Program, Abstract and Information Book

4th Biennial Structural Geology & Tectonics Forum 2016

Sonoma State University
Rohnert Park, CA
August 1st – 3rd

National Science Foundation
WHERE DISCOVERIES BEGIN

THE GEOLOGICAL SOCIETY OF AMERICA®
STRUCTURAL GEOLOGY & TECTONICS DIVISION

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SONOMA STATE UNIVERSITY
School of Science and Technology

SONOMA STATE GEOLOGY

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Finance Committee:
Emily Peterman (Bowdoin College) and Hal Bosbyshell (West Chester University)

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GENERAL INFORMATION

For those staying on campus

Arrival and Check-in:

When you arrive on campus, you can pick up your room key, meal card, and information packet at the Cellar Service Desk (see campus map pages vi-vii). If you are driving to campus, you can also pick up a parking pass from the Service Desk, and they can instruct you on the best lots to park in.

Meals:

If you are staying on campus, your meals are included, and you will have picked up your meal card at the Cellars Service Desk when you collected your room key. You will be eating in "The Kitchens" on the first floor of the Student Center (see campus map pages vi-vii).

Times for meals are as follows:

Breakfast 7/30-8/5	7:00-7:15am
Breakfast 8/6	8:45am
Lunch	12:00-12:15pm
Dinner 7/29-8/3	6:00-6:15pm
Dinner 8/4	6:30-6:45pm
Dinner 8/5	6:45-7:00pm

These times represent when you need to arrive for each of the meals; however, you have as long as you need to eat.

Also, boxed lunches will be provided for all field trip participants.

For those commuting to campus

Arrival and Check-in:

When you arrive on campus, you can purchase a parking pass ($5/day) at either of the two Parking Information Centers near the East Cotati Avenue and the Rohnert Park Express Way entrances to campus (see campus maps page vi-vii). Here you can get directions for the best places to park on campus. Alternatively, you can purchase a parking pass from any of the Parking Permit Meters around campus (see campus map pages vi-vii).

Meals:

If you are commuting to campus, you are on your own with regards to your meals; however, you can purchase food from "The Kitchens" on the first floor of the Student Center, where the on-campus-lodging meeting participants will be dining (e.g., lunch costs $10). There are also other eating options on and around campus:

Charlie Brown's Café (next to the first floor entrance of the campus library)
Lobo's (located on the first floor and east end of the Student Center)
Note: both of these locations are closed on Saturday and Sunday during the summer, and do not serve dinner.

Across the street (i.e., on the south side of E. Cotati Ave) is the "Wolf Den Plaza" which has several restaurants including:

Shangri-La (Himalayan cuisine and highly recommended)
Honey Cuisine (Korean BBQ)
Los Gallos Taqueria
Starbucks
Jimmy John's (a "no-frills counter-serve sandwich chain")
Swirl Time Yogurt Bar
McDonald's
Taco Bell

Field Trip Departures:

All field trips will depart from the D parking lot (see campus map pages vi-vii). All field trips will depart promptly at 8:00 am, so please arrive earlier than the departure time and make sure leave enough time to get breakfast (if desired) before you depart.

Remember that you must have registered for a field trip in order to participate.

Individual field trip leaders can provide information on what to bring on the field trips.

Boxed lunches will be provided for all field trip participants, and should be picked up in the loading area, in parking lot D (see campus map pages vi-vii).

Short Course Locations:

All short courses will be held in Darwin Hall (see campus map pages vi-vii).

See below for specific short course room numbers and start times.

Remember that you must have registered for a short course in order to participate (or contact the short course leader to see if there is any extra room).

Oral and Poster Presentations:

All Forum sessions will be held in the Student Center (see campus map pages vi-vii).

Posters will be displayed in the Student Center, Ballroom D, and will be up for the duration of the Forum. Presenters should try to put up their posters before the beginning of the first session, Monday morning.

During the Forum, all poster presenters will have 2 minutes to give a teaser-preview of their poster. These previews **WILL BE** limited to 2 minutes, with a maximum of 2 PowerPoint slides.

Oral presentations will be held in Student Center, Ballrooms B-C. Please **adhere to the time limits** set by the session conveners.

You may **upload your presentation** (either oral presentation for 2-minute teaser/preview) any time before or during the Forum at:
http://serc.carleton.edu/NAGTWorkshops/structure/2016-Forum/upload,
but please be sure that your presentation is uploaded **at least 24 hours prior to the start of your session**.

Emergency Contact Information:

SSU Police and Safety Services (on duty 24/7): located just west of Lot D (see campus map pages vi-vii)

24-hour non-emergency number: 707-664-4444

All Emergencies: dial 9-1-1

Internet Access:

When you arrive on campus you should be able to connect to the "SSULWAN" network.

On a mobile device, you should immediately be prompted to enter a user name and password; on a laptop, the first time that you open a browser, you will be prompted for the user name and password.

You will need to enter the following:

Username: *SCEvents*

Password: *F16!studentcenter*

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

1 Alumni Grove
2 Anthro. Studies Center
3 Art Building
4 Beaujolais Village
5 Bookstore
6 Cabernet Village
7 Building 49
8 Carson Hall
9 Children's School
10 Cooperage
11 Darwin Hall
12 Donald & Maureen Green Music Center
13 Environmental Technology Center
14 Facilities Management
15 Fieldhouse
16 Gymnasium
17 Holocaust & Genocide Memorial Grove
18 International Hall
19 Ives Hall
20 Joan & Sanford I. Weill Hall
21 Lakes
22 Library (Schulz Info Center)
23 Nichols Hall
24 Observatory
25 Parking & Information Center
26 Person Theatre
27 Police and Parking Services
28 Recreation Center
29 Salazar Hall
30 Sauvignon Village
31 Schulz Information Center
32 Schroeder Hall
33 Stevenson Hall
34 Student Center
35 Student Health Center
36 Technology High School
37 Tuscany Village
38 Verdot Village
39 Vietnam Veterans' Memorial
40 Wine Spectator Learning Center
41 Zinfandel Village

Dining

34 Lobo's Pizza & Pub
34 Overlook
34 Residential Dining
42 Charlie Brown's Cafe
43 Toast
44 Prelude

Services

m Parking Permit Meter
★ Police & Parking Services
707 664-4444 / Police Building
For emergencies, dial 911

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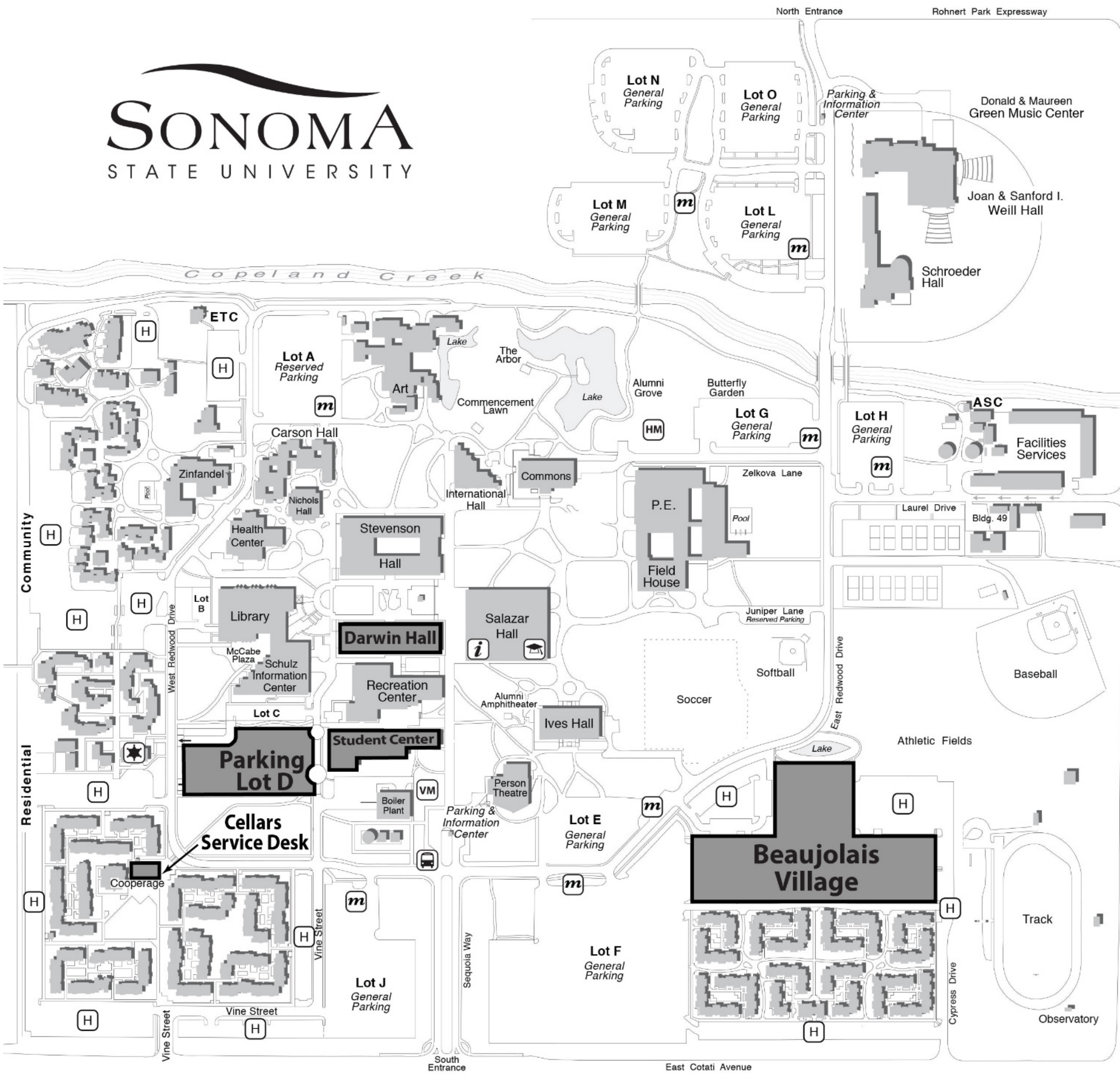

Campus Map

- Police & Safety Services
  707-664-4444 / Police Bldg.
  For emergencies, dial 911
- ASC Anthropological Studies Center
- ETC Environmental Technology Center
- m Parking Permit Meter
- H Residence Hall Parking
- Bus Stop
- Technology High School
- i Campus Tours
- VM Vietnam Veterans' Memorial
- HM Holocaust & Genocide Memorial Grove

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Forum Program

Saturday, July 30th

Field trip 1: Highlights of the Franciscan. *Leaders: David Bero, Sonoma State; Christie Rowe & Samantha Carruthers, McGill University.* **Departs at 8:00am from Parking Lot D**.

This trip will visit two world-famous highlights of the Franciscan Complex in Marin County, the Marin Headlands Terrane and Ring Mountain, to discuss the initiation of subduction in the Jurassic and accretion through the Cretaceous. The Marin Headlands Terrane consists of imbricate thrust sheets of basalt, chert and greywacke and is known for the extraordinary exposure of chaotic chevron folds in the chert sequences. The structural top of the terrane is the Point Bonita Seamount, where well-preserved pillows, dykes and sills are visible on a short walk to the Point Bonita Lighthouse that offers stunning views of the Golden Gate. We will visit the Rodeo Cove Thrust exposures on Cronkite Beach.

Ring Mountain is home to the most diverse collection of high pressure, low temperature metamorphic rocks anywhere in the Franciscan Complex. Eclogite-, blueschist-, amphibolite- and greenschist-facies metabasite blocks occur in a serpentinite matrix mélange below a harzburgite thrust sheet that caps the mountain. The exotic block mélange was thrust over a sliver of blueschist-grade broken formation (including clastics, metabasalts and chert), which was in turn thrust over folded prehnite-pumpellyite-facies sandstones and shales. This is a unique opportunity to hike through the structural evolution and metamorphic inversion that characterizes the subduction complex.

Field trip 2: Eastern Northern Coast Ranges (Wine Country Geology). *Leader: Eldridge Moores, UC Davis.* **Departs at 8:00am from Parking Lot D**.

This one-day field trip plans to traverse parts of the northern Coast Ranges east of Rohnert Park in Sonoma Valley, Napa Valley, and eastward. We will travel through Sonoma Valley, the Mayacamas mountains to the east, Napa Valley, and the Vaca Mountains, between Napa Valley and the Sacramento Valley. We will examine exposures of the three main units of the California active continental margin–the Great Valley sequence, Coast Range Ophiolite, and Franciscan complex, younger volcanic rocks, active branches of the San Andreas fault system, and possible evidence for active folding and thrust faulting.

The trip will be by van, with stops at roadcuts. Walking will be minimal. Climate varies considerably from west to east in the northern Coast Ranges, from cool and maritime near the coast (temperature ~ 20-30°C) to dry and, in the summer, hot (temperature 30-40°C). Please bring: sunscreen, hat, light jacket, water, light walking shoes, TP, etc.

Short Course 1: Introduction to Electron Backscatter Diffraction (EBSD): sample preparation and analysis. *Leader: Matty Mookerjee.* **Start time 10:00am in Darwin Hall, Room 129**.

This course is designed to be a very basic introduction to analyzing crystallographic fabrics via Electron Backscatter Diffraction (EBSD), specifically for individuals who have no previous experience with EBSD. During the morning, we will prepare some quartz-rich thin sections (some of which can be provided by the course participants) for EBSD analysis using an automated grinder/polisher (Buehler EcoMet/AutoMet) and vibratory polisher (Buehler VibroMet). In the afternoon, we will analyze some of those thin sections on the Scanning Electron Microscope via EBSD and EDS (electron dispersive spectroscopy) and produce both crystallographic and chemistry maps, respectively.

Short Course 2: New Methods for Creating Admissible Cross Sections. *Leader: Kurt Burmeister and Scott Giorgis.* Limited to 24 participants. **Start time 1:00pm in Darwin Hall, Room 128**.

This workshop will present a modified version of the classic Busk (1929) and Kink (Suppe, 1989) methods that provides students with a quick and effective approach for constructing geologically admissible cross sections of strata involved in parallel folds. This technique combines the mechanical control of traditional methods with the speed of freehand sketching. In addition to classroom and laboratory applications, this method is particularly well suited for courses that require students to construct cross sections from their own geologic map data. Students in these courses are commonly encouraged to use their field data to sketch subsurface projections. Unfortunately, while constructing cross sections with freehand projections can be a quick and effective method for resolving working hypotheses, this technique requires a level of experience and insight that most students are still developing. Without these skills, students must rely upon the mechanically rigorous methods (e.g., Busk/Arc and Kink methods) if they are to construct geologically admissible cross sections from their data. These formal methods can be cumbersome and often require specialized drafting tools. Furthermore, even the slightest of inconsistencies in a student's field data will often lead to frustrating complications when using traditional cross section construction methods. This informal workshop will provide participants with hands–on opportunities explore this new method and consider ways it can be implemented into existing courses. No prior experience with the Busk and/or Kink methods is needed.

Sunday, July 31st

Field trip 1: Active faulting in the Napa Valley. *Leaders: Alex Morelan, Chad Trexler, and Mike Oskin, UC Davis.* **Departs at 8:00am from Parking Lot D**.

The Mw 6.0 South Napa earthquake occurred on 24 August 2014 along the southern extent of the West Napa fault. Despite its relatively small moment magnitude, the earthquake produced 14 km of surface rupture, with a maximum coseismic right-lateral slip of ~30 cm (right-lateral) in the Browns Valley neighborhood of Napa, 10 km north of the epicenter in American Canyon. The surface rupture on the West Napa fault strikes north-northeast, bending to the north at its northern end, terminating in a series of small stepovers. This field trip will visit sites along the surface rupture where tectonic slip from the 2014 event may still be preserved. Most evidence of the surface rupture has been destroyed by surface processes and infrastructure repair. Additionally, we will visit sites in northern Napa Valley, where new evidence indicates that the West Napa fault transitions to reverse sense and has produced both single-event and composite fault scarps, and folded alluvial fan deposits.

Field trip 2: Inherited structural complexity and active deformation in the eastern Coast Ranges (Eastern Franciscan and CRF). *Leaders: Ben Melosh and Bob McLaughlin, USGS.* **Departs at 8:00am from Parking Lot D**.

This trip will focus on the structural and stratigraphic interfaces between the lower Great Valley Group, the Coast Range ophiolite and parts of the Franciscan Eastern belt in the Cache Creek – Lake Berryessa area of the eastern Coast Ranges. We will explore the structural complexity and juxtaposition of these different terranes and discuss the interaction of older and modern styles of deformation in the area. We will visit outcrops of different terranes and structural domains in the GVG and CRO to key our eyes into the rocks. We will then focus on large-scale relations of terrane boundaries and geometries of active deformation in the region. We are particularly interested in spurring discussions of the influence of fundamental Mesozoic and early Tertiary bedrock structure on the geometry and kinematics of modern deformation.

Short Course 1: Statistical Treatment of Structural Geology Data. *Leaders: Josh Davis, Sarah Titus, and Basil Tikoff.* **Start time 8:00am in Darwin Hall, Room 128**.

Data sets in structural geology and tectonics frequently include geometric data types such as directions, orientations, and ellipsoids. Statistics offers various techniques for understanding the uncertainty inherent in such data, but these techniques are not well known in geology. This short course describes a few basic statistical tools: plotting, averaging, regression, and inference (confidence regions and hypothesis tests). First, we apply these tools to directional data, which include fault poles, lineations, paleomagnetic directions, etc. The second part of the course describes orientation statistics, which treats foliation-lineation pairs, folds, slickensides, crystallographic orientations, and other orientational data. Finally, we introduce ellipsoid statistics, which is applicable to the analysis of ellipsoids, including deformed clasts, SPO, and AMS. No prior experience in statistics is needed. Participants will need their own laptop computers. In the days before the short course, we will send instructions for installing the necessary free software.

Monday, August 1st

8:00-8:10 Forum introduction: *Matty Mookerjee*

8:10-12:00 Session 1: Faulting and Fluid Flow (Student Center, Ballroom B-C)

8:10-8:15 Introduction *James Kirkpatrick, session chair*

8:15-8:35 Talk: Insights into earthquake rupture and recovery from paleoseismic faults, *Christie Rowe, McGill University*

8:40-9:00 Talk: The geomorphic signature of strike-slip faulting, *Alison Duvall, University of Washington*

9:05-9:25 Talk: Parsing the structurally-controlled fluid migration history of the Moab Fault, UT with carbonate clumped isotope thermometry, *Keith Hodson, University of Washington*

9:30-9:50 Talk: Early strain localization associated with a low-angle normal fault system active across the brittle-plastic transition, *Justin La Forge, University of Wyoming*

9:55-10:25 Two-minute poster pitches (participants limited to 2 minutes each with 2 ppt slides)

- **Characterizing the Regional Fluid-flow System of the Wyoming Salient, Sevier Fold-Thrust Belt,** David Brink-Roby, *University of Rochester*
- **Characterizing deformation of Neogene rocks near Point Arena, California,** *Daniel Cicchetto*, *Sonoma State University*
- **Fault System Evolution, Reactivation and Basin Formation during the Late Cenozoic in the Western Great Basin,** *Scott Kerstetter, The University of Texas at Dallas*
- **Fault surface geometry as a record of deformation processes,** *James Kirkpatrick, McGill University*
- **Trapping nanoparticles: A structural approach for concentrating precious metals in vein-hosted ore deposits,** *Nicolas Harrichhausen, McGill University*
- **Microstructures in calcite veins along polygonal faults in the Khoman Formation, Western Desert, Egypt,** *Tyler Ramey, Sonoma State University*

10:25-12:00 Posters and coffee (Student Center, Ballroom D)

12:00-1:00 Lunch

1:00-2:00 Group Discussion: Advances in Cyberinfrastructure in the SG&T Community (Student Center, Ballroom B-C)

2:00-6:00 Session 2: Analog Modeling and Computational Techniques (Student Center, Ballroom B-C)

2:00-2:05 Introduction *Saad Haq, session chair*

2:05-2:25 Talk: Quantifying Deformation in Ridge-Transform Systems: An Example from the Troodos Ophiolite, Cyprus, *Sarah Titus, Carleton College*

2:30-2:50 Talk: The development of out-of-sequence thrusts in mountain belts: Insights from physical models and image correlation, *Saad Haq, Purdue University*

2:55-3:15 Talk: Structural Geology with Structure-from-Motion: Multi-view Photogrammetry at the Whaleback Anticline, Bear Valley, PA, *Juliet Crider, University of Washington*

3:20-3:40 Talk: A Comparison Between Modelling of Coulomb Stress and Field Observations of Off-Fault Strain around Pseudotachylyte Fault Veins, Norumbega Fault System, southern Maine, *Catherine Ross, McGill University*

3:45-4:15 Two-minute poster pitches (participants limited to 2 minutes each with 2 ppt slides)

- **Bayesian Markov chain Monte Carlo methods for modeling rock deformation,** *Joshua Davis, Carleton College*
- **Analog modeling of fault asperity kinematics using a modified squeezebox design and wax media,** *Matty Mookerjee, Sonoma State University*
- **The Influence of Localized Glacial Erosion on Exhumation Paths in Accreting Coulomb Wedges: Insights from Particle Velocimetry Analysis of Sandbox Models,** *Patrick Newman, Purdue University*
- **Analog modeling of Mexican Fold and Thrust Belt in central México,** *Alberto Vásquez* Serrano, *National Autonomous University of Mexico*
- **On the limits of the Inverse SURFOR Wheel in fabric analysis,** *Gary Solar, State University of New York, Buffalo State*
- **Earth-Centered Communication for Cyberinfrastructure (EC3): Incorporating a Joint Cyber-Science and Geoscience Perspective into Designing Field Data Management Systems,** *Taylor Swain, Sonoma State University*

4:15-6:00 Posters and coffee (Student Center, Ballroom D)

6:00-7:00 Dinner

Tuesday, August 2nd

8:00-12:00 Session 3: Regional Tectonics I: Cordilleran Geology (Student Center, Ballroom B-C)

8:00-8:05 Introduction *Elisa Fitz-Diaz and Raphael Gottardi, session chairs*

8:05-8:25 Talk: The Mexican Fold and Thrust Belt: S tructural development, timing and tectonic mechanism, *Elisa Fitz-Diaz, National Autonomous University of Mexico*

8:30-8:50 Talk: Thermomechanics of a detachment shear zone, Picacho Peak, AZ, *Raphael Gottardi, University of Louisiana at Lafayette*

8:55-9:15 Talk: Strain localization and megathrust slip accommodation modes in the Franciscan Complex, California, *John Wakabayashi, California State University, Fresno*

9:20-9:40 Talk: "The Bridge" from Earthscope to EarthsCAN: Across the Northern Cordilleran from the Pacific Ocean to the Beaufort Sea, *Katherine Boggs, Mount Royal University*

9:45-10:20 Two-minute poster pitches (participants limited to 2 minutes each with 2 ppt slides)

- **Three Dimensional Strain and Kinematic Vorticity Analysis of Mylonites from the Bitterroot Lobe Detachment, North American Cordillera,** *Andre Bruvry, Asbestos TEM Laboratories*
- **Deformation of Franciscan blueschists and eclogites at depth in a subduction zone,** *Samantha Carruthers, McGill University*
- **Quantifying Thinning and Extrusion Associated with an Oblique Subduction Zone: an example from the Rosy Finch Shear Zone,** *Forest Fortescue, North Coast Regional Water Quality Control Board*
- **Heterogeneous Exhumation of Mid-crustal Rocks along the Hayes Restraining Bend of the Central Denali Faul,** *Laura Tait, University of California, Davis*
- **Ductile shear zone of the Late Paleozoic at eastern Mexico: The Teziutlán Metamorphic Complex as a Middle America piece for reconstructing Pangea,** *Luis Javier Gutiérrez Trejo, National Autonomous University of Mexico*

10:20-12:00 Posters and coffee (Student Center, Ballroom D)

12:00-1:00 Lunch

1:00-2:00 Group Discussion: SGTF Business and Tectonics White Paper (Student Center, Ballroom B-C)

2:00-6:00 Session 4: Regional Tectonics II (Student Center, Ballroom B-C)

2:00-2:05 Introduction *John Waldron and Yvette Kuiper, session chairs*

2:05-2:25 Talk: Subduction initiation in the Appalachian-Caledonide orogeny, *John Waldron, University of Alberta*

2:30-2:50 Talk: Gondwanan fragments in the Southern Appalachian Piedmont, *Allen J. Dennis, University of South Carolina, Aiken*

2:55-3:15 Talk: A model of subduction of a mid-Paleozoic oceanic ridge - transform fault system in the northern Appalachians: a comparison with modern western North America, *Yvette Kuiper, Colorado School of Mines*

3:20-3:40 Talk: Building the Pamir-Tibet Plateau: Crustal Stacking and Orogen Parallel Evasion of Upper and Middle Crustal Material in the Pamir, *Daniel Rutte, UC Berkeley*

3:45-4:15 Two-minute poster pitches (participants limited to 2 minutes each with 2 ppt slides)

- **Orogen-parallel L-tectonites from Pelling-Munsiari thrust of Sikkim Himalayan fold thrust belt: A kinematic study using multiple, incremental strain markers,** *Jyoti Prasad Das, Indian Institute of Science Education and Research, Kolkata*
- **The Evolution of the Andes of Central Chile and Argentina: Constraints Using Structural Cross Sections, Geophysics, and Thermochronology,** *Marcelo Farias, University of Chile*
- **Characteristics and distribution of brittle-ductile structures associated with dextral transpression along the Larder Lake-Cadillac deformation zone in the southern Abitibi subprovince, Canada,** *Ben Frieman, Colorado School of Mines*
- **The Geometry of Accreted "Packets" in Subduction Zones; Examples from the Eastern Belt of the Franciscan in California and the Torlesse Terrane in New Zealand,** *Thomas C. MacKinnon*
- **The Alleghanian Orogeny from Start to Finish: As Chronicled by the Narragansett Basin, Southeastern New England,** *Daniel Murray, University of Rhode Island*

4:15-6:00 Posters and coffee (Student Center, Ballroom D)

6:00-7:00 Dinner

7:00-8:30 Preparing for an academic career in the geosciences - a special evening session for grad students and post-docs (Darwin Hall, 128) *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.

Wednesday, August 3rd

8:00-12:00 Session 5: Thermochronology, Metamorphic Petrology, and Tectonics (Student Center, Ballroom B-C)

8:00-8:05 Introduction *Howell Bosbyshell, session chair*

8:05-8:25 Talk: Zircon (U-Th)/He Age-eU Correlations Reveal Long-Term Thermal History of Laurentian Basement, *Devon Orme, Stanford University*

8:30-8:50 Talk: Tectonic Evolution of the Yarlung Suture Zone, Lopu Range Region, Southern Tibet, *Andrew Laskowski, University of Arizona*

8:55-9:15 Talk: Testing deformation-enhanced element mobility in plagioclase, *Naomi Barshi, McGill University*

9:20-9:40 Talk: Formation of Plagioclase-Al2SiO5 Coronas on Quartz Inclusions in Garnet During Transtensional Exhumation of High-pressure High-temperature Metamorphic Rock, *Howell Bosbyshell, West Chester University of Pennsylvania*

9:45-10:20 Two-minute poster pitches (participants limited to 2 minutes each with 2 ppt slides)

- **New observations on the northern San Andreas Fault system: Fast slip rates on the Santa Cruz Mountain section of the San Andreas fault and creeping on the San Gregorio fault?,** *Kimberly Blisniuk,* San Jose State University
- **Relict Basin Closure Inferred from Detrital Zircon Provenance in the Caucasus: A Solution to Missing Arabia-Eurasia Convergence?,** *Eric Cowgill, University of California, Davis*
- **Lawsonite Microstructures and Fabric Development at the Slab-Mantle Interface,** *Katherine F. Fornash, University of Minnesota-Twin Cities*
- **Illite growth along a detachment zone and folds of the Sierra de Catorce, San Luis Potosi, Mexico,** *Rodrigo Gutiérrez-Navarro, National Autonomous University of Mexico*
- **Metamorphic and tectonic evolution of a subduction complex: Insights from petrology and fabrics of metagabbro (Sivrihisar massif, Turkey),** *Patrica Kang, University of Minnesota*

10:20-12:00 Posters and coffee (Student Center, Ballroom D)

12:00-1:00 Lunch

1:00-3:15 Session 6: Pedagogy and Structural Geology and Tectonics (Student Center, Ballroom B-C)

1:00-1:05 Introduction *Paul Karabinos, session chair*

1:05-1:25 Talk: Pedagogical Effectiveness of Using Digital Applications for Collection and Interpretation of Sed/Strat and Structural Field Data, *Lawrence Malinconico, Lafayette College*

1:30-1:50 Talk: 3D Models and Animations for Teaching Structural Geology and Tectonics, *Paul Karabinos, Williams College*

1:55-2:05 Demonstration: Topographic Interactive Model (TIM), Phil Mooney, Sonoma State Universit***y & Chad Trexler, UC Davis***

2:10-3:10 Group Discussion: What is working in our Structural Geology Classes and what is not?, *Paul Karabinos* (Student Center, Ballroom B-C)

3:10-6:00 Session 7: Applications of Modern Techniques: Geophysics, Geodetics, and Remote Sensing (Student Center, Ballroom B-C)

3:10-3:15 Introduction *Dan Davis, session chair*

3:15-3:35 Talk: Observing Late Pleistocene Glacial Tectonics using Geophysical Techniques, *Dan Davis, Stony Brook University*

3:35-3:55 Talk: Reconciling GPS and Geologic Observations for Long-Term Deformation of the Cascadia Forearc, *Mark Brandon, Yale University*

3:55-4:10 Two-minute poster pitches (participants limited to 2 minutes each with 2 ppt slides)

- **EarthsCAN a Canadian Bridge from Earthscope into the Future to Maintain North American Geoscience Research Momentum,** *Katherine Boggs, Mount Royal University*
- **New insights about active detachment faulting in Death Valley, California,** *Darrel Cowan, University of Washington*
- **Extensively developed network of non-tectonic synclines in Eocene limestone of the Western Desert, Egypt: an example of hypogene speleogenesis?,** *Barbara Tewksbury, Hamilton College*
- **Intraplate Fault Records >400 ka of Time-Dependent Earthquakes Punctuated by Clustered Seismicity,** *Randolph Williams, University of Wisconsin-Madison*

4:10-6:00 Posters and coffee (Student Center, Ballroom D)

6:00-7:00 Dinner

Thursday, August 4th

Field trip 1: Introduction to the Strabo Data System. *Leaders: Basil Tikoff & Randy Williams, University of Wisconsin.* **Departs at 8:00am from Parking Lot D**.

This 1 day field trip will introduce participants to the Strabo Data system and mobile application using actual outcrop examples. The Strabo Data System is a digital database system for structural geology and tectonics (SGT) data that is designed to facilitate digital recording and sharing of data within our community. The Strabo mobile application (iOS and Android devices) is being developed in conjunction with this database system, and allows quantification and tracking of hierarchical and spatial relations between structures at all scales in the field. We will provide a brief introduction to the underlying database structure with case studies from localities where the system has been deployed. We will then travel to Pt. Reyes where participants will be able to use the Strabo mobile application (iPads will be provided) to map and collect field data from numerous faults exposed in the area.

Field trip 2: Northern San Andreas Fault Deformation, Point Arena. *Leaders: Matty Mookerjee, Daniel Cicchetto, Felix Desperrier, & Nick Bel, Sonoma State University.* **Departs at 8:00am from Parking Lot D**.

During this field trip, we will travel to the northern-most exposure of San Andres Fault related deformation exposed on land, near Point Arena, CA. At the Moat-Creek and Schooner Gulch Beach locations, we will look at deformation within the Neogene Schooner Gulch, Galloway, and Point Arena Formations. The deformation here is interpreted as being the result of either blind or poorly exposed imbricate thrust faults associated with the transpressional deformation along the SAF. There are abundant examples of off-fault-related folding (e.g., small-scale fault-bend-folds, fault-propagation-folds) as well as small-scale faulting structures (wedge faults and normal faults). Large-scale concretions (≈2m in diameter) become involved in the deformation in interesting ways. In addition to the tectonic deformation, we will examine evidence for paleoseismicity in the form of soft sediment deformation and clastic dikes. On our way to Point Arena, we will stop by Shell Beach to see a classic locality of Franciscan geology.

Short Course 1: Teaching Structural Geology: use of tablet-based apps for mapping in our undergraduate structure courses. *Leader: Larry Malinconico, Lafayette College.* **Start time 9:00am in Darwin Hall, Room 128.** Optional afternoon session 1:00-3:00 pm.

This workshop will explore the use of tablet applications for digital field mapping. In the morning session we will try some of the different applications listed below, with the option to test the apps in the field in the early afternoon.

Compasses: GeoCompass 2, Lambert, Field Compass
Vertical measurements: Theodolite
Mapping Programs: Clino, GeoFieldBook
Stratigraphic programs: Stratlogger

While several iPads will be available for use, participants are encouraged to bring their own iPads with Apps installed. Additionally, participants will be encouraged to share their favorite geologic field apps with the group.

Short Course 2: Analysis, statistics, and presentation of geological spherical directional data using Orient. *Leader: Fred Vollmer.* **Start time: 8:00am in Darwin Hall, Room 023.**

Orient is free software in development since 1986 for the analysis of directional data using spherical projections and related techniques. Orient 3 was released in 2015 with numerous enhancements, it is user-friendly for students, but designed for professionals. Following a "quick start" to illustrate ease of use, interactive features, and graphical output, and an introduction to data analysis and spherical projections, a variety of data sets (bedding, foliations, joints, crystallographic axes, paleomagnetic vectors, earthquake epicenters, and fault slickensides) will be used to explore more advanced topics, including contour plots, coordinate rotations, data visualization, confidence regions, spherical distributions, bootstrap statistics, kinematic analysis of fault data, and automated structural domain analysis of refolded folds. Additional topics may include small circle confidence cones (conical folds), cluster analysis (fracture sets and fold limbs), circular histograms, conical data (drill cores), UTM coordinate conversion, locating data on web-based maps, and plotting in Google Earth. The workshop will be informal, allowing discussion and hands-on analysis. Participants are encouraged to bring their own data sets for analysis. Computers will be available, although laptops with Windows, Macintosh, or Linux systems may be used. Participants may opt to attend only the morning session to accommodate travel plans.

Friday, August 5th

Field trip 1: Brewschist IV: Franciscan Complex and Brewpubs of Sonoma County. *Leader: John Wakabayashi.* **Departs at 8:00am from Parking Lot D**.

This trip views rocks near Lake Sonoma and on the Sonoma Coast that bear on a variety of subduction interface processes, such as high-pressure, low-temperature (including blueschist facies) metamorphism, exhumation of such rocks, different styles of subduction megathrust slip accommodation, and the origin of mélanges. We will see exceptional exposures of siliciclastic and serpentinite mélange matrix, with features suggesting sedimentary incorporation of exotic blocks, including rocks exhibiting higher metamorphic grade than the matrix. We will visit blueschist facies sandstones associated with black fault rocks and imbrication of ocean plate stratigraphy (OPS). The fault rocks and imbricated OPS may represent different styles of megathrust slip accommodation. We will also see rocks representing the petrologic Moho (ultramafic cumulates over mantle tectonite) of the Coast Range ophiolite that represents the upper plate "tectonic lid" over the Franciscan. Small breweries of Sonoma County have been at the cutting edge of the USA craft brewing revolution, and will visit two en route (Bear Republic Brewing Company for lunch, and Stumptown Brewing Company), and finish the trip with dinner at the famed Russian River Brewing Company. This is why we call this the Brewschist Tour.

Field trip 2: Active Tectonics of the North Coast**.** *Leaders: Carol Prentice and Steve DeLong (USGS).* **Departs at 8:00am from Parking Lot D**.

This field trip will focus on the geomorphology of the San Andreas Fault and uplifted marine terraces along the Gualala Block, between Fort Ross and Point Arena, CA. We will trace the surface rupture associated with the 1906 San Francisco earthquake, discuss fault slip rate and timing of pre-historic earthquakes, and explore the use of marine terraces to estimate uplift rates and horizontal fault slip rates. In addition, we will investigate variations in uplift rate across the fault and along the coast, as evidenced by overall topography, marine terrace elevations, and cosmogenic radionuclide studies.

Forum Abstracts

Abstracts appear in alphabetical order of the first author's last name.

Testing deformation-enhanced element mobility in plagioclase

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

I present an update on strain-enhanced diffusion in plagioclase through a multiscale theoretical and physical approach. I combined field-scale, thin-section scale, and grain-scale strain and chemical measurements for major and trace elements in naturally deformed plagioclase phenocrysts. I conclude that at low strain and low compositional contrast between primary growth zones, the effect of strain-enhanced element mobility, as predicted from my model, is too subtle to quantify using available analytical techniques. For these conditions, a static diffusion model is sufficient, and geothermobarometers and geochronometers can still be applied to yield accurate results.

New observations on the northern San Andreas Fault system: Fast slip rates on the Santa Cruz Mountain section of the San Andreas fault and creeping on the San Gregorio fault?

Kimberly Blisniuk, San Jose State University
Katherine Guns, University of California, Berkeley
Hudson Washburn, San Jose State University
Carol Prentice, United States Geological Survey
Roland Bürgmann, University of California, Berkeley

To better assess seismic hazard and fault behavior in the San Francisco Bay Area on the San Andreas Fault system, field observations and high-resolution lidar topography data are applied to investigate the San Andreas fault in the Santa Cruz Mountains and the San Gregorio fault near Moss Beach. Field mapping and age constraints on offset landforms reveal slip rates of ~20 mm/yr since ~ 8 ka on the San Andrea fault and creep rates of 0.5 to 1.6 mm/yr on the San Gregorio fault. Mapping at Sanborn County Park near Saratoga reveals a progression of alluvial fans and debris flows offset by ~60 m since 3 ka and ~140-60 m since 7-8 ka. The ages of offset landforms here are constrained with ^{10}Be exposure dating of sandstone surface clast. On the San Gregorio fault, tree lines planted by German immigrants circa 1915 and a sidewalk curb constructed circa 1966 are offset by 50-160 mm and 40-80 mm, respectively. These new observations underscore our current understanding of the San Andreas fault system in this region revealing faster than expected slip rates on the San Andreas fault in the peninsula and evidence of creeping on the San Gregorio fault.

EarthsCAN a Canadian Bridge from Earthscope into the Future to Maintain North American Geoscience Research Momentum

Katherine Boggs, *Mount Royal University*

North America has had > 30 years of continuous large innovative geoscience research programs – COCORP, Lithoprobe (1984 to 2004), Earthscope (2004 to ~2019) and now EarthsCAN (~2017 to ?). Lithoprobe (~1000 geoscientists produced ~1500 scientific publications) serves as evidence for the prolific capacity of a united Canadian geoscience community. Using a Lithoprobe-like approach, spring-boarding off the technical advances of Earthscope, the intention of EarthsCAN is to create new research networks that permit us to approach the challenges facing society with completely new ways of thinking. Globally, climate change, population growth, natural hazards and the need for long term sustainability of resource supply (including materials, energy and food) demand new approaches to Earth Sciences. As demonstrated by the cutting edge multi-discipline presentations at the June 2016 IRIS meeting, installing "The Bridge" an Earthscope-like seismic array in the Yukon and BC could greatly enhance our ability to examine atmospheric – oceanographic - lithospheric interfaces and processes, expanding our ability to study entire Earth Systems. Technological advances during the Earthscope program created increasingly sensitive pressure sensors that are now being used to establish links between microseismicity, solar modal influences (Thomson et al., 2007), the resultant tidal forces (Tolstoy et al., 2002; Thomas et al., 2013), ocean storms and the use of wave heights to establish past climate cycles (Schulte-Pelkam et al., 2004). The enhanced sensitivity to low frequency acoustic signals demonstrated by the Earthscope seismic array has made it possible to examine atmospheric gravity waves (de Groot-Hedlin et al., 2013, 2015) which have a vital role in global-scale circulation and transfer of energy between atmospheric levels, representing the next focus for improving climate and weather modeling (Kim et al 2003). Exciting links are currently being established between the impact of large scale tectonic stresses on topography, fracturing of bedrock, groundwater flow and chemical weathering and the depth of important biogeochemical processes (St. Clair et al., 2015). The inclusion of C-flux monitors (being developed at St Francis Xavier University, Risk et al., 2013) would improve the monitoring of carbon in the soils of the Yukon and BC, which in turn would contribute to improving our understanding of global C-cycles. Combining these instruments together permits the formation of creative new research networks capable of examining entire earth systems with fresh new collaborative perspectives. EarthsCAN brainstorming workshops are scheduled for August 17-19 in Calgary, August 21-23 in Ottawa.

"The Bridge" from Earthscope to EarthsCAN: Across the Northern Cordilleran from the Pacific Ocean to the Beaufort Sea

Katherine Boggs, *Mount Royal University*
Maurice Colpron, *Yukon Geological Survey*
Julie Elliot, *Purdue University*
Roy Hyndman, *Pacific Geoscience Centre, University of Victoria*
Kristin Morell, *University of Victoria*
Pascal Audet, *University of Ottawa*
Mike Schmidt, *Arctic Institute of Canada, University of Calgary*

"The Bridge" is one possible proof of concept for the new EarthsCAN research initiative in the Yukon Territories. The proposal is to fill gaps between the Earthscope Transportable Array seismic stations being installed from 2015 to 2017, the McKenzie Mtn Earthscope Project (MMEP; Schutt et al), seismic sites installed or being installed by the Geological Survey of Canada, the Yukon Geological Survey, Universities of Ottawa and Calgary as well as other industry/government consortia. This concept would create a bridge of seismic stations from the Pacific Ocean across Alaska and the Yukon to the Beaufort Sea. It would also maintain scientific momentum in North America by providing a bridge between Earthscope and EarthsCAN. A recent workshop in Whitehorse provided several appealing and outstanding questions to address in this area of the northern Cordillera. The Yukon Stable Block (YSB) is characterized by a very large magnetic high which is underlain in part by the Paleoproterozoic Wernecke Supergroup (not found anywhere else in the Canadian Cordillera). Cretaceous and Tertiary structures are deflected around the YSB suggesting that there are significantly different crustal compositions and/or thicknesses between the south and the north of the YSB (Colpron). Elliot et al have described complex relative plate motions that are being revealed by GPS observations in Alaska and NW Canada. The previously unrecognized Ellis block is rotating counterclockwise, while the Yakutat block is colliding with North America in a NNW direction, whereas the Alaska panhandle appears to be rotating clockwise into North America. How the resultant strain is being accommodated inland across the McKenzie Mountains is being investigated by the MMEP and the aforementioned agencies. Lidar image analysis and paleoseismic trenching could be used to characterize active faults in the McKenzie Mtns as per the Morell et al study on southern Vancouver Island. There are two other intriguing aspects to the Canadian Cordillera (Hyndman): i) the Yakutat Terrane collision is producing very high coastal mountains and deformation that spreads far inland, a mini Himalayan system; ii) there is a fascinating tectonic transition from the episodic slip and tremors of the young hot Cascadia subduction zone, to the subduction of the Explorer plate, to ridge subduction-slab window and then transition from oblique convergence along the Queen Charlotte Fault under Haida Gwai to pure strike slip motion along the Fairweather Fault in Alaska.

Formation of Plagioclase-Al2SiO5 Coronas on Quartz Inclusions in Garnet During Transtensional Exhumation of High-pressure High-temperature Metamorphic Rock

Howell Bosbyshell, *West Chester University of Pennsylvania*
Elizabeth Noble, *West Chester University of Pennsylvania*
Laura Burns, *West Chester University of Pennsylvania*
Tim Lutz, *West Chester University of Pennsylvania*
Cori Trice, *West Chester University of Pennsylvania*

Textural observations, equilibrium assemblage modeling and garnet isopleth thermobarometry document isothermal decompression of the Sycamore Mills Formation, pelitic gneiss in the Avondale nappe, along the Rosemont shear zone near Media, Pa. The rock contains the assemblage Grt + Sil + Bt + Ksp + Pl + Qtz with accessory Ilm, Rt, Zrn, Mnz, and Mag. Garnet as large as 1.5 cm diameter is characterized by cores containing abundant crystallographically oriented rutile needles up to 200 µm long. Coarse kyanite (<1 mm) and zincian staurolite (~0.3 mm long) inclusions are also present in garnet cores. Garnet rims contain relatively coarse rutile grains (0.25 - 0.5 mm), which parallel a fabric defined by the long dimension of quartz inclusions. Many quartz inclusions are separated from garnet by a narrow (50 - 150 µm) symplectic intergrowth of plagioclase and Al2SiO5. X-ray composition maps show pronounced Ca depletion halos in garnet adjacent to plagioclase. Theriak-Domino models suggest that the mineral assemblage within garnet cores, Fsp + Bt + Ky + Rt + Qtz, is stable between 750 to 800°C over a pressure range of 0.9 to 1.2 GPa. Results from Zr-in-rutile thermometry are consistent with these temperature estimates. While diffusion is likely to have modified the original composition of the garnet core, measured grossular content matches the modeled composition at these conditions. Plagioclase-Al2SiO5 intergrowths on quartz inclusions and Ca-depletion halos in surrounding garnet are the result of near isothermal decompression. Whitney (1991) proposed that such textures form from reactions involving fluid, introduced along fractures in garnet, with aqueous Ca+2 as a product. Isopleth thermobarometry using the composition of garnet from Ca-depletion halos indicate metamorphic conditions of 700 to 750°C and 0.6 GPa. Diffusion modeling may constrain the time required to diffuse sufficient Ca through garnet to produce the plagioclase coronas. Monazite geochronology is ongoing, however, a monazite inclusion along a fracture in garnet yielded an age of 399 ± 14 Ma (Pyle et al., 2006), similar to the age of syn-tectonic monazite in the Rosemont shear zone. We propose that curvature of the orogen at the NY promontory was effectively a restraining bend during a sinistral transpressive regime in the Silurian. A change from sinistral to dextral kinematics by the middle Devonian produced a transtensional regime resulting in rapid uplift of the Sycamore Mills rock.

Reconciling GPS and Geologic Observations for Long-Term Deformation of the Cascadia Forearc

Mark Brandon, *Yale University*

There are two competing interpretations for long-term deformation in the Cascadia forearc. The "rotating block" interpretation (e.g., Wang, 1996; Wells et al., 1998; McCaffrey et al., 2000) argues that forearc deformation is dominated by clockwise-rotating blocks, driven by oblique convergence between the Juan de Fuca (JF) and North American (NA) plates. The "wide wedge" interpretation (Brandon et al., 1998; Pazzaglia and Brandon, 2001; Batt et al., 2001) argues that the forearc region, from the trench to the east side of the forearc high (Coast Ranges), is underlain by a growing subduction wedge, which is actively shortening in a margin-normal direction. GPS data provide a test of these interpretations, but the influence of seismic coupling must be removed to resolve the long-term velocity field. McCaffrey et al. (2013) use the DEFNODE program to invert for a best-fit solution that includes spatially variable seismic coupling, and the rotation and internal deformation within discrete blocks. That solution shows that a block-based model can fit the GPS data, but the model is strongly undetermined, so it seems reasonable to consider other solutions. I have devised a simpler model that provides a more direct test of the wide-wedge interpretation. The observed GPS velocities are defined relative to NA. Coupling at the plate boundary causes velocities to be perturbed in the local direction of JF relative to NA. Coupling is considered to be caused by both seismic coupling, and by tectonic coupling, due to shortening within the wedge. The modern Euler pole for JF relative to NA is poorly resolved because it is based on a plate circuit through the Gulf of California (PVEL in De Mets et al., 2010). My inverse solution finds a new best-fit solution for this Euler pole using the direction of JF/NA plate motion provided by local coupling, and the prior information from De Mets et al. (2010). The solution fully accounts for the observed velocity field in Washington and Canada, without any need for margin-parallel shortening. The solution removes the influence of coupling in northern California and western Oregon, and reveals a wide shear zone that strikes obliquely across this region. The shear zone is consistent with the present NW motion of California due to extension across the Basin and Range. The rotated paleomagnetics directions are also explained by distributed shearing rather than rotation of discrete blocks.

Characterizing the Regional Fluid-flow System of the Wyoming Salient, Sevier Fold-Thrust Belt

David Brink-Roby, *University of Rochester*
Gautam Mitra, *University of Rochester*
Adolph Yonkee, *Weber State University*
Mark Evans, *Central Connecticut State University*

During mountain-belt formation, fluid migration plays an integral role in heat transport, mass transport, hydrocarbon accumulation, and rheology. To better understand the spatial and temporal patterns of regional fluid-flow systems, we integrate structural, petrologic, SEM/EDS, fluid inclusion, and stable-isotope (C and O) geochemical data for the well characterized Wyoming salient of the Sevier fold-thrust belt. We seek to characterize fluid sources (e.g. meteoric waters, connate waters, and metamorphic fluids), driving forces (e.g. topographic relief between the high hinterland and lower foreland, thermally and/or chemically generated gradients, and tectonic loading by thrust sheets and sediment burial), and fluid pathways (e.g. primary and secondary porosity, both within hydrostratigraphic units and along faults).

Focusing on limestone units in the Jurassic Twin Creek Formation, Triassic Thaynes Formation, and Missisippian Lodgepole Formation and correlatives, we identified systematic suites of mesoscopic structures, including veins and multiple minor fault sets. Surveys of cross-cutting relationships establish relative timing of these structures. SEM backscatter and X-ray analysis reveal minor variation in vein geochemistry and reactivation of previous structures. Image analysis of sample-area scans shows that cross-strike veins are most prevalent and have the largest apertures. Analysis of two-phase, aqueous fluid inclusions within veins reveals a decrease in Th from more interior to exterior thrust sheets, suggesting a combination of migrational cooling, shallower structural depths, and meteoric fluid influence. C-O isotopes analysis of paired vein (cross-strike set) and host rock carbonate samples reveal equal $\delta^{13}C$ values for vein-host rock pairs; $\delta^{18}O$ values decrease for both veins and host rock from west to east, showing that host composition altered during regional flow. Along regional faults, analysis reveals low levels of $\delta^{18}O$ within veins relative to host rock, a distinct fluid signature that implies channelized flow and meteoric influence. This data supports the hypothesis that fluid migration ahead of the wedge weakens rock, which undergoes distributed layer parallel shortening, and this deformation and fluid flow are then concentrated along major faults.

Three Dimensional Strain and Kinematic Vorticity Analysis of Mylonites from the Bitterroot Lobe Detachment, North American Cordillera

Andre Bruvry, *Asbestos TEM Laboratories*
Alexa Melcon, *North Coast Regional Water Quality Control Board*
Matty Mookerjee, *Sonoma State University*

Understanding the kinematics and evolution of large-scale, normal-detachment zones associated with the gravitational collapse of over-thickened continental crust is essential in order to improve our fundamental understanding of the mechanisms of orogenesis. Despite the importance of its role in the unloading and exhumation of continental crust, comparatively little is understood about the evolution and kinematics of these low-angle detachment systems. The analysis of quartz crystallographic textures via electron backscatter diffraction (EBSD) combined with three-dimensional strain analysis allows us to develop a more thorough understanding of the material paths within these detachment zones. In particular, we are interested in investigating the role of pure shear driven vertical shortening as it is related to the mechanics and rates of exhumation. Within the North American Cordillera, the Bitterroots Lobe Detachment (BLD) is located on the eastern edge of the Bitterroots metamorphic core complex (MCC) of eastern Montana. Here, orogenesis has produced an over-thickened and gravitationally unstable continental crust that has collapsed via a low-angle detachment, producing the BLD and a kilometer thick mylonitic shear zone. We have calculated the kinematic vorticity number (Wk) in order to compare the relative amounts of pure and simple shear that the shear zone has undergone. We have measured quartz crystallographic axes textures of mylonitized granodiorites collected across a transect through the BLD footwall. These data have been integrated over the entire deforming zone in order to estimate the total amount of vertical shortening. The integration of our three-dimensional strain analysis, with EBSD crystallographic texture data yields a vorticity number that allows us to calculate the amount of mylonite zone-perpendicular thinning within the BLD. Data for the BLD yields a mean shortening of 30% and mean vorticity number of 0.64, which implies nearly equal amounts of pure and simple shear components were active during deformation.

Deformation of Franciscan blueschists and eclogites at depth in a subduction zone

Samantha Carruthers, *McGill University*
Christie Rowe, *McGill University*

Subduction zones produce large earthquakes and tectonic tremor, and the dynamics of these plate boundaries control the rates of plate tectonics. However, the stress conditions at depth cannot be directly observed, so are poorly understood. Blueschist and eclogite form at depths of > 30 km in the subduction zone, and if exhumed, can be used to study stress and temperature conditions close to the plate interface. Due to subduction depth it is impossible to study this in an active environment, so we rely on exhumed rocks from the Franciscan Complex. By developing a detailed deformation history tied to the metamorphic assemblages, I aim to identify when and where the subducting slab deformed and tie that to stress conditions on the deep subduction interface. These blocks have been well-characterized in metamorphic studies, but since they occur in mélange terranes, past researchers have not made use of structural information. To our knowledge, this will be the first study to use high grade blocks from the Franciscan to research the structural aspects of subduction dynamics. I will conduct fieldwork in two locations: Tiburon Peninsula and Jenner Headlands, CA. The blocks are composed of blueschist and eclogite, some bearing garnet and lawsonite that have been dated using Lu-Hf geochronology (Mulcahy et al., 2009; 2014). The individual blocks cannot be connected spatially, however if they deformed under the same P-T conditions we will be able to determine that they show us equivalent parts of the subduction system. I am developing a novel mapping method using a unique internal reference frame for each individual boulder to reveal 3-D rotations in the strain ellipse within each reference frame. I will build 3D models from 100s of field photos using AGIsoft Photoscan Pro software. I will use georeferenced orthophotos projected from the 3D model to create a unique reference frame for each of the boulders to document the structural fabrics. In order to relate the measured strain to paleo-stress along the Franciscan subduction zone, I will measure yield strength of my samples in the rock mechanics lab at Lamont-Doherty Earth Observatory. If we are able to successfully study these samples with our new approach, it will create opportunities to obtain structural data and information from mélanges.

Characterizing deformation of Neogene rocks near Point Arena, California

Daniel Cicchetto, *Sonoma State University*
Felix Desperrier, *Sonoma State University*
Nick Bel, *Sonoma State University*
Matty Mookerjee, *Sonoma State University*

Deformation of the Neogene, Monterey Formation equivalent, Schooner Gulch, Galloway, and Point Arena Formations represents the last of several structural events in the Gualala block. The deformation within these formations is dominated by NW-SE trending meter to the tens of meters scale folds, meter-scale thrust faults, fault propagation folds, fault bend folds, NE-SW striking veins, as well as N-S striking normal faults. Fold axes have an average trend and plunge of 319:07, nearly parallel to the local trace of the San Andreas Fault (SAF). The folds range from open to closed with rounded to angular hinge zones and are inclined to the SW with some sections locally overturned. The Galloway and Point Arena Formations contain 1-3 m diameter dolomite concretions, some of which have quartz overgrowths that show evidence for rotation.

A maximum compression direction of 210° was calculated from an M-plane analysis of the thirteen meter-scale thrust faults and their associated slickenlines. This is consistent with the orientation of our fold axes and thus is nearly perpendicular to the trace of the SAF. Elder (1998) interprets this deformation to be the result of a series of largely blind or poorly exposed imbricate thrust faults formed due to transpression along the SAF system.

Within exposures of calcite-rich, asphaltic mudstone, the Point Arena Fm. records multiple episodes of veining and brecciation. Samples exhibiting high densities of vein material collected from these outcrops were analyzed under cathodoluminescence (CL), electron dispersive spectrometry (EDS), and electron backscatter diffraction (EBSD). The results of these analyses indicate that at least three different episodes of fracturing and mineral precipitation can be documented in this area manifesting in two cross-cutting sets of calcite veins and one set of quartz veins. Because the grain size of many of the calcite veins is so small, individual grains were difficult to distinguish via EBSD and produced low hit rates. We were able to use the variable hit rate of the EBSD analysis along with the band contrast image to differentiate subtle variations in grain size of the vein material, which aided in the determination of cross-cutting relationships. A combination of these three analytical tools was valuable in documenting the off-fault fracturing history adjacent to the SAF.

New insights about active detachment faulting in Death Valley, California

Darrel Cowan, *University of Washington*
Paul Bodin, *University of Washington*
Mark Brandon, *Yale University*

To test our hypothesis that detachment faults in Death Valley are active, we deployed 10 portable seismographs, which continuously recorded 3-channel short-period data at 100 samples per second, for 18 months, from July 2012 through January 2014. We relocated a sub-set of 313 earthquakes, which lie within the footprint of the portable network, using a revised 1D velocity model with individual station corrections. The largest earthquake in our dataset was M ~2.5. Using a total least squares (TLS) solution, we determine that the best-fit plane to the earthquake hypocenters dips 7.8° to the NW (azimuth 326°) beneath central Death Valley and the eastern Panamint Mountains. This azimuth is approximately parallel to the strike of the northern Death Valley fault zone. Our result is entirely compatible with: (1) GPS velocities, from sparse stations in and near Death Valley, of ca. 2 mm/yr NW; and (2) earlier studies, based on stratigraphic evidence and regional structural restorations, hypothesizing tens of kilometers of late Cenozoic dextral transport of tectonic elements. We infer that the Death Valley pull-apart basin is currently opening by oblique slip on (1) an active, but blind, detachment fault, and (2) the system of normal faults bounding the western front of the Black Mountains.

A long-standing question concerns the state of stress attending slip on gently dipping normal faults. At Mormon Point, the Quaternary sediments in the hanging wall above the Mormon Point detachment, which dips NW about 25°, contain dominantly synthetic, and a few antithetic, steeply dipping normal faults with offsets of a few cms to perhaps tens of cms. Groups of students in a senior-level class at the University of Washington have measured the attitudes of the steep faults and stereographically analyzed them to test the hypothesis that they formed in an Andersonian stress state. The analysis involves simply plotting by hand the poles to synthetic and antithetic faults, fitting great circles to the poles, and determining the bisector of the dihedral angle between the great circles. An Andersonian state would predict that the bisector, sigma-1, is perpendicular to the earth's surface. Sigma-1 at Mormon Point plunges ca. 83-88° northwest. We conclude that slip on the Mormon Point detachment occurs as Anderson would predict.

Relict Basin Closure Inferred from Detrital Zircon Provenance in the Caucasus: A Solution to Missing Arabia-Eurasia Convergence?

Eric Cowgill, *University of California, Davis*
Adam Forte, *Arizona State University*
Nathan Niemi, *University of Michigan*
Mikheil Elashvili, *Ilia State University, Tbilisi, Georgia*
Tea Godoladze, *Ilia State University, Tbilisi, Georgia*

Comparison of total plate convergence with the timing and magnitude of upper crustal shortening in active collisional orogens has consistently revealed both large shortening deficits (200 to 1700 km) and significant (30-40%) deceleration of plate motion during progressive collision, the cause(s) for which remain intensely debated. The Greater Caucasus Mountains, which result from post-collisional Cenozoic closure of a relict Mesozoic back-arc basin on the northern margin of the Arabia-Eurasia collision zone, may help reconcile these debates. Here we use U-Pb detrital zircon provenance data and the regional geology of the Caucasus to investigate the width of the now-consumed Mesozoic back-arc basin and its closure history. The provenance data record distinct southern and northern provenance domains that persist in the sedimentary record until at least the Miocene. We propose that closure of the back-arc basin initiated at ~35 Ma, coincident with initial (soft) Arabia-Eurasia collision along the Bitlis suture, and eventually led to ~5 Ma (hard) collision between the Lesser Caucasus arc to the south and Variscan basement along the margin of the Scythian platform to the north to form the Greater Caucasus Mountains. Final basin closure triggered deceleration of plate convergence and tectonic reorganization throughout the collision zone as a whole. We find that post-collisional subduction of such relict ocean basins can both account for shortening deficits, by accommodating convergence with minimal upper crustal shortening, and significantly delay deceleration of plate convergence. Such relict basin closure is likely typical of the early phases of continental collision at the end of a Wilson cycle due to both the irregular nature of colliding continental margins and their propensity to develop extensive back-arc basins during protracted subduction and terrane accretion prior to closure of long-lived ocean basins.

Structural Geology with Structure-from-Motion: Multi-view Photogrammetry at the Whaleback Anticline, Bear Valley, PA

Juliet G. Crider, *University of Washington*
Keith R. Hodson, *University of Washington*
Mary Beth Gray, *Bucknell University*
Arlo Weil, *Bryn Mawr College*

"Structure-from-motion" is a photogrammetric technique to produce high-resolution digital topographic models from standard digital photographs. Rooted in the principles of traditional photogrammetry, SfM offers three major advances: 1) SfM uses automated point matching from photographs at varying distances and view angles ('scale invariant feature transform'), eliminating laborious manual identification of common points and permitting the use of photographs from arbitrary positions. 2) Relative position of the common features is determined by simultaneous inversion of many points from many images. The camera positions and lens geometry are outputs of the inversion rather than required input. 3) Multiview "stereo" is used to densify the initial point cloud to produce highly detailed 3D models, with results equivalent to terrestrial laser scanning. Furthermore, because the model is produced from photographs, the resulting form can be "textured" with the same photos to produce a photorealistic (color) model. Optionally, models are georeferenced with independently surveyed (e.g. by differential GPS) ground control points identified in the model. There are abundant opportunities to leverage this technique for structural geology.

The Whaleback Anticline in Bear Valley, near Shamokin Pennsylvania, is an iconic structure and a popular field trip destination for Structural Geology. The anticline is on the southern limb of the Western Middle-Anthracite-Field Synclinorium in the Alleghanian Valley and Ridge Province. It was excavated during coal mining, revealing the full 3D form of the folded sandstone surface, including a variety of secondary structures. The outstanding exposure permits collection of both the complete 3D form of the surface and a highly detailed record of strain across the fold at a variety of scales. It is an ideal site to test the relationship between fold form and the secondary deformation that results from folding.

At the Whaleback, we are using SfM to: 1) Generate base images for mapping. We use images acquired by remote-controlled aircraft to produce a custom, vertical orthophoto of the field area. 2) Create orthorectified photomosaics of outcrops. SfM can mosaic photos from different distances and perspectives into a single image. Orthorectification removes distortion so that images can be used directly for geometric analyses. 3) Produce a 3D digital surface model for analysis of fold form. At the Whaleback, we have an unusual opportunity to capture the 3D geometry of a large folded surface (wavelength ~35 m). We use SfM to produce both a visual representation and a quantitative description of the fold for further analysis of strain.

Orogen-parallel L-tectonites from Pelling-Munsiari thrust of Sikkim Himalayan fold thrust belt: A kinematic study using multiple, incremental strain markers

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Fault rocks associated with the Pelling thrust (PT) in the Sikkim Himalayan fold thrust belt (FTB) change from SL tectonites to local, transport-parallel L tectonites that are exposed in discontinuous klippen south of the PT zone. By estimating the incremental kinematic vorticity number (Wk) from quartz c-axes fabric, oblique fabric, and subgrains, we reconstruct a first-order, kinematic path of these L tectonites. Quartz c-axes fabric suggests that the deformation initiated as pure shear dominated (~56-96%) that progressively became simple shear dominated in the later stage (~25-54%), as is recorded by the oblique fabric and subgrains in the L tectonites. These rocks record a non-steady deformation; the kinematic vorticity varied spatially and temporally within the klippen. The L tectonites record ~30% greater pure-shear than the PT fault rocks outside the klippen. Additionally, the L tectonites record the greatest pure-shear dominated flow (~47-63%), among the published vorticity data from major fault rocks of the Himalayan FTB. The relative decrease in the regional, transport-parallel simple shear component within the klippen, and associated relative increase of transport-perpendicular, pure shear component, support the presence of a sub-PT lateral ramp in the Sikkim Himalayan FTB. The lateral ramp explains the kinematic evolution of the L tectonites.

Observing Late Pleistocene Glacial Tectonics using Geophysical Techniques

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Glacial tectonic contractional belts display most aspects of thin-skinned tectonics, but at a scale intermediate between those of natural orogenic wedges and laboratory analog models. On Long Island, NY, the Ronkonkoma and Harbor Hills terminal moraines each include a range of push-moraine processes. Sediments exposed by shoreline erosion and by human excavation show small (cm-m) and medium (10s of m) scale folds and faults. In some cases, the prevalence of gravels in fault zones indicates the inversion of the typical competence relations (clays stronger and coarser materials weaker) that is often characteristic of permafrost conditions. We augment our direct observations of sediments through the use of GPR (ground-penetrating radar) and, to a lesser degree, resistivity measurements. Using GPR there is an intrinsic tradeoff between resolution and depth of useful signal penetration. High frequency (500 MHz) antennas can typically resolve objects as small as 5-10 cm, but to a depth of only 4-8m, depending upon the properties of the sediments. Low frequency (50-100 MHz) antennas, however, can penetrate as deeply as 20-40m, but with a resolution typically in the range of 30-70 cm.

One interesting structure that we have imaged is a prominent hill on the campus of Stony Brook University. The hill, known local at "The Wall", is draped with a capping diamict and an internal structure consisting of subhorizontal nearly undeformed sedimentary layers that appear to be outwash sequences deposited while the glacier was still to the north. We interpret The Wall to be the autochthonous footwall of a frontal and lateral lamp, and we believe the capping diamict to be a basal till deposited as the glacier stepped up over the now-relict hill. The allocthonous sediments and ice were then transported southward to where the ice melted and the sediments were deposited. We have carried out extensive surveys in the Hither Hills area of the South Fork of Long Island, 14 km west of the eastern end of the island at Montauk. Hither Hills is a remarkable 4 km by 2 km region of regularly spaced washboard hills cored by folds beneath which we have imaged a detachment surface that is exposed along the eroded shoreline as a till. A range of evidence indicates that his was not a single contractional wedge but, instead, was probably a series of folds formed by semi-periodic re-advances during a time of overall glacial retreat.

Bayesian Markov chain Monte Carlo methods for modeling rock deformation

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When mathematically modeling a rock deformation such as a shear zone, the geologist's goal is to relate the parameters of the model to the observed data. A forward model takes parameter values as input and produces predicted data as output. An inverse model takes observed data as input and produces best-fit parameter values as output. In practice, the inverse model usually amounts to many computations of the forward model, for example in an iterative numerical optimization. The interpretation of results is often complicated by non-uniqueness and uncertainty in the best fit.

In this presentation, we inverse-model rock deformation using Bayesian Markov chain Monte Carlo simulation. The output of this method is a large set of parameter vectors, which approximates the probability distribution of the parameters given the data, giving rich insight into the uncertainty in the fit. Any kind of forward model can be plugged in, as long as suitable 'prior distributions' for its parameters can be identified.

To demonstrate these techniques, we focus on two kinds of data: foliation-lineation orientations, and shape preferred orientation (SPO) ellipsoids arising from rigid and deformable clasts. We compare two classes of forward model: homogeneous (kinematic) and heterogeneous (dynamic) triclinic transpression. We present numerical experiments about the coverage rates of statistical inference methods. These techniques can also be used to evaluate the relative probabilities of differing approaches, offering the geologist a way to evaluate which model is most appropriate in any given situation.

Gondwanan fragments in the Southern Appalachian Piedmont

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The youngest stratified rocks in Carolinia are within the Blacksburg Formation of the Kings Mountain terrane and the Asbill Pond Formation of the Carolina slate terrane. The 4-5 km thick sedimentary section of the Kings Mountain terrane is interpreted to have been deposited on the lower plate of the rifted Gondwanan Rheic margin, probably adjacent to the Paraguan craton, between 522 - 497 Ma. The Asbill Pond Formation is nominally 1-2 km thick and lies in angular unconformity above the Persimmon Fork and Emory Formations; biostratigraphy of the Asbill Pond Formation indicates it belongs to the P. atavus zone (504.5 - 503 Ma) of the Drumian, Series 3, Cambrian. The Asbill Pond Formation is interpreted to have been deposited on the upper plate rift shoulder of Carolinia. Thus the Kings Mountain terrane and the Asbill Pond Formation are interpreted to been deposited on Carolinian basement on either side of the asymmetric Rheic rift detachment. The present disposition of the Kings Mountain terrane between the Charlotte terrane and the central Piedmont shear zone is an artifact of later terrane dispersal. The Kings Mountain terrane is interpreted to have formed near the North Carolina slate terrane; the epiclastic portion of the Battleground Formation accepted detritus from both the older Hyco-Aaron arc and the younger Uwharrie-Albemarle arc. Additionally the epiclastic section records significant input from Rondonian-San Ignacio (1.55-1.3 Ga) and Sunsas (1.28-0.95 Ga) basement. This interpretation is consistent with 1.551 Ga and 1.229 Ga inheritance reported by Mueller et al (1996) for this part of the North Carolina slate terrane. Above the Jumping Branch Manganiferous Member of the Battleground Formation, the Ediacaran-Cambrian component of the detrital spectrum is lost, and all grains are derived from Amazonian-Paraguan Gondwana. Serpentinites of the Hammett Grove Meta-igneous Suite in fault contact beneath the Battleground Formation may represent lithospheric mantle exhumed during rifting.

The geomorphic signature of strike-slip faulting

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Landscape evolution models are a useful means to investigate the longer-term, catchment-wide landscape response to strike-slip fault motion. Our results show that strike-slip faulting induces a persistent state of landscape disequilibrium in the modeled landscapes brought about by river lengthening along the fault alternating with abrupt shortening due to stream capture. Trunk channels that drain across the fault record this cycle of transience in the form of knickpoints and convexities along the channel profile. Although all the trunk channels modeled show some evidence of horizontal fault motion, the magnitude and character of perturbations to channel form appear to be slip-rate dependent. The models also predict that, in some cases, ridges oriented perpendicular to the fault migrate laterally in conjunction with fault motion. We find that ridge migration happens when slip rate is slow enough and/or soil creep and river incision are efficient enough that the landscape can respond to the disequilibrium brought about by strike-slip motion. Regional rock uplift relative to baselevel also plays a role, as the generation of topographic relief is required for ridge migration. In models with faster horizontal slip rates, stronger rocks or less efficient hillslope transport, ridge mobility is limited or arrested despite the continuance of river lengthening and capture. In these cases, prominent steep, fault-facing facets form along well developed fault valleys. Comparison of landscapes adjacent to fast-slipping (>30 mm/yr) and slower-slipping (~1 mm/yr or less) strike-slip faults in California, USA, reveals features that are consistent with model predictions. Our results highlight a potential suite of recognizable geomorphic signatures that can be used as indicators of horizontal crustal motion and geomorphic processes in strike-slip settings even after cycles of river capture have diminished or erased apparent offset along the fault.

The Evolution of the Andes of Central Chile and Argentina: Constraints Using Structural Cross Sections, Geophysics, and Thermochronology

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The Andes at the latitude of Santiago of Chile have been recently on the focus of structural discussion with two different models explaining differently block accommodation during mountain building: on one hand, one model suggests that shortening has been accommodated mostly by west-vergent thrusts synthetic to the Nazca slab subduction; on the other hand, in our preferred model, shortening has been accommodated by east-vergent thrusts rooted into the lithospheric mantle through a west-dipping ramp connected to the slab at ca. 60 km depth. Here, we do a review on this problematic including new constraints using thermochronological modeling. Modern evolution of this region began with the inversion of a Paleogene extensional basin at ~22Ma, focusing shortening mostly in the western side of the belt. At 16-15 Ma, deformation migrated and propagated eastward into the east-vergent Aconcagua fold-and-thrust. Deformation continued in this area until ~10 Ma, when immediately to the east started the uplift of the basement that forms the Argentinean Frontal Cordillera through deep rooted east-vergent ramps with the underthrusting of the Cuyania-Precordillera terrain. Simultaneously, western sectors of the inverted basin and of the fold-thrust belt suffered out-of-sequence thrusting and backthrusting shortening. During this time, surface uplift was higher and produced the current topography of the cordillera. Considering the available data, shortening migrated from west to east and its final results shows that the eastern side of the belt did accommodate about 70% of total shortening mainly by east-vergent thrusts. Estimates of shortening do balance well with crustal thickening along this time, implying a deep distribution of thickening from east to west. Therefore this evolution is evidencing that the western flank of the Andes is the retro-wedge and the eastern side is the pro-wedge. Advances in structural-thermochronology modeling shows that despite folding and thrusting of the western side of the belt, the western Andes behave relatively passive to deformation, being mainly tilted to the west. Regarding the structure at depths visualized by seismic tomography, mountain building will be the result of the South American lithosphere subduction beneath the Andes, where the Nazca subduction will act as a boundary condition rather than deforming directly the continental lithosphere. Similar results can be extrapolated elsewhere along the Chilean Andes, where shortening has been largely smaller than that accommodated in the eastern flank of the belt, where interaction of old basement with stratified series produced the underthrusting that distributed crustal thickening in a simple shear mode.

The Mexican Fold and Thrust Belt: Structural development, timing and tectonic mechanism

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The Mexican Fold and Thrust Belt (MFTB) is the southernmost expression of the Cordilleran Orogenic System (COS). The overall trend of the MFTB is NW-SE, although in the Monterrey salient the trend of the MFTB changes to an E-W orientation to form a primary oroclinal fold. The MFTB consists of folded and reverse-faulted Mesozoic-Eocene strata dominated by carbonates alternating with shale and sandstone. Jurassic evaporite horizons provide detachment surfaces in some parts of the orogen, as do Upper Jurassic carbonaceous shale units. Structural geometry is controlled by the spatial distribution of paleogeographic elements, such as Jurassic extensional basins and basement blocks, and detachment horizons at varying stratigraphic levels, as well as the direction of transport, which is dominated by NE-directed tectonic transport throughout the belt. The structural style is generally thin-skinned, although high-angle faults can be observed at several localities cross-cutting the thin-skinned, shallowly-dipping faults and associated folds. The strain distribution generally satisfies critical wedge predictions, decreasing toward the foreland. Values of shortening greater than 70% are present in the hinterland of central Mexico; these decrease systematically to values <15% to the front of the range where Late Eocene onlap sequences around the Gulf of Mexico plain unconformably overlie deformed strata of the orogenic wedge. Exceptions to this pattern of regional shortening values are well documented and are related to lateral variations in mechanical properties caused by facies variations, notably massive platformal carbonates as contrasted with thinly-bedded basinal carbonates. The timing of deformation has been constrained using Ar-Ar systematics on illite generated by layer-parallel slip in the flanks of chevron folds and are in good agreement with the age of synorogenic sedimentary successions. The results published to date suggest episodic pulses of deformation between 90-80 Ma, 75-65 Ma and 55-42 Ma. Each of these shortening events progressively affects rock units lying farther to the east. Effects of subsequent shortening are accentuated on the westernmost exposures of the thrust belt and are evident on a map scale by abrupt fold trend variations, compared to the linear axial traces of frontal folds. The tectonic cause of the deformation in the MFTB has been widely discussed but remains enigmatic. In south-central Mexico there is evidence of accretion between the Guerrero Terrane and Mexican mainland after the closure of the Arperos-Alisitos Basin. Nevertheless, late Aptian Guerrero accretion appears to have preceded accumulation of synorogenic foreland-basin deposits by 20 m.y., and detrital zircon grains derived from Cenomanian volcanic rocks equivalent to La Posta intrusive suite (98-91 Ma) indicate that shortening took place in a retroarc setting. We therefore infer that subduction of the Farallon slab was the primary driving mechanism of shortening in the MFTB, and therefore previously posited gravitational models for deformation are untenable. However, the extent of the Guerrero Terrane alone is insufficient to account for deformation as far north as Monterrey and Chihuahua or as far south as Puebla and Oaxaca. We discuss an integrated tectonic model that considers new constraints on stratigraphy, patterns and timing of deformation and sedimentation, as well as the most recent outcomes on Cretaceous-Paleogene arc-related magmatism in the Guerrero and Sierra Madre terranes.

Lawsonite Microstructures and Fabric Development at the Slab-Mantle Interface

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Lawsonite, a Ca-Al rich hydrous mineral, is of critical importance to element and water cycling in subduction zones because it has a high water content (11.5 wt.% H_2O), is stable at high pressures (and may be the main hydrous phase at P > 2.5 GPa), and is a significant reservoir for trace elements in high-pressure assemblages, particularly the REE, Sr, Pb, Th, and U. In addition, the presence, abundance, and crystallographic orientation of lawsonite can significantly affect the deformation and rheological behavior of subducted oceanic crust and associated sediments, and may influence the seismic properties of subducted slabs. The scarcity of well-preserved lawsonite in subduction-related rocks exhumed to the Earth's surface, particularly in eclogite, however, has prevented a comprehensive understanding of the deformation behavior of lawsonite and the factors controlling the development of fabrics in lawsonite, which are important for understanding the effects of lawsonite on the physical properties of subducted slabs.

One of the few places in the world with fresh, unaltered lawsonite in eclogite and blueschist facies rocks is the Sivrihisar Massif, Turkey, which contains a coherent sequence of lawsonite-bearing metabasaltic and metasedimentary rocks that were metamorphosed and deformed at the slab-mantle interface (45 – 80 km depth), and therefore provide an opportunity to systematically compare lawsonite fabrics in rocks with different modal amounts of rheologically significant minerals (e.g., glaucophane, omphacite, lawsonite, quartz), integrated with information about lawsonite crystal size (aspect ratio), compositional zoning patterns, shape, and twinning. Studies to date of lawsonite CPO from natural lawsonite-bearing assemblages have resulted in two types of patterns: one type is characterized by a concentration of [001] axes parallel to lineation and the other is characterized by a concentration of [001] axes perpendicular to foliation. We have documented the first type in lawsonite-bearing metabasalt (eclogite, blueschist) and the second in lawsonite-bearing quartzite, but other researchers have documented both types in metabasalt. Regardless of variations in lawsonite CPO or rock type, omphacite and glaucophane CPO remain consistent across the analyzed samples. Quartz c-axis patterns vary in eclogite-facies and blueschist-facies quartzite, although lawsonite CPO in quartzite does not vary. Samples in which lawsonite is polycrystalline or occurs as aggregates, such as from the core of eclogite pods, tend to yield more diffuse patterns. Ongoing research is investigating the parameters that control lawsonite CPO, and evaluating the consequences of lawsonite fabric for subduction processes.

Quantifying Thinning and Extrusion Associated with an Oblique Subduction Zone: an example from the Rosy Finch Shear Zone

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The Rosy Finch Shear Zone (RFSZ) is a NNW trending transpressional zone along the eastern margin of the Sierra Nevada mountain range, and the southernmost shear zone within the Sierra Crest Shear Zone. Dextral shear, resulting from oblique subduction along the western margin of the North American Plate (ca. 90 Ma), combined with subduction zone orthogonal shortening is concentrated within the RFSZ. Highly deformed metasedimentary and metavolcanic rocks within the zone have a prominent foliation with a mean dip, dip direction of 79°, 236° and a steeply plunging, penetrative, stretching lineation with a trend, plunge of 178°, 73°. Here, we present both three-dimensional strain analysis and crystallographic texture data in order to determine the mean kinematic vorticity number (W_m) and the relative amounts of pure and simple shear within the RFSZ. These two independent methods, using data collected from samples along two E-W transects, both indicate that there is a significant component of pure shear within the zone, with a mean of approximately 75% pure shear. Using the vorticity data, we calculated the amount of across-the-zone thinning. Samples collected from the 0.65 km zone of interest have yielded a mean shortening of nearly 20.3%, or approximately 166 m. In addition, three-dimensional strain analysis yields a mean Lode's ratio of 0.202, and a mean Flinn's k-value of 0.585, indicate a general flattening deformation, and a mean octahedral shear strain (ε_s) of 0.407. Assuming no volume change, these data suggests that there was approximately 174 m of vertical extrusion within this segment of the RFSZ in response to this obliquely convergent plate margin.

Characteristics and distribution of brittle-ductile structures associated with dextral transpression along the Larder Lake-Cadillac deformation zone in the southern Abitibi subprovince, Canada

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This study investigates the structural characteristics and extent of strain associated with the Larder Lake-Cadillac deformation zone (LLCdz) in the southern Abitibi subprovince in Ontario, Canada. The structural history along the regional scale LLCdz and its immediate splays is well-constrained, because orogenic gold deposits are spatially associated with these deformation zones. However, the distribution of strain away from the immediate deformation zones is poorly constrained. New structural data is used here to investigate structural controls on orogenic gold mineralization and to better establish the role of strain localization mechanisms in the development of these zones.

We present new structural data from a ~7x10 km area around the LLCdz in Kirkland Lake, Ontario. The dominant structural fabric is a steeply NNW- or SSE-dipping penetrative foliation (S_D) and an associated moderately to steeply NE-plunging mineral/elongation lineation (L_D). S_D/L_D is best developed in ENE-trending high-strain zones (HSZs) that are <1m to >100m in width, spaced at ~500 m, and occur up to 15 km from the LLCdz. Within the HSZs, S_D is associated with dextral shear sense indicators such as Z-folds and sigma clasts and is commonly defined by sericite- and/or iron-carbonate mineral-rich folia. We interpret that L_D developed during dextral shear and is indicative of a subvertical extension component. This is consistent with earlier interpretations of dextral transpression along the LLCdz. Brittle deformation features within the HSZs include discrete fault planes with reverse shear sense indicators, fault gouge, cataclasite, and pseudotachylite-like structures. Furthermore, the HSZs commonly contain shallowly dipping vein sets, pervasive Fe-carbonate metasomatism, and sulfide mineralization. Kinematic analysis of the fault and slickenside lineation data indicates that they developed during NNW-SSE shortening. In general, both brittle and ductile structures in the HSZs are marked by pervasive Fe-carbonate metasomatism and both display complex mutually cross-cutting relationships. The major HSZs in the study area are spatially coincident with structures interpreted to have originated as brittle fault zones. Thus, it appears as if the early development of brittle damage zones, including cataclasites and pseudotachylite-like textures, produced favorable zones for progressive ductile shear localization. The association between alteration and deformation in the transpressional HSZs as far as 10 km from the LLCdz suggests that relatively distal HSZs may be prospective for orogenic gold in the Kirkland Lake area. Overall, the Kirkland Lake area provides a unique location to investigate how strain localization processes control fluid flow and orogenic gold mineralization along regionally extensive deformation zones.

Thermomechanics of a detachment shear zone, Picacho Peak, AZ

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The Picacho Mountains form the western part of an extensive Miocene metamorphic core complex, including the Tortolita, Catalina, and Rincon Mountains in southern Arizona. The study area of Picacho Peak is located on the south end of a north-south running mountain range, 40 miles NW of Tucson. The Picacho Peak detachment shear zone is divided into three levels: (1) a lower plate, consisting of undeformed to mylonitized quartz-feldspatic Oracle granite, (2) a middle plate made of altered and fractured Oracle granite, (3) an upper plate composed of Miocene allochtonous volcanic and sedimentary rocks. The three plates are separated by detachment zones associated with chloritic breccia. The rocks in this area have undergone middle Tertiary mylonitic deformation. In the lower plate, the quartz grains display regime 2 to 3 microstructures and shows extensive recrystallisation by subgrain rotation and grain boundary migration. The recrystallized grain size ranges between 20 and 50 microns in all samples. Quartz crystallographic preferred orientation measured using EBSD (9 samples) shows that recrystallization was accommodated by dominant prism <a> and minor rhomb <a> slip, suggesting deformation temperature ranging from 450°C to 550°C, compatible with previously published data. In contrast, the middle plate exhibits much evidence of cataclastic flow, with fractured, sutured, and serrated grains of quartz and feldspar, indicating limited crystal plasticity. 3D strain analyses of plagioclase porphyroblasts show that strain is homogeneous throughout the lower and middle plates with bulk strain Rs ranging from 1.6 to 1.8. The data also show that axial ratios and angular orientations are consistent throughout the samples, indicating that strain deformation is dominant over original grain shape. These preliminary results suggest that the detachment shear zone evolved at its peak strength, close to the dislocation creep/exponential creep transition, where mechanical instabilities caused strain hardening, embrittlement, and eventually seismic failure.

Illite growth along a detachment zone and folds of the Sierra de Catorce, San Luis Potosi, Mexico

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Elisa Fitz-Diaz, *National Autonomous University of Mexico*

The Sierra de Catorce (SC) range is located in the Mesa Central in northeastern Mexico, includes the westernmost exposures of the Mexican Fold and Thrust Belt (MFTB) and easternmost structures of the Basin and Range province in Mexico. On an E-W oriented cross-section, through the N-S trending SC, Mesozoic strata were shaped in an anticlinorium-like structure. We present data from structural analysis, optical microscopy, Scanning Electron Microscopy (SEM), characterization of clay minerals with X-ray diffraction (XRD), and illite Ar-Ar dating. These data allow us a better understanding of illite growth during folding and thrusting, and a more accurate interpretation of the age of shortening affecting Cretaceous units on the western most exposures of the MFTB.

The Mesozoic strata in SC include: 1) a Triassic succession of siliciclastic sandstone and shale showing ductile E-W shortening by folding, with vertical axes and a pervasive, continuous, planar, N-S trending cleavage developed at very low-grade metamorphic conditions. 2) A Jurassic succession of volcaniclastic succession interpreted as "Nazas Arc" in central Mexico, which also shows a pervasive, sub-vertical pencil N-S trending cleavage associated with open folds, which according to illite crystallinity data was formed in the anchizone. This cleavage is also present in red siltstone and continental conglomerates deposited on top of the Nazas arc rocks. 3) A Late Jurassic shale carbonate succession on top of these units developed a strong bed parallel foliation and lineation that in thin section shows a mylonite texture with S-C microstructures that suggest a direction of transport to the east. This deformation localization zone separates cleavage dominated shortening in the Jurassic clastic units below, from fold-dominated shortening in the upper Cretaceous carbonates above it. 4) Layers of Early Cretaceous basinal carbonates above the detachment zone were shortened by folding, and the folds are in general asymmetrical, verging to the NE. 5) Finally, Late Cretaceous turbidites also show fold with a similar geometry as those in the Cretaceous carbonates, but with a more intense associate cleavage.

After the mesoscopic analysis, three samples were selected to apply ^{40}Ar-^{39}Ar illite dating; two samples were collected in the limbs of two mesoscopic folds, one from Early Cretaceous limestone and one from Late Cretaceous turbidities (Samples 2 and 3), and the third from a clay rich, highly deformed zone in the detachment zone localized in the Jurassic limestone (Sample 1). For illite age interpretation, we used illite XRD characterization, illite polytype quantification, SEM textural observations and analysis and stepwise incremental heating of three fractions of each sample (<2 µm, 0.2-1µm and <0.05µm) in light of recent theory on Ar-Ar degasification of fine grain particles. Based on these analyses we determined that the populations of illite in the samples were formed in the following ranges: Sample 1: 69-74 ± 1 Ma, Sample 2: 54-92 ± 1 Ma and sample 3: 54-75 ± 1 Ma. Overall, these data indicate that the deformation observed in SC was accumulated over ~30 Ma, with folding starting about 92 Ma, intense folding and faulting between 74 and 65 Ma, and refolding at about 55 Ma.

Ductile shear zone of the Late Paleozoic at eastern Mexico: The Teziutlán Metamorphic Complex as a Middle America piece for reconstructing Pangea

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The Teziutlán Metamorphic Complex (TMC) in eastern-central Mexico crops out as isolated tectonic windows adjacent to eastern crystalline basement of Oaxaquia. The TMC consists of an assemblage of metasedimentary and metaigneous rocks of the Late Paleozoic, in which it's observed polyphase of deformation in low to medium metamorphic grade that preserves gneissic, schistose and mylonitic textures. The age of deformation is constrained between the minimum age of deposition at Mississippian-Permian in protoliths as well the tonalitic suite intrusions and the overlayed slightly deformed red beds with detritus derived from a Permo-Triassic volcanic arc. The TMC structurally consists of a pile up by mylonitic shearing, in which is possible to distinguish four lithodemic units: i) La Soledad Lithodeme, represents the lowermost unit composed by mylonitc quartz feldspar gneisses, metagabbros interfingering with mica schist; ii) Chicuaco Lithodeme, constituted by meta rhyolite, meta granitic-tonalitic gneisses and mica chlorite schist; iii) Cozolexco Lithodeme is a mafic association composed by meta basalts intercalated with meta gabbros and tonalites; and iv) the uppermost unit, El Mirador Lithodeme, is a lithologic association consisting of white mica schist interlayered with meta volcanosediments. Foliation S_1 is observed like lepidoblastic and nematoblastic texture with Chl+Msc+Act, also quartzofeldspatic granoblastic domains in gneissic bands. S_1 foliation is closed recumbent refolded to F_2 and transposed in axial planar foliation to $S_{2/1}$, both with vergence at 220° SW /40°. Altogether with kinematic indicators given by feldspar porphyroclast and pyrite shadow pressures with σ and δ figures, mica fish and S-C´ fabric which are produced by a subhorizontal shear zone with top to the SW. On this study, K-Ar and Ar-Ar ages were extracted from white mica and amphibole immersed in the foliated and mylonitic fabric, which indicate that cooling ages occurred between 310±4 Ma and 270±3 Ma. Such range of time reflects a tectonothermal event in the Permian, which is in good agreement with the diachronic and progressive approaching between peri-Gondwanan and southeastern Laurentia terranes at the last stages of Pangea assemblage; regarding that TMC represent a critical piercing point for understanding assembly of Pangea in the Middle America segment.

The development of out-of-sequence thrusts in mountain belts: Insights from physical models and image correlation

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Analog models of thrust wedges in conjunction with analytical solutions have provided a robust framework to simulate and predict the progression of deformation in convergent Coulomb wedges. The inherent complexity of even the simplest modeling rheologies (e.g., variations in frictional behavior of sand) used to simulate deforming rocks in analog models can produce deformation that is a reasonable approximation for the complexity of the observed deformation in nature. The application of digital image correlation (DIC) methods has allowed us to precisely quantify the kinematics of these models, allowing for the high-resolution calculation of the evolving deformation fields. Utilizing both Eulerian and Lagrangian DIC methods has provided insights into both the instantaneous and long-term deformational response of frictional thrust wedges due to variations in mass flux (i.e., erosion, deposition, and accretion) and/or boundary conditions and has allowed us to examine deformation at a variety of time and length scales in developing wedges. The determination of where and when deformation is occurring, along with an understanding of modeling material properties allows us to develop a simple mechanical explanation to explain out-of-sequence deformation in frictional thrust wedges occurs.

Trapping nanoparticles: A structural approach for concentrating precious metals in vein-hosted ore deposits

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Super-saturation of silica is common in fault fluids. This may coincide with pressure changes associated with fracturing, or with transport across temperature gradients in a hydrothermal system. These conditions lead to precipitation of amorphous silica, which will subsequently recrystallize to quartz under typical geologic conditions. Additionally, the changing pressure and temperature conditions may promote the precipitation of precious metals (such as gold), as well as trap suspended pre-existing nanoparticles within amorphous silica phases. We report evidence for silver nanoparticles, and for electrum, an alloy of gold and silver, that is associated with recrystallized amorphous silica at the Brucejack epithermal gold-silver deposit in northwest British Columbia, Canada. We propose a deposit model in which transport of nanoparticles in suspension and as a solution, allows for a higher flux of gold and silver within a hydrothermal system than does transport as a solution alone. This high flux may account for the extraordinarily high gold concentrations, up to 41 582 ppm, that are commonly reported across 0.5 m to 1.5 m intervals at Brucejack. Structural data and maps of electrum-bearing quartz-carbonate stockwork veining are presented, showing that major stockwork systems are related to extension and normal faulting in subaqueous volcanic sequences. Electrum within quartz-carbonate stockwork at Brucejack is extremely localized within veins, with host rock and vein material immediately surrounding the richest mineralization typically averaging much lower grades of gold and silver (<1 ppm Au). We propose that fault rupture concentrates and localizes electrum deposition by trapping silver and gold nanoparticles within rapidly precipitated amorphous silica, at specific structural sites. Repeated rupture events could concentrate electrum even further. Recrystallization of amorphous silica to quartz may cause localized remobilization of electrum and the formation of the ore textures that are observed today.

Parsing the structurally-controlled fluid migration history of the Moab Fault, UT with carbonate clumped isotope thermometry

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Brittle deformation and faulting alter host rock permeability, but feedbacks associated with fluid migration and diagenesis produce temporal and spatial variability. The complexity of these interacting systems makes it difficult to reconstruct fluid migration histories, especially in cases of varying styles of structural deformation. Fault-hosted cements are a physical record of fault-controlled fluid flow, and their chemistry reflects source-fluid composition and mineralization conditions. For carbonate cements and veins, stable isotopes of carbon and oxygen provide valuable insight into mineralization temperatures and fluid sources, but cannot give a unique solution unless one of these components is known. This study employs carbonate clumped isotope thermometry to independently constrain mineralization temperatures of carbonate cements. Our results highlight connections between structural deformation and fluid migration at scales from microstructures to kilometer-long fault segments, and reveal the lasting influence of the earliest structures on fault zone permeability. We apply clumped isotopes to a well-characterized natural laboratory: the Moab Fault, Utah. At Courthouse Junction, a beautifully exposed and intensively studied fault-segment intersection, fault-hosted cementation is closely associated with a well understood sequence of structural deformation, including two styles of cataclastic deformation bands and mode I fractures. Prior work by others identified cements derived from multiple fluid sources with a range of precipitation temperatures, but did not clearly separate the influences of source and temperature or connect periods of cementation to different styles of structural deformation. Our new textural observations and clumped isotope analyses identify three episodes of cementation at this outcrop, featuring both marine and meteoric fluid sources. Cool marine fluids are the source for an early period of cementation, closely associated with deformation bands and fractures along their cores. Second, warm meteoric fluids record subsurface fluid migration following the formation of joints associated with the main period of fault slip, with a range of temperatures indicating continued permeability during exhumation. Late stage cements appear to mark a return to cool cementation conditions. Cement properties from different segments of the Moab Fault and around segment intersections reveal the fault-scale fluid migration history during the growth and interaction of independent segments. Using the distributions of discrete cementation episodes, we gain insight into the important controls on fault zone permeability, such as growth of the damage zone and focused deformation around segment intersections and relay zones. These findings provide a new perspective on fault-fluid interaction, and demonstrate the power of clumped isotopes for problems in structural diagenesis.

Metamorphic and tectonic evolution of a subduction complex: Insights from petrology and fabrics of metagabbro (Sivrihisar massif, Turkey)

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Blueschist and eclogite belts mark the locations of subduction zones. These high-pressure/low-temperature (HP/LT) belts, however, are typically affected by subsequent collision, thermal overprinting, and/or fluid infiltration, all of which disrupt the high-pressure physical and chemical features of the subducted plate. The Sivrihisar massif of the Tavşanlı Zone in Turkey is one of the rare localities in the world where HP/LT rocks are well exposed. It consists of lawsonite eclogite and blueschist facies metabasalts and metasedimentary rocks (marble, quartz + mica- and calc- schists). The HP/LT unit has fault contacts with metaperidotite and metagabbro/diabase to the north and metaperidotite to the south. The fine-grained HP/LT rocks with basalt protoliths have been well studied, but less attention has been paid to metagabbro, which occurs as rare pods within blueschist, calc-schist, and quartzite. Ongoing study of the HP/LT metagabbro includes new petrographic and microstructural data and P-T estimates, and comparison with previous results from mebasalts and metasedimentary units to understand the deformation and metamorphic evolutions in the context of subduction zone dynamics.

Sivrihisar metagabbro is dominated by lawsonites with variable grain size, ranging from 30 µm to 1800 µm long. Fine-grained lawsonite is located in the matrix and defines a preferred orientation, whereas coarser grains are present as inclusions in amphibole and deformed, porphyroblastic clinopyroxene. Some of the coarse-grained lawsonite has replaced clinopyroxene. Some lawsonite and clinopyroxene exhibit partial alteration to chlorite. Metabasaltic layers associated with the metagabbro pods are interlayered with marble and quartzite, and are characterized by millimeter-scale alternations of blueschist (chloritized glauchophane + recrystallized, fine-grained lawsonite (60 µm)) and eclogite (fine-grained lawsonite + partially chloritized, coarse-grained omphacite with inclusions of glaucophane + garnet with inclusions of lawsonite, clinopyroxene and glaucophane).

Mineral and bulk-rock compositions will be used to estimate P-T conditions at the time of peak assemblage equilibration. Estimated P-T conditions will be compared with the previous results of lawsonite-eclogite (~26kbar, 500°C) and lawsonite blueschist (12kbar, 380°C). Results will be integrated with previous P-T-d studies, which indicate that metabasaltic and metasedimentary layers record part of the exhumation history. Our hypothesis is that metagabbro likely records a similar P-T path, as indicated by textural similarities with metabasalt, such as the presence of lawsonite ± glaucophane inclusions in clinopyroxene porphyroblasts. However, the presence of garnet in metabasaltic layers and absence of garnet in metagabbro may indicate some differences; alternatively, metagabbro and metabasalt may have different bulk compositions, accounting for different mineral assemblage.

3D Models and Animations for Teaching Structural Geology and Tectonics

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Interactive 3D models help students visualize and apply fundamental concepts in structural geology and tectonics. Trimble SketchUp is a useful way to create such models and animations; there is a free version and the professional version is free to educators. Interactive SketchUp models show how the stereographic projection is used to plot the trend and plunge of lines and the strike and dip of planes, and how to measure angles between geometric features. 3D models also illustrate how to use structure contours to test if a contact is planar or folded, find the true thickness of a formation, determine strike and dip of planar features, estimate slip on faults, and create cross-sections. SketchUp models can simulate plate tectonic geometry on the surface of a sphere, and be used to demonstrate the Euler pole of rotation between two plates. Models can be exported as COLLADA digital asset exchange (.dae) files and incorporated into an iBook or uploaded to a web service designed to share 3D models such as Sketchfab. It is also possible to export models as 3D PDFs, and animations can be exported in a variety of movie formats to facilitate sharing and dissemination.

Fault System Evolution, Reactivation and Basin Formation during the Late Cenozoic in the Western Great Basin

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An array of WNW- and NNE-striking faults connects the NW-trending northern Eastern California shear zone and central Walker Lane. The faults syndepositionally controlled the spatial distribution and thickness of three volcanic and sedimentary sequences that record the degree of kinematic linkage between faults and reactivation during three episodes of extension in the late Cenozoic. In the early to mid-Miocene, a 40 km long and 4 to 6 km wide system of WNW-trending half-grabens developed under north-south extension and controlled the deposition of a sequence of andesite and sedimentary rocks. WNW-striking normal faults bounded the half-grabens to the north and south, and juxtaposed asymmetric wedges of basin-fill up to 1500 m thick with Paleozoic metasediments and Mesozoic pluton. NNE- to NS-striking transfer faults segmented the half-grabens and accommodated an 8 km long dog-leg step in the basin system. Between 12 to 4 Ma, reactivated WNW- and NNE-striking faults formed the boundaries of NNE-trending half-grabens that developed in the upper plate of a northwest-dipping, low-angle normal fault. NNE-striking faults were reactivated as normal faults that formed the east and west boundaries of asymmetric basins that controlled deposition of a mid-Miocene to Pliocene sequence of tuff, lava flows, and sedimentary rocks that exhibit a maximum thickness of 2250 m. WNW-striking faults that were reactivated as strike-slip faults accommodated differential displacement between the NNE-trending basins in the upper plate of the detachment. Beginning at 4 Ma, NNE-striking normal faults reorganized into their present configuration as splays off of a single WNW-trending sinistral transcurrent fault that stretches 60 km to the east from the Fish Lake Valley fault of the Eastern California shear zone. NNE-striking normal faults localize the deposition of a Pliocene to Holocene succession of fluvial and lacustrine sediments, basalt, and overlying alluvial deposits within the contemporary basins.

Fault surface geometry as a record of deformation processes

James Kirkpatrick, *McGill University*

Fault slip surfaces, where displacement is localized during earthquakes, exert a primary control on fault strength, stability, off-fault stresses and rupture characteristics. Slip surfaces are non-planar, or rough, and although distinct features can be identified on the surfaces at outcrop scale they have characteristic geometry, regardless of the tectonic setting or rock type. The self-affine scaling of the surface geometry is controlled by fracturing of the rock during slip, and is direct evidence for scale-dependent strength of rocks. However, at the extremes of observational length scales, the scaling behavior changes. At length scales of tens to hundreds of micrometers or less, the roughness is isotropic, marking a change in wear mechanism. Analysis of the reflector corresponding to the Costa Rica subduction zone megathrust in 3-D seismic data also suggests a transition to isotropy at several km. This dimension matches the spacing of horsts and grabens on the oceanic plate, and indicates processes external to the fault impact the mechanical behavior. These insights highlight the importance of fault geometry to fault mechanics and show how faults can used to constrain the physical controls on slip.

A model of subduction of a mid-Paleozoic oceanic ridge - transform fault system in the northern Appalachians: a comparison with modern western North America

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Mid-Paleozoic crustal-scale dextral northeasterly trending ductile-brittle fault systems and large volumes of igneous rocks are characteristic of the northern Appalachians in eastern New England and Maritime Canada. These can be interpreted as having resulted from a subducted oceanic ridge-transform fault system, in which the fault systems formed as a result of subduction of transform faults, and the igneous rocks formed above a slab window. The model is similar to that of formation of the San Andreas fault system. In the model, a ridge-transform system existed in the Rheic Ocean, and was subducted below parts of Ganderia, Avalonia and perhaps Meguma, in Maine, New Brunswick and Nova Scotia. The westward subduction zone jumped from the Laurentian side of Avalonia and Meguma to their eastern margins, as a result of their accretion.

A latest Silurian transition from arc to within-plate magmatism in the Coastal Volcanic Belt in eastern Maine is interpreted as the onset of ridge subduction. Examples of increased latest Silurian to Devonian within-plate magmatism include the Cranberry Island volcanic series and Coastal Maine Magmatic Province in Maine, and the South Mountain Batholith in Nova Scotia. Widespread Devonian to earliest Carboniferous granitic to intermediate plutons, beyond the Coastal Volcanic Belt towards southern Maine and central New Hampshire, may outline the shape of a subsurface slab window.

Where the ridge-transform system was subducted, plate motions changed from predominantly convergent between the northern Rheic Ocean and Laurentian plates to predominantly dextral between the southern Rheic Ocean and Laurentian plates. This dextral motion resulted in crustal-scale dextral strike-slip fault systems within the continental crust, such as the Norumbega fault system in Maine and the Kennebecasis-Belle Isle-Caledonia-Clover Hill fault system in New Brunswick. While similar dextral strike-slip fault systems exist to the north in Newfoundland and to the south in the southern Appalachians, there is no evidence for extensive mid-Paleozoic igneous rocks, suggesting the model probably does not apply in those areas.

San Andreas-type faults, and evidence for their formation as a result of ridge-transform subduction, may be difficult to recognize in ancient orogenic belts. This is partly because of their rare occurrences, and partly because of overprinting by subsequent tectonic events. One characteristic of the Norumbega and San Andreas fault systems is that they abruptly end on a contemporaneous convergent system. Where other ancient large-scale intracontinental strike-slip fault systems abruptly end on a coeval convergent system, a Mendocino-style triple junction may have existed also.

Early strain localization associated with a low-angle normal fault system active across the brittle-plastic transition

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The Chemehuevi detachment fault (CDF) system exposed along the Colorado River extensional corridor in the Chemehuevi Mountains (SE California) hosts exceptional exposures of a denuded fault system related to Miocene extension. Here, we characterize strain localization associated with the early history of extension along an associated small slip (1-2 km) low-angle normal fault, the Mohave Wash fault (MWF), initially active across the brittle-plastic transition. Strain localized in three principal ways across its 23-km-long down-dip exposure (temperatures of < 150° to > 400°C): into a brittle fault zone, localized, disseminated quartz mylonites, and syntectonic dikes hosting mylonitic fabrics. Brittle deformation in these crystalline rocks was concentrated into a 10–62-m-thick brittle fault zone that hosts localized zones of intense cataclasite series fault rocks ≤ 3 m thick and rare pseudotachylite. Crystal-plastic deformation localized into thin quartz mylonites hosted in the footwall that increase in thickness down-dip. A transect in the slip direction (NE), highlights variations in the mechanisms of strain localization. At initially shallow structural depths, footwall mylonites are absent; at ~9 km down dip, centimeter-scale mylonitic quartz veins and dike margins are common; at ~18 km down dip, centimeter-scale phyllonites are exposed; at ~23 km down dip direction, the footwall hosts disseminated zones of mylonitic quartz of varying intensities. Lastly, strain localized in meter-scale syntectonic intermediate–felsic dikes at ≥ 18 km down dip, which are rotated and attenuated into parallelism with the overriding fault zone, and host well-developed L-S tectonite fabrics. Deformation mechanisms of quartz associated with this fault system record progressively hotter dislocation-creep deformation down dip from bulging (BLG) recrystallization (deformation T of ~280–400°C), and subgrain rotation (SGR) recrystallization (deformation T of ~400–500°C) ~9–23 km down dip to SGR and grain boundary migration (GBM; deformation T of ≥ 500°C) ~23 km down dip. Crystallographic preferred orientations in quartz indicate NE-directed non-coaxial dislocation creep deformation, collinear the MWF slip direction, with an increase in deformation temperatures from ≤ 500°C to ≥ 500°C down-dip. Microstructures associated with mylonitic intermediate and felsic composition dikes indicate deformation by diffusion creep with grain boundary sliding in all phases, suggestive of relatively 'hot' deformation shortly after emplacement. These microstructures support previous studies that constrain the CDF system to be a gently NE-dipping structure and highlight the mechanisms active in localized deformation. Overall, the composite character of the MWF suggests localized, episodic and competing mylonitic, brittle, and magmatic processes that accommodate extension during early low-angle normal fault slip.

Tectonic Evolution of the Yarlung Suture Zone, Lopu Range Region, Southern Tibet

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The Lopu Range, located ~600 km W of Lhasa in southern Tibet, exposes a continental high-pressure (HP) metamorphic complex structurally beneath India-Asia (Yarlung) suture zone assemblages. New geologic mapping, 14 detrital U-Pb zircon (n=1895 ages), 11 igneous U-Pb zircon, and nine zircon (U-Th)/He samples reveal the structure, age, provenance, and time-temperature histories of Lopu Range rocks. From N to S, the region exposes Eocene Gangdese arc rocks, the Oligocene-Miocene Kailas Formation, U. Cretaceous-Paleogene forearc strata, ophiolitic and sedimentary-matrix mélange, and metasedimentary rocks of Indian passive margin (Tethyan) affinity. In the range core, Cambrian high-grade and Permian low-grade meta-Tethyan rocks are in the footwall of a domal, top-N shear zone below mélange—similar to other continental HP metamorphic complexes in the NW Himalaya. A depositional contact between basal forearc strata (MDA 97 ± 1 Ma) and ophiolitic mélange indicates ophiolite formation in a forearc setting prior to L. Cretaceous time. A hbl-plag-ep paragneiss block in ophiolitic mélange along the top-N, S-dipping Great Counter thrust (GCT) was deformed during L. Jurassic-E. Cretaceous time and cooled below ~180 C by ~110 Ma based on U-Pb and zircon (U-Th)/He data. We interpret this sample to record Lhasa terrane-Neo Tethyan subduction initiation followed by forearc extension. Five Gangdese arc granitoids yielded U-Pb ages between 49-37 Ma. They intrude subduction-accretion mélange, and may record southward trench migration and/or steep subduction following collision initiation. The GCT cuts older suture zone structures, placing forearc on Kailas Fm. and mélange on forearc during the latest stage of Kailas Fm. deposition. The ~N-S oriented Lopukangri and Rujiao faults bound the range, together comprising a horst that cuts the GCT. The faults initiated by ~16 Ma based on a U-Pb zircon age of a dike that cuts a footwall splay of the Lopukangri fault and are likely related to Miocene-recent orogen-parallel extension. Five other leucogranite U-Pb ages between 17-15 Ma record crustal melting during extension onset. Seven zircon (U-Th)/He ages from the horst block record 12-6 Ma cooling below ~180 C. The tectonic evolution of the Yarlung suture in the Lopu Range region can be explained by cycles of slab rollback, breakoff and underthrusting during Cretaceous-Paleogene time, suggesting that slab dynamics played an important role in the Himalayan-Tibetan orogen.

The Geometry of Accreted "Packets" in Subduction Zones; Examples from the Eastern Belt of the Franciscan in California and the Torlesse Terrane in New Zealand

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Accretionary complexes contain rocks with a variety of structural styles ranging from melange to relatively intact beds. This study focuses on some lesser deformed accreted rocks in areas with exceptional exposures: glaciated rocks of the Torlesse near Arthur's Pass, New Zealand, and stream-cut exposures of the Franciscan Eastern Belt in Grindstone and Thomes Creeks, California. The structural style in both areas consists of relatively intact, mappable "packets" of rock separated by faults. This structural style appears to be common in accretionary complexes but the geometry of the packets can only be documented with confidence where exposures are nearly 100%. In both areas studied, rocks are mainly turbidites of prehnite-pumpellyite to lower blueschist grade, described as "broken formation" with no melange or exotic blocks present. The dominant structural features are steeply dipping beds, cut by thrust faults typically oriented at a modest angle to bedding. Fault spacing ranges from ~100 to 600 meters with the angle between bedding and faults usually ranging from 0° to 35°. Between faults, bedding continuity/stratigraphy is generally well-preserved. However, local disruption and folding, including isoclinal folds, may be present.

Deformation associated with the fault traces is variable. In some cases fault contacts are sharp and there is little deformation of adjacent beds. In other cases, small folds, boudinage, and intense fracturing and veining define fault zones. Intensity of deformation varies along the fault plane and is commonly more intense on one side than the other.

The faults described above represent primary surfaces along which "packets" of relatively intact rocks were accreted. This study and others show that these fault-bounded packets can be traced along strike for a few km to at least 10 km or more where not cut by younger faults. The faults appear to form after a period of diffuse, largely extensional shear in semi-consolidated sediments; as rigidity increases, shear becomes localized along fault surfaces.

Deformation associated with the faults is roughly an order of magnitude less than that described in the literature for "megathrusts." It is therefore inferred that the megathrust boundary driving the accretionary process is located some distance structurally below the accreted packets and is not preserved in the areas studied.

Pedagogical Effectiveness of Using Digital Applications for Collection and Interpretation of Sed/Strat and Structural Field Data

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One of the most difficult hurdles that students new to geologic mapping have is the visualization of structure and stratigraphy as they learn field methodologies. Some of this stems from the steep learning curve of having to deal with maps, measurements and plotting of data. We have developed two tablet apps that help the students move more quickly to visualization and interpretation that helps them understand both the temporal and spatial relationships of geologic field data. In StratLogger, the user records bed thickness, lithofacies, biofacies, and contact data in preset and modifiable fields. Each bed/unit record may also be photographed and location referenced by the iPad. As each record is collected, a column diagram of the stratigraphic sequence builds in the app, complete with color, lithology, and fossil symbols. The recorded data from any measured stratigraphic sequence can be exported as the live app-drawn column image. GeoFieldBook, using the onboard GPS and image base, records observations and then displays them in real time on the map base with strike/dip, fault or joint symbols correctly oriented. The app allows the user to select from five different structural data situations: contact, bedding, fault, joints and "other", as well as to develop five custom-designed data pages. Observations are stored as individual records within a user defined project folder. The exact information gathered depends on the nature of the observation, but common to all pages is the ability to log date/time, lat./long. and pictures directly from the tablet. Map images are easily captured for use in other programs. Because analysis and interpretation of the geologic data is subsequently done using digital methodologies (GIS, Google Earth, Stereonet, spreadsheet and drawing programs), the collection of the data in digital form allows for a much easier transition to interpretation and display once the students have returned from the field. In addition to making it easier to visualize in the field, the students can more quickly progress to higher-order interpretation back in the lab without the tedium of analog to digital transfers. We now have seven years worth of data documenting the effectiveness of digital methodologies in the collection and analysis of structural and stratigraphic field data.

Analog modeling of fault asperity kinematics using a modified squeezebox design and wax media

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Fault movement is strongly influenced by the physical characteristics of the fault surfaces. Fault surfaces are generally non-planar, and have a certain amount of roughness to them, which manifests as fault asperities. In order for a fault to continue moving along its preexisting surface, the asperities must either move past each other, which involve moving a large volume of rock around these obstacles, or create new fractures that "decapitate" and pulverize these asperities, ultimately leading to a smoother fault surface. We explore a new way to investigate fault asperity kinematics using a squeeze-box analog deformation rig. The more typical and classic squeeze-box model uses sand and/or clay to demonstrate fault and fold deformations. We have designed and built a new analog modeling rig that utilizes a dual wax analog model. One constituent is white spherical wax particles that have been embedded in a lower-melting-temperature black matrix wax. Deformation of the analog material is facilitated by the addition of heating elements lining the underside and exterior walls of the squeeze-box reservoir. An aluminum asperity is secured to the floor of the reservoir. Additional overburden is simulated with a polyethylene bag filled with lead shot that rest on the top surface of the wax block during deformation. Once the deformation experiment is completed, the wax block can be finely sectioned, polished and scanned in preparation for analysis. Here, we provide proof of concept by demonstrating that we were able to generate realistic looking deformation features at different strain rate and temperature model conditions.

The Alleghanian Orogeny from Start to Finish: As Chronicled by the Narragansett Basin, Southeastern New England

Daniel Murray, *University of Rhode Island*

The Avalon zone of New England consists of a collage of terranes accreted onto ancestral eastern North America during Mid-to Late Paleozoic times. In New England the Alleghanian orogeny represents the final amalgamation of this zone against Laurentia during the assemblage of Pangaea. For most terrains affected by the Alleghanian orogeny in New England the evidence for that event is seen as either an overprinting of earlier Neoproterozoic or Paleozoic orogenic fabrics, or as a faintly and poorly constrained imprint on granitoids. An exception is the Narragansett basin (NB), a Devonian to earliest Permian basin that has been variably deformed and metamorphosed, and intruded by the Narragansett Pier Granite (NPG). Abundant megaflora, radiometric dates, and structural and petrologic analysis of the NB provide the basis for a detailed and nuanced chronology for the Alleghanian orogeny. This presentation will summarize that diverse data and use it to place constraints on models for Alleghanian tectonism, as it affected southeastern New England. It is also noteworthy that the NB is unique in that it contains coal that ranges from anthracite in the north to graphite in the south. This progressive metamorphism of organic material in the context of orogenesis is nowhere else so well preserved, as will also be seen in the presentation.

Our understanding of the Narragansett basin draws from the collective efforts of many individuals, and there is an extensive literature to that effect. Below are two recent articles that not only summarize current thinking, but also provide entrées to primary sources.

Fetherston, D., Murray, D.P., and Wintsch, R.P., 2014, Alleghanian metamorphism of the southern Narragansett Basin, RI: Hinged burial and exhumation. Guidebook to geologic field studies in Rhode Island and adjacent areas. New England Intercollegiate Geologic Conference 106th Annual Meeting, p. B5-1 to B5-19.

Murray, D.P., Skehan, J.W., and Raben, J., 2004, Tectonostratigraphic relationships and coalification trends in the Narragansett and Norfolk basins, New England: Journal of Geodynamics, 37, ps. 583-611.

The Influence of Localized Glacial Erosion on Exhumation Paths in Accreting Coulomb Wedges: Insights from Particle Velocimetry Analysis of Sandbox Models

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Saad Haq, *Purdue University*

Glacial erosion rapidly alters the landscape and is thought to directly impact the location and development of faults in mountain belts. The rapid removal of overburden is thought to affect the distribution of slip on thrust faults, and in some cases cause the development of new structures within the older part of the wedge. Using digital image correlation techniques we quantify the impact of localized erosion on the location of slip on deformational structures, and the general path of material through a wedge. We compare cross-sectional kinematic data from developing models of erosional and non-erosional sandbox models of a Coulomb wedges. To do this, we employ Lagrangian particle tracking velocimetry (PTV) using the open-source Python PTV toolkit Trackpy, among a suite of other data analysis tools. By extracting a robust set of particle trajectories from the cross-sectional images and comparing them to the local surface topography, we determine a high-resolution record of exhumation rates in addition to uplift rates. We also utilize high-resolution Eulerian particle image velocimetry (PIV) to provide a quantitative measure of fault activity throughout the wedge. This combination allows us to interpret particle pathways as a consequence of motion on active structures and wedge morphology. In our experiments, we observe that localized glacial erosion has a direct impact on material pathways leading to increased, but locally asymmetric, rates of exhumation. These trajectories are also more vertical oriented below the zone of erosion, and both reactivation and initiation of new of structures in the older part of the wedge are needed, periodically, to maintain force balance within a critically balanced wedge.

Zircon (U-Th)/He Age-eU Correlations Reveal Long-Term Thermal History of Laurentian Basement

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Andrew K. Laskowski, *University of Arizona*
Peter W. Reiners, *University of Arizona*

The long-term (> 1 Ga) thermal histories of cratons are enigmatic, with geologic data providing only limited snapshots of their evolution. We use zircon (U-Th)/He thermochronology and age-composition correlations to understand the Proterozoic-Phanerozoic thermal history of Archean Wyoming province rocks exposed in the northern Laramide ranges of western North America. Zircon (U-Th)/He ages from crystalline rocks from the hanging wall of major Laramide thrust faults in the Wind River Range (54 ages) show distinct negative correlations with effective uranium (eU) concentrations. Zircons show a range of ages from 582 Ma at low eU to 33 Ma across a wide range of higher eU from about 1000-7000 ppm. We use a radiation damage and annealing model to fit these age-eU correlations, documenting a multistage thermal history of the Precambrian basement. The best fit to the Wind Rivers data involves two phases of cooling: 1800-1600 Ma and 900-700 Ma followed by slower cooling until 525 Ma. During the Phanerozoic, these samples were heated to maximum temperatures between 160-125°C, prior to Laramide cooling to 50°C between 60-40 Ma. The most recent parts of this thermal history are consistent with published apatite (U-Th)/He and fission-track constraints on the timing of Laramide exhumation in the Wind Rivers (~60 Ma), but our model also constrains the pre-Cenozoic history of these rocks. These data are consistent with cooling associated with Yavapai-Mazatazal tectonism followed by two phases of Meso- and Neoproterozoic intracratonic extension.

Microstructures in calcite veins along polygonal faults in the Khoman Formation, Western Desert, Egypt

Tyler Ramey, *Sonoma State University*
Aubrey Coon, *Hamilton College*
Barbara Tewksbury, *Hamilton College*
Matty Mookerjee, *Sonoma State University*

Polygonal faults are layer-bound normal faults that are arranged in broadly polygonal networks in fine-grained sedimentary rocks. Polygonal fault systems have been recognized in over 100 marine basins worldwide. The only extensive on-land exposure of polygonal faults occurs in Cretaceous chalk of the Khoman Formation near Farafra Oasis in the Western Desert of Egypt. The polygonal network consists of thousands of low-slip normal faults that occur in clusters and that are marked by low ridges formed by multi-phase calcite veins that occur along faults in the chalk. The origin of polygonal faults remains the subject of controversy, although most models involve formation during early during diagenesis in association with layer shrinkage and fluid expulsion. Previous work proposed that the calcite veins in the Khoman accompanied formation and evolution of the polygonal fault network and are a manifestation of repeated cycling of pore fluid pressure, failure, and associated fluid expulsion. This study tests that hypothesis by examining the microstructures of the veins using standard petrography analysis along with Electron Backscatter Diffraction (EBSD), Electron Dispersive Spectrometry (EDS), Cathodoluminescence (CL) and Darkfield (DF) imaging.

In a thin sections cut parallel to calcite fibers and perpendicular to vein walls, a crack-seal structure is very clear and marked by prominent arcuate dark bands consisting of inclusions of fine chalk fragments and tiny slivers of chalk wallrock. These features are characteristic of shear veins formed by repeated cracking, opening of the vein in the shear direction at the vein/wallrock interface, inclusion of wallrock fragments at the site of cracking, and precipitation of an increment of optically continuous calcite, which seals the vein again.

The presence of shear veins showing crack-seal structure indicates that calcite vein formation accompanied repeated slip along the normal faults in the Khoman. Although we cannot rule vein formation during a later episode of unrelated fault activity, the simplest explanation is that the veins and polygonal faults are contemporaneous. These veins may reflect something fundamental about polygonal fault formation and fluid expulsion and deserve further detailed study.

A Comparison Between Modelling of Coulomb Stress and Field Observations of Off-Fault Strain around Pseudotachylyte Fault Veins, Norumbega Fault System, southern Maine

Catherine Ross, *McGill University*
Christie Rowe, *McGill University*
Mark Swanson, *University of Southern Maine*

Static stress changes caused by fault motion may be of significant magnitude around fault bends, ends, and intersections, and have been shown to partially explain aftershock distributions aftershocks (Poliakov et al., 2002). In the brittle-ductile transition zone, these stress concentrations may be relaxed after earthquakes by ductile flow. Small-scale deformation features adjacent to pseudotachylyte-filled fault veins may record deformation in response to static stress changes in the wallrock caused by slip on non-planar or intersecting fault surfaces.

Starting from an existing pseudotachylyte map of the Fort Foster Brittle Zone in Kittery, Maine (Swanson, 2013) we mapped the deformation structures in detail at several selected sites of the outcrop surface. High-resolution photographs and field measurements were taken where pseudotachylyte fault veins bend and there were associated near-fault small-scale deformation features. A ~3 m^2 area of outcrop was selected for Coulomb3 stress modelling. It was observed that the general deformation pattern between two pseudotachylyte veins was characterized by a simple pattern: when one fault bends away from the other, the deformation in between the two is characterized by mm- to cm-scale pseudotachylyte injection veins; where the faults are parallel to each other, the deformation style is characterized by ductile features such as tight isoclinal kink and bend drag folds.

The pseudotachylyte photo-mosaic was then used as a basemap in Coulomb3 software in order to build an idealized fault model. The rake and slip of the earthquakes which formed the pseudotachylytes are not known, so we assumed that the shear zone is primarily dextral, and we use the average scaling of normal earthquakes to make estimates of the slip. The predicted stress change orientation and magnitude distribution were produced by Coulomb3. We compare the stress change distributions from the models to the distribution of small near-fault structures mapped in the field. The distribution of stresses is similar to the distribution of shortening and extensional strain measured in the wallrock, therefore we conclude that static stress changes were accommodated plastically in the compressional region where the two faults propagated parallel to each other and in a brittle manner in the extensional region behind the rupture tip in the post-seismic time interval. This suggests that damage occurs over the entire fault by more than just the propagating tips and also suggests that the type of deformation is heavily influenced by the geometry and heat diffusion of the pseudotachylytes.

Insights into earthquake rupture and recovery from paleoseismic faults

Christie Rowe, *McGill University*

Ancient faults preserve evidence of past earthquake rupture, aseismic creep, and interseismic healing, but our ability to read the record is incomplete. There are two key differences between earthquake slip and creep that have the potential to be preserved in rocks. First: the slip velocity is sufficiently high that the frictional heat production on the slip surface is faster than the conductive heat dissipation, resulting in a net temperature rise. If the slip is sufficiently localized and the normal stress is high enough, this temperature rise can dissociate hydrous minerals, cause rapid maturation of organic compounds, and melt fault rock, producing pseudotachylytes. These reactions are recorded in fault rock mineralogy and composition and can be used to estimate coseismic temperatures from < 250°C up to

> 1400°C. Examples will be shown from an ancient subduction thrust fault in Alaska (the Pasagshak Point thrust) and from the plate boundary in the Japan Trench which ruptured in the 2011 Tohoku Earthquake.

A second difference between seismic and aseismic slip on faults is that seismic slip is *dynamic*, that is, that the slipping area expands in size at rates comparable to the shear wave velocity in the rocks (~ 3 km/s), which results in extreme stress gradients in the wall rock at the rupture tip. The stressing rate exceeds the speed at which fractures can propagate through the wall rock, resulting in distinctive patterns of very closely spaced and branching fractures, and sometimes pulverization. In some faults, these fractures are the dominant form of off-fault damage and may cause permeability spikes through the fresh fracture networks. Examples will be shown from the Pofadder Shear Zone (South Africa).

With these fossil earthquake signatures in hand, we can identify ancient seismic rupture planes and use these to map out the geometry of earthquake ruptures at the outcrop scale (10^{-3} - 10^{3} meters), which is below the resolution and location uncertainty of earthquake seismology in most active faults. Using an example from the Norumbega Shear Zone in Maine, I will show that earthquakes can rupture multiple parallel and non-parallel surfaces simultaneously. This discovery is consistent with recent deconvolutions of multiple rupture planes from earthquakes with a large non-double couple component in their focal mechanisms, suggesting that this may be a common phenomenon. Outcrop studies may be able to elucidate the consequences for slip distribution and help explain spatial variations in fracture energy and stress drop which are barely resolvable in seismic data.

Building the Pamir-Tibet Plateau: Crustal Stacking and Orogen Parallel Evasion of Upper and Middle Crustal Material in the Pamir

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The gneisses of the Central Pamir Domes and (meta-)sediments in their cover document crustal stacking of a ~10 km thick Ediacaran–Paleogene succession to a thickness of >35 km and their exhumation along bi-vergent, top-to-N and top-to S, normal-sense shear zones. The giant South Pamir Shakhdara-Alichur gneiss-dome system formed similarly by N-S extension along bivergent detachments. Prograde amphibolite-facies metamorphism in the domes and low-grade metamorphism in their hanging wall is dated at ~40 Ma (Lu-Hf garnet, U-Pb titanite) [Smit et al., 2014; Stearns et al., 2015] and ~33 Ma (K/Ar sericite). Rapid retrograde metamorphism—driven by crustal extension—started at ~22 Ma and ended at ~12 Ma (multi-method thermochronology; Stearns et al. [2013]). These Gneiss Domes offer a unique window into the Eocene-Miocene state of the Asian middle crust of the Pamir-Tibet Plateau. We suggest that ~22 Ma initiation of N–S extension is the result of gravitational collapse forced by Indian slab breakoff. What caused the termination of N–S gravitational collapse at ~12 Ma? We integrate Indias northward underthrusting and Asian crustal shortening and show that Indian mantle lithosphere was likely underthrusting the Pamir by ~12 Ma; Coupling with the crust ended the N–S extension. After further northward underthrusting, the Indian mantle lithosphere collided with Asia's cratonic root at ~10 Ma and forced its delamination which is continuing today and represented by the Pamir slab [Kufner et al., 2015]. Prior to doming, top-to-N thrust stacking accommodated thickening in the upper crust, with displacements of single thrust sheets of >30 and >19 km. At depth, ductile flow formed km-scale recumbent fold nappes. We reconstruct their geometry by structural mapping and U-Pb zircon dating, documenting repetition of metatuffite, and paragneiss layers. In the interior of the domes, amphibolite-facies deformation fabrics with prograde kyanite define an E-W stretching lineation. Associated microstructures indicate top-to-E and top-to-W shear senses. Chocolate tablet boudinage indicate vertical flattening during bulk crustal thickening. We suggest that prograde E-W stretching relates to an early orogen-parallel flow component in the middle crust, contemporaneous with crustal stacking during bulk top-to-N convergence prior to ~22 Ma. Material likely evaded laterally out of the Pamir, contributing to >60 km thick crust in the Hindu Kush, west of the India-Asia frontal collision. In the Neogene, crust extruded laterally from the Pamir Plateau to the west by dextral wrenching and E–W extension; this component of deformation is accommodated by E–W shortening in the Afghan-Tajik Depression.

On the limits of the Inverse SURFOR Wheel in fabric analysis

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A major component of fabric analyses is to determine the shape and orientation of the finite grain-shape ellipsoid. When protolith geometries of grains are known many methods have returned a strain ellipse(oid). In cases of metamorphic textures such control is not enjoyed because recrystallization overprints or destroys fabrics progressively. Instead the analyses return both the bulk and phase grain-shape ellipse(oid) shapes and orientations, but not, necessarily, the strain ellipse(oid). Regardless, all methods require an understanding of uncertainties and limits of their use. One successful fabric analysis method is the inverse SURFOR wheel (Panozzo, 1987, JSG) that uses grain boundary intercepts with a grid of parallel lines inside a circle (the wheel). The present study was planned to investigate the limits of this method using 2-D analog experiments where in each the object shapes and orientations are known and arranged into artificial lattice patterns. The Inverse SURFOR wheel method uses the wheel of parallel lines superimposed on 2-D imagery of grain boundaries. Intercepts of the wheel lines with grain boundaries are recorded at each 10° of rotation of the wheel through 180°. In principle, the fewest intercepts are found along the long aspect of the fabric, and the most along the short aspect (an inverse). A plot of counted intercepts at each rotation is smoothed with a sinusoidal curve. The shape of the fabric ellipse is found by the ratio of values of the curve crest and trough. The orientation of the ellipse is found by the crest and trough coordinate angle values relative to the 0° reference line as the short and long axis orientations, respectively. Comparison of results with the imagery of natural textures has shown consistency in grain-shape patterns. To test how well the method reveals fabrics, experiments began with circles and squares as controls that returned no preferred fabrics. Experiments using ellipses and diamonds with preferred lattice patterns, spacing, and orientations returned agreement in ellipse shapes with 8-12% uncertainties, and with artifacts in data patterns caused by object spacing, and object size vs. wheel line spacing. Results confirm consistent method reliability, and also confirm the value of the fitting of the sinusoidal curve as the way to determine the ellipse shape and orientation, rather than using raw intercept maxima and minima. However, in cases of multiple fabrics, such as folded and S-C fabrics, caution must be employed to recognize these, and to count each component separately because a bulk analysis returns a combined result.

Earth-Centered Communication for Cyberinfrastructure (EC3): Incorporating a Joint Cyber-Science and Geoscience Perspective into Designing Field Data Management Systems

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The geosciences rely heavily on investigating the natural world in situ, i.e., within "the field." In order to include field data into the cyberinfrastructure development efforts that are currently ongoing (e.g., EarthCube), we need to design field data management systems that can be incorporated into the typical field, geoscience workflows as unobtrusively as possible. To this end, the NSF-funded, EC3 project organized two field excursions in August '14 and '15 to Yosemite National Park and Owens Valley, which brought together representatives from both the geoscience and cyberinfrastructure communities. A major outcome of these interactions included discussions on both the positive and negative aspects of mobile devices (e.g., smart phones, tablets, ruggedized laptops, GPS, etc.) for field data collection. Unfortunately, no current standard exists with respect to the usage of these tools. This non-standardization is a significant challenge with respect to data sharing and designing an effective and transferrable cyberinfrastructure. As a group exercise, the EC3 participants created ranked lists of software/hardware recommendations for a field data management system and a list of metadata that should ideally be captured by the system. While several field data collecting apps exist for both the iOS and Android operating systems, there is some concern about the accuracy of these devices as well as the longevity, sustainability, and extensibility of these small-scale, independent mobile apps. During the EC3 trip, all participants were encouraged to take planar orientation measurements on a demarcated natural surface with their individual phones using several different commercially available apps. Preliminary results suggest that the data range was greater than 50° in the strike direction. In another group exercise, the project participants discussed potential use-cases for an idealized EarthCube, integrated, database management system; in small groups they brainstormed different research and educational opportunities that such a system would provide. In order to facilitate scientific discovery, we need new data collection and management techniques that dovetail with current cyberinfrastructure activities to make field collection more efficient and real-time data synthesis more feasible.

Heterogeneous Exhumation of Mid-crustal Rocks along the Hayes Restraining Bend of the Central Denali Fault

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The right-lateral transpressive Denali fault has been a principal feature in Alaskan tectonics for over 60 million years and offers the chance to study exhumation mechanisms of rocks from below the brittle-ductile boundary. Both $^{40}Ar/^{39}Ar$ K-feldspar and mica cooling ages show greatest exhumation close to the fault on the north side of the Hayes restraining bend in the Eastern Alaska Range and indicate ongoing exhumation in this region since 25-27 Ma. Here, deformed orthogneisses and metasedimentary country rocks display generally subvertical to steeply N-dipping foliations with obliquely plunging lineations. The concentration of youngest cooling ages (as young as 15 Ma for mica and 6 Ma for K-feldspar) at the apex of the bend appears to support the idea that rocks to the north of the fault have been relatively fixed with respect to the bend since the Miocene. Vorticity analyses provide an opportunity to better understand the mechanisms for exhumation along this section of the Denali fault and were carried out on samples of both orthogneiss and quartz-rich metasedimentary rock. The kinematic vorticity number (Wk) for each sample was determined using two different methods: 1) the Vorticity Diagram Method, which relates the length of the maximum (λ_1) and minimum (λ_3) principal strain axes ratio (R_{XZ}) to the orientation of λ_1 with respect to foliation, and 2) the LPO method, which relates R_{XZ} to the angle (β) between the flow plane (as determined by EBSD analysis) and the foliation. C-axis pole figures generated from EBSD data yield predominantly single girdle patterns, which are suitable for the LPO method, although several display unusual patterns that may require use of the a-axes to determine Wk. Preliminary results suggest that deformation in this section of the fault is dominated by pure shear (Wk < 0.71), especially in areas of greatest exhumation at the apex of the restraining bend.

Extensively developed network of non-tectonic synclines in Eocene limestone of the Western Desert, Egypt: an example of hypogene speleogenesis?

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High resolution satellite imagery of the Western Desert of Egypt reveals an extensive network of long narrow synclines developed in Early Eocene limestone. These structures are unusual and have characteristics not typical of tectonic fold structures. The terrain is dominated by long narrow synclines (100-400 m across) with shallow limb dips, porpoising hinges with shallow plunges, and multiple basin closures along their lengths. Synclines are similar in scale across the region, with no parasitic folds and no larger structures. Two dominant orientations are common (NNW-SSE and WNW-ESE), parallel to two prominent joint sets in the limestones. Synclines from the two trends branch, merge, and curve into one another, forming a network. Over large parts of the area, narrow synclines are the only fold structures present and form isolated downwarps 1-3 km apart in otherwise flat-lying limestone. Where synclines are locally more closely spaced, inter-syncline areas are broadly anticlinal, but geometries suggest that they are "accidental anticlines" formed by the proximity of two nearby syncline limbs rather than by an active anticline-forming process. Syncline limbs are commonly cut by faults striking parallel to bedding but dipping more steeply than bedding toward syncline cores. The syncline network and related faults developed in a narrow time window between Early Eocene deposition of the limestones and formation of cross-cutting faults associated with Red Sea rifting.

The characteristics of the syncline network are consistent with sag of limestone layers, which can be caused by a variety of subsurface volume reduction mechanisms or by mobilization of underlying shale sequences. All the likely suspect mechanisms have problems, however. No evaporites have been reported in the Western Desert stratigraphic column. We see no evidence of epigenic karst processes at a scale that could produce the synclines. Long-term subaerial exposure of units deeper in the section occurred in shale units, rather than limestones, which argues against collapse of paleokarst. Mobilization of underlying shales and accompanying sag of overlying limestone layers sounded plausible until we did a country-wide survey of synclines, which revealed remarkably consistent orientations over huge distances. Silica diagenesis remains a possibility, although consistency of orientations is also a problem for this mechanism. We are currently exploring hypogene speleogenesis, with upward migration of fluids along joints and faults and dissolution of the limestones at depth. Fluid aggressiveness might have come from CO_2 (perhaps supercritical) associated with widespread igneous activity during the Eocene and Oligocene in Egypt.

Quantifying Deformation in Ridge-Transform Systems: An Example from the Troodos Ophiolite, Cyprus

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Ridge-transform intersections are common features along divergent plate boundaries, recording complex deformation from both spreading and faulting processes. The Troodos ophiolite in Cyprus preserves a ridge-transform system defined by the NS-striking Solea Graben (paleoridge) and the EW-striking Arakapas fault (paleotransform). The excellent exposures of crustal rocks including gabbros, sheeted dikes, and lavas on the outside and inside corners of the system allow us to reconstruct deformation in two dimensions across a slice of oceanic lithosphere.

Many previous studies of deformation in the ophiolite used coupled paleomagnetic and structural data. To restore paleomagnetic directions, especially from the sheeted dike complex, these studies (1) relied on the paleomagnetic reference direction for the ophiolite, which is nearly due west in present-day coordinates, and (2) assumed that dikes intruded vertically. These studies examined patterns along 1D transects either perpendicular to the ridge, when interested in seafloor spreading processes, or perpendicular to the transform, primarily to determine the sense of motion on the Arakapas fault.

We take a different approach to characterizing deformation, made possible by the large paleomagnetic and structural datasets, including our own new paleomagnetic results from ~40 sites. Our assumptions are that (1) the paleomagnetic and structural data closest to the ridge should serve as the reference direction for rocks away from the ridge, and (2) dikes did not have to intrude vertically, but magmatic activity was localized near the ridge. Changing the reference frame to the ridge allows us to track the deformation behavior over time. For the outside corner, this means examining changes in the data as a function of westing; for the inside corner, as a function of easting. By tracking deformation along three ridge-perpendicular transects in the southern, central, and northern parts of the ophiolite, we show how the results vary not only by easting/westing but also by distance from the ridge-transform intersection. Our analysis incorporates statistical techniques, such as geodesic regression of the structural and paleomagnetic data, to quantify variation over space.

Analog modeling of Mexican Fold and Thrust Belt in central México

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In central Mexico, the Mexican Fold-and-Thrust Belt (MFTB) presents particular characteristics different to other fold-thrust belts. The presence of important sedimentary facies changes in the pre-tectonic units plays an important role in the deformation style, shortening accommodation and kinematic evolution. Field observations and direct dating of deformation have contributed to our understanding of the development of this orogenic wedge. Nevertheless, there are some fundamental aspects that we need to know: What is the importance of the facies changes in the history of deformation? How is deformation accommodated near the borders of the facies change? What is the influence of lateral mechanical characteristics of the pre-tectonic units on the deformation of the syntectonic deposits? What is the role of superficial processes (erosion and sedimentation) in the deformation of the orogenic wedge in central Mexico?

To answer these questions we use scaled analog models to study the kinematic evolution of fold-and-thrust belts. Sand-box modeling is frequently used to generate scaled orogenic wedges in natural gravity conditions. For the models, we used different sands with different friction angles to model the lateral mechanical variation in pre-tectonic rocks, product of the facies changes. Our results indicate that the kinematic evolution, deformation style (dominance of folds in the basins and thrusts in the platforms) and strain variations (more in the basins and less in the platforms) of the MFTB is related spatially with the mechanical properties in the pre-tectonic rocks, the geometry of the borders between platforms and basins, and the weight of syntectonic deposits. The deformation within syntectonic deposits depends on its position in the wedge, with high simple shear strain concentrated on the border zone between platforms and basins, while pure shear dominates in the middle part of the basins. These results are congruent with the field observations and shortening estimations reported in previous work.

Integrated software for the analysis and presentation of directional data, with spherical projections, bootstrap statistics, kinematic analysis, cluster partitioning, and data visualization

Frederick W. Vollmer, *State University of New York at New Paltz*

Orient is a free professional directional data analysis and spherical projection program, with a user-friendly interface and simple data input. Orient has been in development since 1986, and introduced modified Kamb contouring, Point Girdle Random diagrams, orientation fields, and automated domain analysis.

In 2015 Orient 3.0 brought a new level of accuracy and speed, with interactive data analysis, UTM coordinate conversions, digitizing, and integration with Microsoft Excel, LibreOffice, Adobe Illustrator, InkScape, CorelDRAW, and Google Earth. Features included circular histograms and frequency plots; upper and lower hemisphere orthographic, stereographic, and equal-area projections; Fisher, Watson, and Bingham confidence cones; unlimited coordinate system and data rotations; extensively configurable plots and symbols; color gradient plots; and vector graphics.

New updates through version 3.4 have added bootstrap analysis; Kent distribution statistics; best-fit conical fold axes and small circles; cluster partitioning for axis, vector, and girdle distributions; kinematic data error calculation and orthonomalization; data point weighting; translucent display of hidden data; and numerous other fixes and upgrades.

Strain localization and megathrust slip accommodation modes in the Franciscan Complex, California

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Numerical models of subduction produce broad (multi-km thickness) zones of displacement that accommodate subduction megathrust displacement and exhumation of subduction complex rocks. Such displacement zones are commonly referred to as a "subduction channels". Many assert that mélanges represent the exhumed analogs of such channels, and that subduction slip and exhumation results in tectonic mixing of the blocks in matrix. Field relationships in the Franciscan Complex of California contradict such models. Franciscan mélanges with exotic blocks that have been considered type examples of exhumed subduction channels show evidence for incorporation of blocks by sedimentary sliding prior to burial and subsequent tectonic deformation. These mélanges are commonly less than 1 km in thickness and are variably deformed sedimentary packages rather than shear zones. In contrast, more limited (tens of meters thick) fault zones show progressive deformation from imbricated ocean plate stratigraphy to block-in-matrix geometry; such zones lack exotic blocks. Megathrust slip appears to have been accommodated in two modes, accretionary and non accretionary. For the accretionary mode a series of faults accommodated the transfer of the unit from the subducting to the upper plate. Whereas the megathrust slip in such cases is accommodated on faults spanning the full structural thickness of the unit (several km), most of the rock shows little if any penetrative strain. The faults accommodating the accretion range from cm-scale brittle fault zones to networks of brittle faults that may collectively span tens of meters. Non-accretionary megathrust zones may have accommodated most of the ~13000 km of Franciscan subduction slip. Such zones separate accreted units with notable contrasts in lithology and have a thickness of <50 m. Most of the exhumation of Franciscan rocks was accommodated by upper plate extension, and cross-sectional extrusion (thrust fault below, normal fault above). Faults accommodating exhumation appear to have been discrete features of minimal thickness (also tens of meters or thinner). This is consistent with sharp contrasts in metamorphic grade across narrow (10s of m and thinner) faults instead of broader metamorphic gradients.

Subduction initiation in the Appalachian-Caledonide orogen

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Brendan Murphy, *St. Francis Xavier University*

The Appalachian-Caledonide orogen was the first to be interpreted as a zone of plate-tectonic collision in a landmark paper by Tuzo Wilson 50 years ago. However, Wilson's original question 'Did the Atlantic close and then reopen?' addresses only part of the supercontinent cycle, spanning the transition from closing oceans, through supercontinent assembly, to breakup and ocean spreading. The transition from separation to convergence was not addressed by Wilson, but the initiation of subduction in new oceans remains a poorly understood part of the supercontinent cycle.

In the Appalachian-Caledonide system, rifting representing final stages in the breakup of Rodinia continued to at least ~550 Ma, producing an ocean with numerous hyperextended margins and microcontinental blocks. These include both peri-Laurentian and peri-Gondwanan terranes. Arcs were present in the developing ocean by 505 Ma. In the development of the orogen, the earliest stages of deformation of peri-Laurentian and peri-Gondwanan rocks took place concurrently from latest Cambrian into Early Ordovician. Deformation close to the Laurentian margin is characterized as Taconian (in N. America) or Grampian (in Europe) whereas deformation of the Gondwanan margin, is characterized as Penobscottian (in N. America) or Monian (in Europe). Most models for these deformation episodes require that subduction was initiated along former passive margins on both sides of the young Iapetus Ocean. However, the record in Mesozoic-Cenozoic oceans suggests that spontaneous inversion of passive margins is tectonically unlikely.

In an alternative model, convergence was localized at arc systems, which entered the Iapetan realm from an external ocean, a process similar to the entry of the modern Caribbean and Scotia plates into the Atlantic. Thus the Taconian and Penobscot deformation episodes may have occurred at different points on a single sinuous subduction system. Closure of the Iapetus eventually incorporated both peri-Gondwanan and peri-Laurentian microcontinents, with their records of early deformation, into a complex orogen. A number of lines of evidence suggest that arcs were not generated by inversion of the passive margin of Iapetus. Many show juvenile signatures suggesting that they did not originate on older margins, nor in the new lithosphere formed by rifting of Rodinia.

These observations, and Wilson's original comparison with the Atlantic, suggest that spontaneous inversion of passive margins is unlikely to have localized subduction. Instead arc systems entered the newly formed oceans formed by breakup of Rodinia and initiated ocean closure.

Intraplate Fault Records >400 ka of Time-Dependent Earthquakes Punctuated by Clustered Seismicity

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Laurel Goodwin, *University of Wisconsin-Madison*
Warren Sharp, *Berkeley Geochronology Center*
Peter Mozley, *New Mexico Tech*

We present here the results of U-Th geochronology of calcite veins in the Loma Blanca normal fault zone (Rio Grande rift, New Mexico) that constrain earthquake recurrence intervals over the past ~550 ka, thereby providing the longest, most complete paleoseismic record ever documented. U-Th analysis of these calcite veins allows us to delineate 14 distinct earthquake events. These results demonstrate that for a period of over 400 ka the Loma Blanca fault produced earthquakes with a mean recurrence interval of 40 ± 7 ka. The coefficient of variation for these events is 0.42, indicating strongly periodic seismicity consistent with the time-dependent model of earthquake recurrence. However, this time-dependent series is punctuated by an episode of clustered seismicity at ~430 ka. Recurrence intervals associated with this earthquake cluster were as low as 3-9 ka. Breccia veins formed during the ~430 ka earthquake cluster record carbon isotope signatures consistent with having formed through pronounced degassing of a CO_2 charged brine during post-failure fault-localized fluid migration. This observation suggests that subsurface CO_2 may have exerted a substantial influence on the earthquake recurrence behavior of the Loma Blanca fault. Collectively, our results indicate that strongly periodic, time-dependent earthquake behavior associated with intraplate normal faults may be interrupted by transient, but substantial increases in earthquake recurrence of up to 1 order of magnitude. Seismicity in these settings can therefore be both time-dependent and clustered given sufficient lengths of observation, and relatively rapid recurrence intervals associated with clustered seismicity may be controlled in part by variations in subsurface CO_2.

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Notes

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