closely-spaced bands. All types of deformation bands seem to act as small faults, accommodating mm- to cm-scale offsets. We examine the orientation of deformation bands from three locations at varying distances northeast of the San Andreas fault: Parkfield (1-3 km), Kreyenhagen Hills (23 km), and Kettleman Hills (32 km). Each location is part of a relatively young fold developed in the fault borderlands. At each site, we find two conjugate sets of deformation bands. These bands tend to be steeply dipping (>75°) and mutually cross-cutting, with an angle between sets that varies from 55° to 85°. When appropriate markers are present on vertical faces, the apparent sense of motion is normal. At Parkfield, we also identify apparent strike-slip motion on horizontal outcrop surfaces. Right-lateral motion is associated with one conjugate set, and left-lateral motion is associated with the other. Restoration of each fold limb to horizontal produces more asymmetry in the orientations of deformation bands, suggesting that these structures formed during or late in the folding process.

By bisecting the acute angle between conjugate sets of deformation bands, we estimate the orientation of the local stress directions including S_{Hmax}. We find that S_{Hmax} is highest at Parkfield, with values of ~55°, comparable to results from the SAFOD pilot hole and earthquake focal mechanisms. The value of S_{Hmax} is ~45° at Kreyenhagen Hills and ~40° at Kettleman Hills. This pattern of decreasing S_{Hmax} with distance from the fault is not consistent with other estimates of stress directions from the region, such as those from the World Stress Map. However, the angle between S_{Hmax} and the local fold strike for each site is consistently 50-60°. Therefore, we suggest that estimates for S_{Hmax} far from the San Andreas fault may be controlled not by the fault but instead by anisotropies caused by local structures such as folds.

EllipseFit 3: A New Computer Program for Integrated Geological Finite Strain Analysis

Frederick Vollmer, *SUNY New Paltz*

EllipseFit 3 is an entirely new version of EllipseFit, an integrated program for geological finite strain analysis. It is designed for determining two and three-dimensional strain from oriented photographs in field and laboratory based structural geology studies. The graphical interface and multi-platform deployment also make it ideal for teaching introductory or advanced structural geology laboratories. EllipseFit 3 is currently implemented for Windows 32, Macintosh 10.5^{+}, and Linux (Ubuntu) 64 bit platforms. It is free.

EllipseFit is suitable for determining two and three dimensional strain using various objects including center points (Fry analysis), lines, ellipses, and polygons. Polygons include pebbles, fossils, or particles of any initial shape. Dirringer and Vollmer (2013), for example, calculated strain from a population of deformed graptolites using the polygon method. The analysis of strain from deformed populations of initially random polygons is therefore widely applicable to many rocks in thin section, hand sample, or on suitable outcrops.

EllipseFit allows digitizing polygons directly as vector-based polygons, or indirectly by flood fill. The first and second order polygon moments are calculated and converted to equivalent ellipses (e.g., Steger, 1996). The mean ellipse has been shown to be equivalent to the applied strain (Mulchrone and Choudhury, 2004). Mean ellipse calculations include shape- matrix eigenvalue (Shimamoto and Ikeda, 1976), mean radial length (Mulchrone, et al., 2003), and hyperboloidal vector mean (Yamaji, 2008). Error analysis is done analytically and using bootstrap techniques. The initial data set can be unstrained to check variation of the calculated pre-strain fabric. Given three or more oriented sections from a sample, EllipseFit calculates the three dimensional strain using the method of Shan (2008), with calculation of section misfits.

Graphical analysis includes the analytical Wellman method (Vollmer, 2011), normalized Fry (Erslev, 1988), polar Elliott (Elliott, 1970) and Rf/Phi (Dunnet, 1969) diagrams, strain maps, and a variety of polar and cylindrical hyperboloidal projections (stereographic, equal area, etc.) with automatic contouring. The Elliott plot is one of a family of polar hyperboloidal projection, while the Rf/Phi is a type of cylindrical hyperboloidal projection. EllipseFit 3 includes image transformations for straining images, and unstraining them to pre-deformed states. It includes image analysis routines, such as Prewitt, Sobel, and Kirsch edge detection filters, thresholding and pixel remapping. EllipseFit 3 is fully rewritten from EllipseFit 2, with tens of thousands of lines of code, in Free Pascal, a professional open source compiler that runs on over 40 operating systems.

New Thermochronologic, Paleomagnetic, and Fault-Slip Constraints on Pliocene Tectonics and Provenance, North Coast Marine area, Trinidad and Tobago

John Weber, *Grand Valley State University*
Jenny Arkle, *University of Cincinnati*
Scott Giorgis, *SUNY, Geneseo*
Jean-Claude Hippolyte, *Aix-Marseille Université*

Many important gas reservoir units in the North Coast Marine area are Pliocene-aged sandstones. The Pliocene is also a critical time in the transition from fossil Caribbean-South American plate oblique convergence to modern transform (strike-slip) tectonics.

New paleomagnetic data span key Plio-Pleistocene exposures in Trinidad and Tobago. Adjacent to the Central Range Fault in Trinidad, Plio-Pleistocene samples pass fold and reversals tests, and record 40±7˚ of clockwise rotation since the Pliocene. These data are compatible with modern transform tectonics being active as early as the Pliocene. Prior work in Tobago showed ~90˚ of clockwise rotation since the Cretaceous. New data from the mid-Pliocene Rockley Bay Formation give essentially modern paleomagnetic directions showing that Tobago has not experienced tectonic rotation since the mid-Pliocene. Thus, southeast-directed oblique plate motion of the Caribbean plate likely ceased by the Pliocene when modern eastward plate motion, together with a narrowing and a southward shift in the plate boundary, occurred.

Fault-slip data collected from 23 sites in Tobago from rocks ranging from Cretaceous (Albian) to Quaternary in age highlight four principal phases of onshore deformation: 1) Quaternary-Pliocene N-S extension, 2) *NNW-SSE compression associated with strike-slip and reverse faults, 3) *NE-SW extension that was tilted by Phase 2 faults, and 4) the oldest *NE-SW compression associated with foliated basement rocks (*provisionally given in current unrotated coordinates). Phase 1-type extensional faulting likely associated with strike-slip pull-apart steps, gravitational collapse of the obducted Tobago arc/forearc, and possibly also hinge rollback created the accommodation space offshore that was synchronously filled in by Pliocene clastic reservoir units. N-S extension continued into the Quaternary and continues even to today.

New thermochronology data include fission-track (FT) ages and time-temperature histories for a suite of 14 apatite fission-track (AP FT) samples from across the Northern Range (NR), Trinidad and in the Paria Peninsula, Venezuela. These data clearly show that the western NR (WNR) was being erosionally exhumed through ~110°C (=T blocking) in the Mio-Pliocene (ca. 6-5 Ma), at rapid rates of 0.6 mm/m.y. Whereas in the eastern NR (ENR) exhumation rates were slower (~0.2 mm/m.y.) and AP FT ages are older (ca. 13-18 Ma). New drainage-basin-wide 10Be TCN (terrestrial cosmogenic nuclide) data show slower and geographically reversed modern erosion rates, lower in the WNR (0.02-0.03 mm/m.y.) than in the ENR (0.05-0.1 mm/m.y.). AP FT samples from Tobago yield old ca. 45 Ma ages. Work in-progress using new detrital samples from onshore and offshore Pliocene reservoir units, and new samples from exposed Trinidad and Tobago basement rocks, will generate additional AP and ZR (zircon) FT data, and new AP (T blocking=70°C) and ZR (Tblocking=180°C) (U-Th)/He data. We aim to test whether the North Coast Marine Pliocene clastic fill was derived solely from the WNR or had additional sources, and if so, what and how significant these were.

New GPS Evidence for Continental Transform Fault Creep, Central Range Fault, Trinidad, Caribbean-South American Plate Boundary and Geological/Hazard Implications

John Weber, *Grand Valley State University*
Chris Churches, *Grand Valley State University*
Richard Robertson, *UWI-SRC*
Pete La Femina, *PSU*
Halldor Geirsson, *PSU*

Most continental plate boundary transform faults exhibit stick-slip behavior and lock elastically. Important exceptions include segments of the Hayward, Parkfield, and central San Andreas Faults. Studying how and why fault creep occurs has implications for our understanding how faults work in general and how to better assess their associated hazards. Trinidad is located in the Caribbean-South American (Ca-SA) dextral transform plate boundary. Weber et al. (2001, 2011), using triangulation-to-GPS geodetic measurements, discovered that the 072°-trending Central Range Fault (CRF) is the active transform in Trinidad, accommodating ~two-thirds of the total ~20 mm/yr ~E-W Ca-SA plate motion with an aseismic, interseismic slip rate of 12 ± 3 mm/yr. We build on this earlier work using new high-precision data collected between 1994 and 2014 from a set of ~25 continuous and episodic GPS stations that we processed using GIPSY-OASIS II. 2-D elastic fault dislocation modeling of the new GPS velocity field gives a best-fit (reduced $\chi 2$ = 4.119) interseismic slip-rate of 14 ± 1 mm/yr and a fault locking depth of 0.083 ± 0.153 km (model parameters given at 1σ uncertainty determined via empirical bootstrapping method). The shallow locking depth is well resolved, indicating that the CRF largely creeps. However, a sparsity of data in the east leaves open the possibility of some/more locking there. The new results are consistent with the one prehistoric (~2.7 - .55 ka; Prentice et al., 2010) earthquake trenched along the CRF being of small magnitude or possibly related to a slow-slip event, and with the low permanent neotectonic, strike-slip strain recorded/observed in the walls of the fault (Giorgis et al. 2011). We propose that a rigid northern block bounds a soft, weak, thick, Paleogene-shale-rich covered southern block along a sharp 072°-oriented inherited (?) boundary along which the neotoectonic strain concentrates. The lack of sharp, conclusive creep offsets that were searched for, but not observed on the ground (Weber et al. 2011) could mean that the CRF creeps across a relatively broad (dm-scale?) zone. We next plan to establish a series of creep arrays and a network of microseismometers and additional cGPS stations to better quantify the behavior of the CRF.

Role of Dolomite in the Development of Weak Fault Zones

Rachel Wells, *Texas A&M University*
Julie Newman, *Texas A&M University*
Steven Wojtal, *Oberlin College*

Rock adjacent to low-temperature (<200°C) fault zones typically are cut by veins with a range of orientations relative to the thrust surface. Two exposures of the Copper Creek thrust fault, TN (separated ~40 km along strike) contain numerous fault parallel calcite veins within a narrow (2-24 cm thick) shear zone. Both exposures contain Rome Formation (shale, siltstone, and dolomite) in the hanging wall and Moccasin Formation (shale and limestone) in the footwall; the primary difference between the two exposures is the thickness and location of a thick dolomite bed in the hanging wall. One exposure contains a 1-3 m thick dolomite bed within 1-10 m of the fault plane (with shale immediately adjacent to the fault plane), whereas the other exposure contains an ~8 m thick dolomite bed immediately adjacent to the fault plane. Meso- and microfractures (with little displacement) are common in the dolomite rocks. Within the calcite veins at each exposure, microstructures suggest grain size reduction by plasticity-induced fracturing followed by diffusion creep of fine-grained calcite. The lack of mesoscopic fabrics and deformation microstructures in the wall rocks suggest that deformation was primarily accommodated within these calcite filled veins and not within shale adjacent to the fault.

Similar mesoscopic structures and distribution of microstructures prevail at the Town Knob fault, TN, where the numbers of veins increase within the dolomite (Rome Formation) hanging wall and the limestone (Conasauga Group) footwall towards a narrow, "vein-like" shear zone. Curiously, the veins here contain both calcite and feldspar.

Along both the Copper Creek and Town Knob faults, the veins have formed within or near dolomite units located within the Rome Formation. At the macroscale, the Copper Creek, Town Knob and other thrust faults tend to occur in comparable sections of the Rome Formation containing dolomite beds.

Both the Copper Creek and the Town Knob faults formed at contacts between dolomite and shale or limestone. We hypothesize that the contact between the stronger dolomite beds and the weaker shale/limestone beds created a stress concentration, resulting in fracturing between the dolomite and shale or limestone. These fractures created passageways for fluids, allowing the precipitation of weaker material. Continued development of veins with low flow strengths and subsequent localization of deformation along the veins are a plausible mechanism to accommodate substantial displacement along these thrust faults.

Continuous Thermal Histories from MDD Modeling of $^{40}Ar/^{39}Ar$ K-feldspar Analyses and Applications to Extensional Tectonics

Martin Wong, *Colgate University*
Phillip Gans, *University of California, Santa Barbara*
Peter Zeitler, *Lehigh University*
Bruce Idleman, *Lehigh University*
Damien Roesler, *Colgate University*

Most tectonic processes impart a thermal signature on the crust, which has made thermochronology a critical tool for constraining the timing, magnitude, rate and spatial patterns of tectonic deformation. Most thermochronometers have a single closure temperature and therefore record cooling through one point along a T–t path of a sample. Thus, reconstruction of a complete thermal history requires the application of multiple thermchronometers and interpolation of a cooling history between point constraints, which may lead to inaccurate thermal histories. An ideal thermochronologic system would instead record a continuous thermal history over a broad range of temperatures.

One of the best opportunities to extract continuous thermal histories is the use multiple diffusion domain (MDD) modeling of $^{40}Ar/^{39}Ar$ K–feldspar diffusion data. $^{40}Ar/^{39}Ar$ K–feldspar age spectra typically show increasing ages with higher temperature step–heating experiments, suggesting the presence of multiple diffusion domains, each with a characteristic closure temperature. Domain modeling combined with inversion of the $^{40}Ar/^{39}Ar$ data can be used to constrain a set of thermal histories that satisfy the measured age spectrum. For most K–feldspar samples, MDD modeling can constrain the continuous thermal history of a sample from ~300–150°C, which is applicable to a wide range of tectonic processes and therefore represents a potentially powerful technique. However, remaining uncertainties about whether this technique yields geologically meaning thermal histories continues to hinder a broader application of this method to new geologic problems.

Here we present an overview of the MDD method and its assumptions. We then present two field-based case studies at tilted normal fault blocks in the Basin and Range, the Grayback block in AZ and Gold Butte block in NV, that document that the MDD approach is capable of producing high precision and geologically meaningful continuous thermal histories that are well calibrated with other thermochronometers. Finally, we show how MDD thermal models can be applied to investigate the timing, magnitude and rate of extensional exhumation, constrain paleo-geothermal gradients, and the initial dip of low–angle normal faults. These results document the potential utility of the MDD approach to addressing a wide spectrum of tectonic questions.

Rapid Uplift of the Kumkuli Basin since ~5 Ma as a Consequence of Large-Scale Transpressional Faulting within the Northern Tibetan Plateau

Petr Yakovlev, *University of Michigan*
Marin Clark, *University of Michigan*
Hong Chang, *Chinese Academy of Sciences, Xi'an, China*
Jiang Yi, *Chinese Academy of Sciences, Xi'an, China*

The north to northeast convergence of India with Eurasia is accommodated in northern Tibet predominantly by the left-lateral Altyn Tagh and Kunlun strike-slip faults via eastward motion of the Qaidam Basin and north-central plateau, respectively. West of ~91°E, where the east-west trending Kunlun Fault is within ~300 km of the northeast-southwest trending Altyn Tagh, it location becomes ambiguous. The Kumkuli Basin lies immediately to the northwest of this region, and contains Oligo-Pliocene strata that have undergone a minimum of 9 km or ~21% shortening, and resulted in a ~1 km high range front. Uplift of the Quimen Tagh range along the southern margin of the Qaidam Basin isolated Kumkuli, and marked the beginning of basin infilling, where the stratigraphic sequence is primarily comprised of Oligocene conglomerates and Mio-Pliocene fluvial to lacustrine sediments. Long-term Miocene aridity in the Kumkuli basin is indicated by the presence of distinct 0.2-2 m thick gypsum-rich siltstone beds. South to north paleocurrent directions, and abundant limestone and chert clasts in basin strata indicate sourcing of material from 150 km to the south in the Hoh Xil Basin. A notable coarsening upward sequence from mudstones to conglomerates at the top of the Pliocene section marks the transition from basin infilling to the initiation of deformation, which continues into Quaternary time. We use ^{36}Cl cosmogenic radionuclide dating to estimate the age and erosion rates at the tops of two folded alluvial fan surfaces, and reconstruct their original depositional elevations based on local geomorphology to derive Quaternary vertical uplift rates of 3.5-5.7 mm/yr. Estimated subsurface fold geometries translate vertical uplift into shortening rates of ~1.8 mm/yr, which are consistent with a Pliocene initiation age for deformation. The 1997 Mw 7.6 Manyi earthquake focal mechanism and associated aftershocks indicate that strike-slip faulting south of the Kumkuli Basin may begin to run sub-parallel to the Altyn Tagh fault. We link the Manyi seismic zone to the Kunlun fault based on regional seismicity, and a distinct transition from a westerly to a west-southwest trend of the Kunlun Fault as described by the 2001 Mw 7.8 Kokoxili rupture. We interpret shortening within the Kumkuli Basin to be the consequence of large-scale transpressional shear between the Altyn Tagh Fault and the Manyi seismogenic zone, both of which accommodate ~10 mm/yr of left-lateral deformation.

Author Index

Author Index

Author Index

Author Index

Notes

STRUCTURAL GEOLOGY & TECTONICS DIVISION
GEOLOGICAL SOCIETY OF AMERICA