

CURRICULUM VITAE - KARL MUELLER

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EDUCATION

1992 Ph.D. Geology, University of Wyoming
1984 M.Sc. Geology, San Diego State University
1982 B.S. Geology, San Diego State University

POSITIONS HELD

2003 - present Associate Chair for Graduate Studies, University of Colorado
2002 - present Associate Professor, University of Colorado
2001 Fellow - Japan Society for the Promotion of Science, Kyoto University
1995 - 2002 Assistant Professor, University of Colorado
1993 - 1995 Postdoctoral Research Associate, Princeton University
1992 - 1993 Visiting Assistant Professor, University of Montana
1990 - 1991 Lecturer, University of Wyoming
1987 - 1989 Research Assistant, University of Wyoming
1989 (summer) Geologist, Amoco Production Company
1986 - 1987 Geologist, West and Associates
1984 - 1986 Geologist, Arco Exploration Company

RESEARCH INTERESTS

My research aims to understand how the upper crust responds to active contraction along plate boundaries and within continental interiors. I am interested in how slip on blind thrusts is transferred upward into overlying folds. My work is driven by the societal need to forecast the locations of future earthquakes in populated areas, and the scientific aim of understanding the physical mechanisms that govern the active growth of folds. I study active folds in Southern California, the New Madrid seismic zone, Japan and Taiwan. Besides study of active folds, I have sought to understand why recent uplift of southern California and northern Baja California occurs and whether it is related to crustal thinning or heating of the mantle in the Gulf of California. I am also interested in understanding how erosion in the Taiwanese thrust belt has affected the evolution of compressive there at relatively small areal and temporal scales. A more recent aspect of my research is aimed at understanding the mechanisms that govern growth of fault-related folds on Mars. I also have worked to develop methods of defining the rupture parameters of past earthquakes in the American mid-continent using models of elastic stress transfer.

PEER-REVIEWED PAPERS

1. Hough, S., Bilham, R., Mueller, K., Stephenson, W., Williams, R., and J. Odum, in review, Wagonloads of Sandblows: Bulletin Seismological Society of America.
2. Mueller, K., and Golombek, M., 2004, Compressional structures on Mars: Annual Reviews Earth and Planetary Sciences, 32, 435-464.
3. Mueller, K., Hough, S., and Bilham, R., 2004, Investigating 1811-1812 New Madrid mainshocks with instrumentally recorded aftershocks: Nature, 429, 284-288.

4. Ishiyama, T., Mueller, K., Togo, M., Okada, A., and Takemura, K., 2004, Geomorphology, kinematic history and earthquake behaviour of the active Kuwana wedge-thrust anticline, central Japan: *Journal of Geophysical Research* (in press).
5. Lee, J.C., Rubin, C., Mueller, K., Chen, Y.G., Chan, Y.C., Sieh, K., Chu, H.T., and W.S. Chen, 2004, Quantitative analysis of movement along an earthquake thrust scarp: a case study of a vertical exposure of the 1999 surface rupture of the Chelungpu Fault at Wufeng, western Taiwan: *Journal of Asian Earth Sciences*, 23, 263-273.
6. Mueller, K., Kier, G., Rockwell, T., and C. Jones, Quaternary Rift-Flank Uplift of Southern California and Northern Baja California: *Tectonics*, (in press).
7. *Bielecki, A.E., and Mueller, K.J., 2002, Origin of terraced hillslopes on active folds in the southern San Joaquin Valley, California: *Geomorphology*, 42, 131-152.
8. Mueller, K.J., and Pujol, J., 2002, 3D geometry of the Reelfoot blind thrust: implications for moment release and earthquake magnitude in the New Madrid seismic zone: *Seismological Society of America Bulletin*, 91, 1563-1573.
9. Guccione, M.J., Mueller, K.J., *Champion, J., Sheperd, S., Carlson, S.D., and Odhiambo, B., 2002. Stream response to repeated coseismic folding, Tiptonville Dome, western Tennessee: *Geomorphology*, 43, 313-349.
10. *Champion, J.A., Tate, A., Mueller, K.J., and Guccione, M., 2001, Geometry, numerical modeling and revised slip rate for the Reelfoot blind thrust and trishear fault-propagation fold, New Madrid seismic zone: *Engineering Geology*, 62, 31-49.
11. Lee, J.C., Chen, Y.G., Sieh, K., Mueller, K., Chen, W.S., Chu, H.T., Chan, Y.C, Rubin, C., Yeats, R., 2001, A Vertical Exposure of the 1999 Surface Rupture of the Chelungpu Fault at Wufeng, Western Taiwan: Structural and Paleoseismic Implications for an Active Thrust Fault: *Seismological Society of America Bulletin*, 91, 914-929.
12. Rubin, C., K. Sieh, Y.G. Chen, J.C. Lee, H.T. Chu, R. Yeats, K. Mueller and Y.C. Chan, 2001, Post-earthquake response, 1999 Chi-Chi earthquake: Evidence for past earthquakes: *Eos*, 82, 565-567.
13. Bendick, R., Bilham, R., Fielding, E., Gaur, V., Hough, S.E., Kier, G., Kulkarni, M.N., Martin, S., Mueller, K., and M. Mukul, 2001, The January 26, 2001 Bhuj Earthquake: India, *Seismological Research Letters*, 72, 329-335.
14. Rivero, C., Shaw, J.H., and Mueller, K.J., 2000, Insights into the origin of blind thrust faults in coastal southern California: The Oceanside and Thirtymile Bank thrusts: *Geology*. 28, 891-994.
15. Mueller, K. J., *Champion, J.A., Guccione, M., and Kelson, K., 1999, Fault slip rates in the modern New Madrid seismic zone: *Science*, 286, 1135-1138.
16. Grant, L.B., Mueller, K.J., Gath, E.L., Cheng, H., Edwards, L., Munro, R., and Kennedy, G., 1999, Late Quaternary uplift and earthquake potential of the San Joaquin Hills, southern Los Angeles Basin, California: *Geology*, 27, 1031-1034.
17. Mueller, K.J., Cerveny, P.K., Snee, L.W., and Perkins, M.E., 1999, Chronology of Polyphase Extension in the Windermere Hills, NE Nevada: *Geological Society of America Bulletin*, 111, 11-27.

18. Walls, C., Rockwell, T.R., Mueller, K., Bock, Y., Williams, S., Pfanner, J., Dolan, J., P. Fang, 1998, Escape Tectonics in the Los Angeles Metropolitan Region and Implications for Seismic Risk: *Nature*, 394, 356-360.
19. Mueller, K., and Suppe, J., 1997, Growth of Wheeler Ridge Anticline, California: Implications for fault-bend folding behaviour during earthquakes, *Journal of Structural Geology*, 19, 383-396.
20. Mueller, K., and Talling, P., 1997, Geomorphic evidence for tear faults accommodating lateral propagation of an active fault-bend fold, Wheeler Ridge, California, *Journal of Structural Geology*, 19, 397-411.
21. Mueller, K.J., and Rockwell, T.R., 1995, Late Quaternary activity of the Laguna Salada fault in northern Baja California, Mexico: *Geological Society of America Bulletin*, 107, 8-18.
22. Mueller, K.J., and Snoke, A.W., 1993, Progressive overprinting of normal fault systems and their role in Tertiary exhumation of the East Humboldt-Wood Hills metamorphic complex, northeast Nevada: *Tectonics*, 12, 361-371.
23. Mueller, K.J., 1993, Geologic map of the Windermere Hills, Elko County, Nevada, (with cross sections and descriptions of geologic units): *Nevada Bureau of Mines and Geology Field Studies Maps*, No. 4, scale 1:48,000. Area covers (4) 7.5 minute quadrangles.
24. Mueller, K.J., and Rockwell, T.R., 1991, Late Quaternary structural evolution of the western margin of the Sierra Cucapa, Baja California Norte: in Dauphin, J., and Simoneit, B., (ed) *The Gulf and Peninsular Province of the Californias*, *AAPG Memoir* 47, 249-260.

SYMPOSIA VOLUMES

- Mueller, K.J., 2000, Evaluating blind thrust hazards with structural analysis, geomorphology and trench excavations; examples for southern California and New Madrid: Active fault research for the New Millennium, *Proceedings of the Hokudan International Symposium on Active Faulting*, Hokudan, Japan (eds) K. Okamura, K. Takada, and H. Goto, p. 299-314.
- Mueller, K.J., 1999, Geomorphic criteria for establishing the kinematics of active fault-related folds: McClay, K., and Munoz, J., (eds) *Thrust Tectonics-99*, Royal Holloway, London, p. 90-93.

CONFERENCE ABSTRACTS

- Ishiyama, T., Mueller, K., and Togo, M., 2004, Coseismic fold scarp associated with historic earthquakes on the Yoro active blind thrust, the Nobe-Ise fault zone, central Japan, *Eos, Trans American Geophysical Union*, Fall Meet. Suppl., Abstract
- A. Vidal, K. Mueller, M. Golombek, 2003, Balanced crustal cross sections across wrinkle ridges on Solis Planum, Mars, from MOLA topography: *Eos, Trans American Geophysical Union*, 84, (46), Fall Meet. Suppl., Abstract P41A-0392 F960
- S.E. Hough, K. Mueller, R. Bilham, N. Ambrasays, S. Martin, 2003, Remotely triggered earthquakes in intraplate regions: Distributed hazard, Dependent Events: *Eos, Trans American Geophysical Union*, 84, (46), Fall Meet. Suppl., Abstract S31G-07 F1062
- J. Pujol, K. Mueller, P. Shen, V. Chitupolu, 2003, Seismotectonics of the San Fernando Basin, *Eos, Trans American Geophysical Union*, 84, (46), Fall Meet. Suppl., Abstract S52I-03 F1144

- P. Upton, K.J. Mueller, P.O. Koons, L. Powell, 2003, Reorganization of Strain in Response to Erosional Forcing at Intermediate Scales: Puli Embayment, Western Taiwan: *Eos, Trans American Geophysical Union*, 84, (46), Fall Meet. Suppl., Abstract T31F-0899 F1391
- Vidal, A., Mueller, K., and M. Golombek, 2003, Axial Surface mapping of wrinkle ridges on Solis Planum, Mars from MOLA topography: Constraints on subsurface blind thrust geometry: *Proceedings of the 34th Lunar and Planetary Science Conference*, 33, abstract 1125 CD-ROM.
- Cannon, E. C., K. J. Mueller, Y. Sugiyama, N. Kitada, and S. Sundermann (2003). Coseismic Growth and Seismic Hazards of Blind Thrust Faults in Osaka Basin, Japan - The Uemachi Fault System, IUGG 2003 XXIII General Assembly of International Union of Geodesy and Geophysics, Abstracts Week B, B.521.
- Cannon, E. C., K. J. Mueller, Y. Sugiyama, N. Kitada, and S. Sundermann (2003). Late Quaternary Paleoseismic History Of The Uemachi Blind Thrust System In Metropolitan Osaka, Japan, Based On High-Resolution Stratigraphic Analysis Of Fault-Propagation Folds, Abstracts with Programs - Geological Society of America, 2003 Annual meeting.
- Hough, S.E., Mueller, K., and R. Bilham, 2003, Where was the 23 January 1812 New Madrid Mainshock: *Seismological Research Letters*, 74, 204.
- Ishiyama, T., Mueller, K., Togo, M., Takemura, K., and A. Okada, 2002, Geomorphology and Kinematics of the Nobi-Ise Active Fault Zone, Central Japan: Implications for the kinematic growth of tectonic landforms within an active thrust belt: *Eos, Trans American Geophysical Union*, 83, (47), Fall Meet. Suppl., Abstract S11B-1140.
- Mueller, K., Chen, Y., and L. Powell, 2002, Modern Strain and Structural Architecture of the Central Taiwanese Orogen – Evidence for Active Backstepping in Response to Erosion?: *Eos, Trans American Geophysical Union*, 83, (47), Fall Meet. Suppl., Abstract T61B-1279.
- *Powell, L., Mueller, K., and Y. Chen, 2002, Geomorphic Constraints on Patterns of Shortening and Erosion in the Puli Basin: Hinterland of the Central Taiwan Thrust Belt: *Eos, Trans American Geophysical Union*, 83, (47), Fall Meet. Suppl., Abstract T61B-1270.
- *Tate, A., Mueller, K.J., and Golombek, M.P., 2002, Kinematics and Structural Inversion of Wrinkle Ridges on Lunae and Solis Plana – Implications for the Early History of Tharsis: *Proceedings of the 32nd Lunar and Planetary Science Conference*, 33, 1828.
- *Tate, A., Mueller, K.J., and Golombek, M.P., 2002, Geometry and Kinematics of Wrinkle Ridges on Lunae and Solis Plana, Mars: Implications for Fault/Fold Growth History, *Proceedings of the 32nd Lunar and Planetary Science Conference*, 33, 1836.
- Ishiyama, T., Mueller, K. J., Togo, M., Sato H., Suzuki, Y. and Okada, A., 2002, Geomorphology and kinematics of the Kuwana anticline: evidence for active wedge thrusting in central Japan, Abstracts 2002 Joint Meeting of Earth and Planetary Science Joint Meeting, J029-P020.
- Mueller, K., Chen, Y., and G. *Kier, 2001, Erosion-Induced Backstepping and Reactivation of the Chelungpu Thrust: Implications for patterns of modern strain release in west-central Taiwan: (invited abs) *Eos, Trans American Geophysical Union*, 82, (47), p. F1178.
- *Cannon, E., Mueller, K., Sugiyama, Y., and N. Kitada, 2001, Coseismic growth of active fault-propagation folds by heterogeneous shear, Kansai region, Japan: *Eos, Trans American Geophysical Union*, 82, (47), p. F1230.
- *Sundermann, S., and K. Mueller, 2001, Late Quaternary Uplift Rates and Geomorphology of the Santa Fe Springs and West Coyote Folds, Los Angeles Basin, California: *Eos, Trans American Geophysical Union*, 82, (47), p. F803.
- Pujol, J., Mueller, K., and S. Peng, 2001, Tomographic Imaging of Basement Structure and Active Faults in the San Fernando-Northridge Region, Southern California: *Eos, Trans American Geophysical Union*, 82, (47), p. F803.
- *Tate, A., Mueller, K., and M. Golombek, 2001, Geometry and kinematics of wrinkle ridges on Lunae and Solis Plana, Mars: Implications for fault/fold history: *Eos, Trans American Geophysical Union*, 82, (47), p. F724.
- *Kier, G., Mueller, K., and T. Rockwell, 2001, Origin of Regional Uplift across Southern California and Northern Baja California: *Eos, Trans American Geophysical Union*, 82, (47), p. F1252.

- Bendick, R., Bilham, R., Fielding, E., Gaur, V., Hough, S., *Kier, G., Kulkarni, M., Martin, S., Mueller, K., Mukul, M., 2001, Geodetic investigation of the January 26, 2001 Bhuj earthquake, Gujarat, India: (invited abs) *Eos, Trans American Geophysical Union*, 82, 261.
- Fielding, E. J., Bilham, R., Rogez, F., Hensley, S., Rosen, P. A., Mueller, K., 2001, SAR Interferometry and Optical Image Changes of Kachchh, India: Applications to the 26 January 2001 Earthquake Geomorphology and Co-Seismic Strain: (invited abs) *Eos, Trans American Geophysical Union*, 82, 256.
- *Tate, A., Golombek, M., and Mueller, K., 2001, Morphology of Wrinkle Ridges on Lunae and Solis Plana, Mars from MOLA Topography: Implications for their Kinematic Development: *Proceedings of the 22nd Lunar and Planetary Science Conference*, 32, 1444.
- Guccione, M.J., Shepherd, S., Odihambo, B. Mueller, K., and *Champion, J., 2000, Response of the Mississippi and small floodplain rivers to coseismic folding, Tiptonville dome, western Tennessee, *Geol. Soc. America Abst w. Prog.* 32, 55-56.
- Mueller, K.J., 1999, Determining slip rates and kinematics of blind thrusts using geomorphic and trench criteria for fault-related folds: (invited abs) *Geol. Soc. America Abst w. Prog.* 31, 124.
- *Champion, J.A., Mueller, K.J., and Guccione, M., 1999, Fault slip rates, structural style, seismic moment and magnitudes for the last 2.3 ka - Lake County Uplift, New Madrid: *Geol. Soc. America Abst w. Prog.* 31, 114.
- *Champion, J.A., Mueller, K.J., and Guccione, M.J., 1999, Structural style, fault slip rates, seismic moment and magnitudes for the last 2.3 ka, Lake County uplift, New Madrid: *Geol. Soc. America Abst w. Prog.* 31, 302.
- Guccione, M.J., *Champion, J.A., and Mueller, K.J., 1999, Dating deformation and slip rates along the Reelfoot Scarp, New Madrid seismic zone using radiocarbon dates from an abandoned Mississippi River meander: *Geol. Soc. America Abst w. Prog.* 31, 114.
- *Landau, J.E., and Mueller, K.J., 1999, Structural and geomorphic development of the active Los Lobos and San Emigdio Folds, southern San Joaquin Valley, California: *Geol. Soc. America Abst w. Prog.* 31, 79.
- Shaw, J.H., Rivero, C., Suess, M.P., and Mueller, K.J., 1999, Defining concealed earthquake sources with subsurface structural models, seismicity, and surficial neotectonic constraints: *Geol. Soc. America Abst w. Prog.* 31, 124.
- Mueller, K.J., Kelson, K.I. and R. Crippen, 1998, Growth of Lake County Uplift by Fault-Related Folding: Implications for Structural Style and High Fault Slip Rates (≥ 7.3 mm/yr) in the New Madrid Seismic Zone. (invited abs) *Eos, Trans American Geophysical Union*, 79, 205.
- Mueller, K.J., Grant, L.B., and E. Gath, 1998, Late Quaternary Growth of the San Joaquin Hills Anticline - A new Source of Blind Thrust Earthquakes in the Los Angeles Basin.: *Seismological Research Letters*, 69, 161-162.
- *Bielecki, A.B., and K.J. Mueller, 1998, High-Resolution Geomorphic Analysis of Active Fold Limbs in the Southern San Joaquin Valley using the RASCAL Laser Altimeter. (abs) *Eos, Trans American Geophysical Union*, 79, 212.
- Guccione, M.J., *Champion, J.A., Mueller, K.J., and Lawrence, W.L., 1998, Use of Archeology and Geomorphology to constrain the age of abandoned meanders within the Lake County Uplift, New Madrid Seismic Zone: *Geol. Soc. America Abst w. Prog.* 30, 122.
- *Champion, J.A., Guccione, M.J., Lawrence, W. L., and Mueller, K.J., 1998, Use of Archeology and geomorphology to date surface deformation, New Madrid seismic zone, central United States, *American Quaternary Association Program and Abstracts of the 15th Biennial Meeting*, 96.
- Keller, E.A., Mueller, K.J., and L.D. Gurrola, 1997, "Big Bend" of the San Andreas fault: Hypothesis of tectonic extrusion: *Geol. Soc. America Abst w. Prog.* 29, 6, 235.
- Mueller, K. J., 1997, Recency of Folding Along the Compton-Los Alamitos Trend: Implications for Seismic Risk in the Los Angeles Basin (abs) *Eos, Trans American Geophysical Union*, 78, 702.
- Mueller, K.J., 1996, Tectonic geomorphology of active fault-bend folds: methods for determining slip rates and obliquity on blind thrusts (abs): *Geol. Soc. America Abst w. Prog.* 28, 86.

Mueller, K.J., 1995, Very long-term records of blind-thrust earthquakes recorded in active fault-related folds, Tranverse Ranges, California, USA: *International Union for Quaternary Research XIV Congress*, p. 195.

COLLABORATORS

Sue Hough, USG-Pasadena; Thomas Rockwell, San Diego State University; Jose Pujol, University of Memphis; Matthew Golombek, NASA/Jet Propulsion Lab; Roger Bilham and Craig Jones, University of Colorado-Boulder; John Shaw, Harvard University; Margaret Guccione, University of Arkansas; Kerry Sieh, Caltech; Charles Rubin, Central Washington University; Tatsuya Ishiyama, Japanese Geological Survey; Yue-Gau Chen, National Taiwan University; Jian-Cheng Lee, Academia Sinica, Taipei;

INVITED LECTURES

I've presented invited talks on my research at the ERI - University of Tokyo, 2004; University of Arkansas, 2004; National Taiwan University, 2001, 2002; Univ. of Nevada, (2001), Kyoto Univ. (2001), Osaka Univ. (2001), Kansai Geotechnical Association (2001); Geological Survey of Japan – Tsukuba (2001, 2004); Geographical Survey Institute–Tokyo (2001); Univ. of Illinois (2000), Academia Sinica, Taipei, Taiwan (2000), Caltech (1998), Univ. of Southern California (1998); U.S. Geological Survey, Golden (1996 and 1997); Exxon Production Research, Houston (1996); Franklin and Marshall College (1996); Univ. of Wyoming (1996, 2002), Colorado State Univ. (1996); NASA Goddard (1995).

COURSES TAUGHT: CU-BOULDER

Structural Geology (Geol 3120), Structural Field Geology (Geol 4720), Historical Geology (Geol 1020), Physical Geology (Geol 1010), Neotectonics (Geol 5700), Adv. Structural Geology (5700)

STUDENTS SUPERVISED

Bielicki, Adam, M.S., 1998 “Structural and Geomorphic Analysis of Enigmatic Terraced Hillslopes formed on Active Folds in the Southern San Joaquin Valley using High Resolution Laser Altimetry” Graduated, December 1998.
Champion, Jocasta, M.S., 1999 “Structural and Geomorphic Analysis of Tiptonville Dome, Northwestern Tennessee” Graduated, December 1999
Landau, Jon, M.S., 1999 “Tectonic and Geomorphic Development of Active Folds and Blind Thrusts in the Southern San Joaquin Valley” Graduated, December 1999
Tate, Alex, M.S., 2001 “Geometry and Kinematics of Wrinkle Ridges, Lunae and Solis Plana, Mars” Graduated Summer 2001.
Kier, Grant, M.S., (2002) “Origin of Regional Uplift across Southern California and Northern Baja California” Graduated December 2002.
Powell, Lauren, M.S., (2003) “Tectonic Response to Erosion – Chelungpu Embayment, Central Thrust Belt, Taiwan.
Sundermann, Sean, M.S., “Geomorphology and Kinematics of Blind Thrusts in the southern Los Angeles Basin, California” Graduated Summer 2004
Eric Cannon, PhD., (expected 2005) “Seismotectonics of a Strongly Partitioned Transpressive Plate Boundary, Kansai Region, Japan”
Arwen Vidal, PhD (expected 2006) Wrinkle Ridge Tectonics –Solis Plana and Amenthes Rupes, Mars.

UNDERGRADUATE MENTORING

Department of Geological Sciences Mentor Program, 2004 – Elizabeth Wolfe
Undergraduate Honors Thesis, 2004 – Ryan Tolene - Summa Cum Laude

Southern California Summer Intern Program, 2003 – Ryan Tolene
Undergraduate Research Opportunity Program (UROP), 2001 – Ryan Tolene
Undergraduate Research Opportunity Program (UROP), 2000 - Mathew Brabeck
Undergraduate Research Opportunity Program (UROP), 2000 - Maxwell Thompson
Department of Geological Sciences Mentor Program, 2002 – Ryan Tolene
Department of Geological Sciences Mentor Program, 2000 - Mathew Brabeck
Department of Geological Sciences Mentor Program, 2000 - Maxwell Thompson
Undergraduate Research Opportunity Program (UROP), 1999 - Grant Kier
Southern California Summer Intern Program, 1999 - Grant Kier
Undergraduate Thesis, 1998 - Alex Tate, Norwich University, UK
Department of Geological Sciences Mentor Program, 1997 - Elliot Larson
CU - Boulder Office of Undergraduate Affairs, 1996 - Brian Graham
CU - Boulder SMART Program, 1996 - Patricia Nyugen - Amherst College
Undergraduate Honors Thesis, 1996 - Jocasta Champion - Summa Cum Laude

FIELD EXCURSIONS

As part of the curriculum for the courses I teach in structural geology, field mapping and neotectonics, I run field excursions in the western USA. These trips range from short trips to the Colorado Front Range and Medicine Bow Mountains of Wyoming to examine compressive folds and thrusts in addition to spectacular salt structures in the Roaring Fork Valley of Western Colorado. I also run a longer trip to the area around Moab in Utah to examine extensional fault systems related to dissolution of large salt swells and erosion along the Colorado River, growth strata deposited in mini basins, a salt diapir and small scale structures in normal fault zones. I also lead a week long trip through eastern California and western Nevada examine active extensional and strike slip fault systems in Death Valley, Fish Lake Valley, the volcanic tablelands near Bishop and the Owens Valley. As part of a new departmental initiative for incoming graduate students I also run an introductory trip to the Colorado Front Range and Rocky Mountain National Park that examines local stratigraphy and structures, glacial landforms and Precambrian rocks.

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