KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FIFTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2012 Amherst College, Amherst, MA

Dr. Robert J. Varga, Editor Director, Keck Geology Consortium Pomona College

> Dr. Tekla Harms Symposium Convenor Amherst College

Carol Morgan Keck Geology Consortium Administrative Assistant

Diane Kadyk Symposium Proceedings Layout & Design Department of Earth & Environment Franklin & Marshall College

Keck Geology Consortium Geology Department, Pomona College 185 E. 6th St., Claremont, CA 91711 (909) 607-0651, keckgeology@pomona.edu, keckgeology.org

ISSN# 1528-7491

The Consortium Colleges

The National Science Foundation

ExxonMobil Corporation

KECK GEOLOGY CONSORTIUM PROCEEDINGS OF THE TWENTY-FIFTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY ISSN# 1528-7491

April 2012

Robert J. Varga Editor and Keck Director Pomona College Keck Geology Consortium Pomona College 185 E 6th St., Claremont, CA 91711 Diane Kadyk Proceedings Layout & Design Franklin & Marshall College

Keck Geology Consortium Member Institutions:

Amherst College, Beloit College, Carleton College, Colgate University, The College of Wooster, The Colorado College, Franklin & Marshall College, Macalester College, Mt Holyoke College, Oberlin College, Pomona College, Smith College, Trinity University, Union College, Washington & Lee University, Wesleyan University, Whitman College, Williams College

2011-2012 PROJECTS

TECTONIC EVOLUTION OF THE CHUGACH-PRINCE WILLIAM TERRANE, SOUTH-CENTRAL ALASKA

Faculty: JOHN GARVER, Union College, Cameron Davidson, Carleton College Students: EMILY JOHNSON, Whitman College, BENJAMIN CARLSON, Union College, LUCY MINER, Macalester College, STEVEN ESPINOSA, University of Texas-El Paso, HANNAH HILBERT-WOLF, Carleton College, SARAH OLIVAS, University of Texas-El Paso.

ORIGINS OF SINUOUS AND BRAIDED CHANNELS ON ASCRAEUS MONS, MARS

Faculty: ANDREW DE WET, Franklin & Marshall College, JAKE BLEACHER, NASA-GSFC, BRENT GARRY, Smithsonian

Students: JULIA SIGNORELLA, Franklin & Marshall College, ANDREW COLLINS, The College of Wooster, ZACHARY SCHIERL, Whitman College.

TROPICAL HOLOCENE CLIMATIC INSIGHTS FROM RECORDS OF VARIABILITY IN ANDEAN PALEOGLACIERS

Faculty: DONALD RODBELL, Union College, NATHAN STANSELL, Byrd Polar Research Center Students: CHRISTOPHER SEDLAK, Ohio State University, SASHA ROTHENBERG, Union College, EMMA CORONADO, St. Lawrence University, JESSICA TREANTON, Colorado College.

EOCENE TECTONIC EVOLUTION OF THE TETON-ABSAROKA RANGES, WYOMING

Faculty: JOHN CRADDOCK. Macalester College, DAVE MALONE. Illinois State University Students: ANDREW KELLY, Amherst College, KATHRYN SCHROEDER, Illinois State University, MAREN MATHISEN, Augustana College, ALISON MACNAMEE, Colgate University, STUART KENDERES, Western Kentucky University, BEN KRASUSHAAR

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO

Faculty: DAVID DETHIER, Williams College Students: JAMES WINKLER, University of Connecticut, SARAH BEGANSKAS, Amherst College, ALEXANDRA HORNE, Mt. Holyoke College

DEPTH-RELATED PATTERNS OF BIOEROSION: ST. JOHN, U.S. VIRGIN ISLANDS

Faculty: *DENNY HUBBARD* and *KARLA PARSONS-HUBBARD*, Oberlin College Students: *ELIZABETH WHITCHER*, Oberlin College, *JOHNATHAN ROGERS*, University of Wisconsin-Oshkosh, *WILLIAM BENSON*, Washington & Lee University, *CONOR NEAL*, Franklin & Marshall College, *CORNELIA CLARK*, Pomona College, *CLAIRE MCELROY*, Otterbein College.

THE HRAFNFJORDUR CENTRAL VOLCANO, NORTHWESTERN ICELAND

Faculty: *BRENNAN JORDAN*, University of South Dakota, *MEAGEN POLLOCK*, The College of Wooster Students: *KATHRYN KUMAMOTO*, Williams College, *EMILY CARBONE*, Smith College, *ERICA WINELAND-THOMSON*, Colorado College, *THAD STODDARD*, University of South Dakota, *NINA WHITNEY*, Carleton College, *KATHARINE*, *SCHLEICH*, The College of Wooster.

SEDIMENT DYNAMICS OF THE LOWER CONNECTICUT RIVER

Faculty: SUZANNE O'CONNELL and PETER PATTON, Wesleyan University Students: MICHAEL CUTTLER, Boston College, ELIZABETH GEORGE, Washington & Lee University, JONATHON SCHNEYER, University of Massaschusetts-Amherst, TIRZAH ABBOTT, Beloit College, DANIELLE MARTIN, Wesleyan University, HANNAH BLATCHFORD, Beloit College.

ANATOMY OF A MID-CRUSTAL SUTURE: PETROLOGY OF THE CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE, GRENVILLE PROVINCE, ONTARIO

Faculty: WILLIAM PECK, Colgate University, STEVE DUNN, Mount Holyoke College, MICHELLE MARKLEY, Mount Holyoke College

Students: *KENJO AGUSTSSON*, California Polytechnic State University, *BO MONTANYE*, Colgate University, *NAOMI BARSHI*, Smith College, *CALLIE SENDEK*, Pomona College, *CALVIN MAKO*, University of Maine, Orono, *ABIGAIL MONREAL*, University of Texas-El Paso, *EDWARD MARSHALL*, Earlham College, *NEVA FOWLER-GERACE*, Oberlin College, *JACQUELYNE NESBIT*, Princeton University.

Funding Provided by: Keck Geology Consortium Member Institutions The National Science Foundation Grant NSF-REU 1005122 ExxonMobil Corporation

Keck Geology Consortium: Projects 2011-2012 Short Contributions— Grenville Province, Ontario Project

PETROLOGY AND STRUCTURE OF THE CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE ITS HANGING WALL, GRENVILLE PROVINCE, ONTARIO

Project Faculty: WILIAM H. PECK, Colgate University, STEVEN R. DUNN, Mount Holyoke College MICHELLE J. MARKLEY, Mount Holyoke College

GEOCHEMISTRY AND GEOCHRONOLOGY OF CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE THRUST SHEETS IN SOUTHERN ONTARIO, GRENVILLE PROVINCE KENJO S. AGUSTSSON, California Polytechnic State University, San Luis Obispo Research Advisor: Scott Johnston

CONFLICTING KINEMATICS OF THE SALERNO CREEK DEFORMATION ZONE, GRENVILLE PROVINCE, ONTARIO NAOMI BARSHI, Smith College

Research Advisor: Jack Loveless

THERMOBAROMETRIC EVIDENCE FOR A COMMON CENTRAL METASEDIMENTARY BELT AFFINITY OF THE BANCROFT AND ELZEVIR TERRANES, ONTARIO, CANADA NEVA FOWLER-GERACE, Oberlin College

Research Advisor: F. Zeb Page

HETEROGENEOUS DEFORMATION OF GABBROIC ROCKS CALVIN MAKO, University of Maine Research Advisor: Christopher Gerbi

PETROLOGY AND GEOCHEMISTRY OF THE ALLSAW ANORTHOSITE: A SCAPOLITIZED META-ANORTHOSITE IN GRENVILLE PROVINCE, ONTARIO EDWARD W. MARSHALL, Earlham College

Research Advisor: Meg Streepey Smith

GARNET-BIOTITE GEOTHERMOBAROMETRY OF THE CENTRAL METASEDIMENTARY BELT BOUDARY THRUST ZONE OFTHE GRENVILLE PROVINCE, ONTARIO, CANADA A DIC ALL MONDE AL University of Toyon at El Daso

ABIGAIL MONREAL, University of Texas at El Paso Research Advisor: Jasper G. Konter

CARBON ISOTOPE THERMOMETRY IN THE CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE GRENVILLE PROVINCE, ONTARIO BO MONTANYE, Colgate University Research Advisor: William H. Peck

CALCITE-GRAPHITE THERMOMETRY IN THE SOUTHWESTERNMOST CENTRAL METASEDIMENTARY BELT, GRENVILLE PROVINCE, SOUTHERN ONTARIO JACQUELYNE NESBIT, Princeton University Research Advisor: Blair Schoene

USING STRUCTURAL ANALYSES TO ASSESS POSSIBLE FORMATION MECHANISMS OF THE CHEDDAR GNEISS DOME

CALIE SENDEK, Scripps College Research Advisor: Linda Reinen

Keck Geology Consortium Pomona College 185 E. 6th St., Claremont, CA 91711 Keckgeology.org

USING STRUCTURAL ANALYSES TO ASSESS POSSIBLE FORMATION MECHANISMS OF THE CHEDDAR GNEISS DOME

CALLIE SENDEK, Scripps College Research Advisor: Linda Reinen

INTRODUCTION

This project uses structural data from field measurements and oriented samples to provide insight into the formation of the Cheddar Gneiss Dome. The Cheddar Dome is one in a series of five gneiss domes in the Harvey Cardiff Domain of the Central Metasedimentary Belt, part of the Mesoproterozoic Grenville Province of Ontario. Gneiss domes are structures associated with major orogenic events worldwide. Definitions vary, but they are generally recognized as circular to oval-shaped bodies consisting of two parts: metamorphic-plutonic cores, and a surrounding mantle of supracrustal rocks with domical contact parallel layering (e.g. Yin, 2004). The core of the Cheddar Dome is composed of meta-alaskite from the Methuen granite suite (1250-1240 Ma) (Lumbers & Vertolli, 2000; Timmerman et al., 1997). Rocks that mantle the dome consist largely of marble and metasedimentary rocks, predomintantly amphibolites (Lumbers & Vertolli, 2000).

A wide variety of gneiss dome formation mechanisms have been proposed, including diapirism due to contrasts in physical rock properties, various types of faulting, and superposition of multiple folding events. The extent of current research has led to the development of a classification scheme linking the physical characteristics of domes to their mechanism of formation (Yin, 2004). However, domes are formed in dynamic environments where changing stress and strain patterns coalesce to develop their structures. This complicates the process of making conclusions about strain paths from the finite strain patterns recorded in dome rocks. Nonetheless, different processes of development do correlate with distinctive structural geometries. This study provides an analysis of these geometries, and proposes a model for the formation of the Cheddar Dome that is consistent with variations in the orientation of foliation and lineation.

METHODS

In order to characterize the structure of the Cheddar Dome, two main approaches were taken. The first was to analyze structural measurements of foliation and lineation using field techniques, ArcGIS, and stereonet analysis. The second was to look for sense of shear through analysis of thin sections from oriented field samples.

Field data and oriented samples were collected during a two-week field session in July 2012. Samples were collected from a variety of rock types in both the core and mantle to represent the geologic range of the dome. Field measurements focused on compositional and tectonic foliations and mineral lineations. Twenty-seven samples were taken at fourteen sites. Twenty-three of them were made into oriented thin sections, cut perpendicular to foliation and parallel to mineral lineation, if present. Seventeen samples are from mapped amphibolites areas, three from the granitic gneiss core, one from a pegmatite within the core, a marble from the mantle, and a biotite schist. Thin sections were analyzed for sense of shear.

The structural measurements were collected at 16 sites during the field session and were mapped using ArcGIS and added to a compilation of field data put together by Nick Culsahw which included field data he collected between 1977-79, as well as data from Hewitt (1957) and Culshaw (1981). His data were scanned from a hard copy map and georeferenced. A database of structural information was created by digitizing lineation and foliation measurements. For the purpose of this study, only his tectonic foliations, compositional foliations, mineral stretching lineations, and c-axis orientation of quartz grain measurements were included. These data show a dominant foliation (Fig. 1) and lineation (Fig. 2). In order to make other structural patterns apparent, the foliations within thirty degrees to either side of the dominant orientation were removed from data sets. The dome was divided into seven regions based on common foliation patterns (I-VII, Fig. 3). All stereographic projections were plotted using Stereonet 32 (free software maintained by Dr. K. Roeller, available at http://www.ruhr-uni-bochum.de/hardrock/downloads. html) and contoured using cosine sums as the density calculation

RESULTS

Orientations of Foliation and Lineation

Both the Cheddar Dome and its mantle show a wide variety of foliation attitudes, with a clear maximum striking east-northeast and dipping moderately to the southeast (Fig. 1). Lineation in the region trends east west. In the mantle, lineation plunges moderately to



Figure 1. Left – stereonet plot of the poles to tectonic and compositional foliation in the Cheddar Dome region. Right – contoured stereonet showing the dominant attitude of the poles.



Figure 2. Contoured stereonet plots of lineation in the core (Left) and mantle (Right).

the east. In the dome core, lineation shows a wider range of moderate to shallow plunges to both the east and west (Fig. 2).

Figure 3 presents the same foliation data as above, but subdivided into seven regions. In some cases there is a significant difference in dip within these data sets, reflected in separate maxima on the contour plots. The central region (region I) shows very strong concurrence with the overall foliation trend, with foliations dipping moderately to the southsoutheast. In Figure 3, the region I stereonet is the only stereonet to include foliations with dip directions between 130-190 degrees. Moving clockwise around the dome from the top center, region II, in the northeast, has two maxima. Foliations associated with the strongest maximum dip steeply to the northeast, away from the dome core. Sub-horizontal foliations make up the second maximum. Region III contains foliations dipping primarily away from the dome to the southeast. The two maxima of region IV demonstrate the curvature of the foliation around the domical contact, with foliations striking east-northeast, but dipping moderately to the north and south. Region V is the southeast side of the dome and most foliation here dips moderately to the northwest and towards the dome core. A second maximum is composed of mantle foliations of similar strike that dip shallowly away from the center of the dome. The west side of the dome shows two distinct zones of foliation. Region VI, on the southwest side of the dome, shows a foliation dipping moderately to the southwest, away from the dome. Region VII, on the west side of the dome, shows two maxima, with foliation dipping steeply to the east. In summary, foliation dips both towards and away from the dome center in both the core and mantle. Some regions show two maxima for foliation orientation, while others show a single maximum. Foliations in the northeast, east, and south more consistently show dips away from the dome core. Foliations in the north and northwest dip toward the core, along with those in region V.

Sense of shear

Although amphibolites in the dome's mantle show strong foliation and lineation defined by compositional banding and orientation of amphibole and biotite

25th Annual Keck Symposium: 2012 Amherst College, Amherst, MA



Figure 3. Structural and geologic map of the cheddar dome showing seven subdivisions accompanied by contoured stereonets of the poles to foliation in each region. For all regions except I these plots exclude foliations striking between 130-190 degrees ($\pm 30^{\circ}$ of dominant regional foliation). (Geology from Ontario Geological Survey).

grains, they lack a clear sense of shear at the scale of hand samples or thin sections. Instead, most of these rocks appear to have statically annealed (Fig. 4).

DISCUSSION

The possible mechanisms for the formation of the Cheddar Dome can be narrowed based on geologic setting. Yin's classification scheme groups mechanisms into three categories, those created by diapirism and contrasts in rock properties, those created by faults, and those created by multiple folding events (2004). The Grenville Orogeny has not been associated with deep-rooted extensional detachment faults, nor is the dome within a large transform or strike slip zone, and thus this dome is unlikely to be associated with these two styles of shear zone. The most probable mechanisms are therefore multiple folding events, thrust-duplex development, and diapirism.

Multiple phases of folding can superpose to form dome shaped exposures (Yin, 2004). Evidence of at least three generations of folding is documented in an area west of the domes (Divi & Fyson, 1973). However, the axial planes of these folds are too close to parallel to form domical shapes, as is expected from pulses collisional events. In order to create domes from multiple folding events the axial planes must



Figure 4. Image of a thin section from amphibolite mantle sample demonstrating static annealing.

be closer to orthogonal than are found in the region of the Cheddar Dome (Van der Pluijm & Marshak, 2004).

Domes associated with thrust-duplex development require a roof fault and a basal thrust. The warped roof fault composes the perimeter of the thrusted dome area. No domical-parallel thrust faults have been mapped surrounding the Cheddar, making this mechanism unlikely. This process has been postulated as a plausible mechanism of dome formation, but examples in the literature are scarce (Yin, 2004).

Diapirism is the mechanism for dome formation that has been cited elsewhere in the Canadian Grenville (e.g. Gervais et al., 2004). By this process, a density inversion causes lower layers of rock to ascend adiabatically through the crust to emplacement. Planar sections of these frozen diapirs appear as gneiss domes. Analogue models of diapiric flow provide insight into expected patterns of lineation and foliation produced by this mechanism (Dixon, 1975). Different degrees of domical development and cross section depth lead to different foliation patterns. In an early stage diapir, necking is not well developed and the foliations dip away from the center of the diapir at all depths. As the feature develops, necking becomes more intense and foliations and lineations begin pointing inwards at greater depths. Figure 5 illustrates the expected distortion of foliation and development patterns of lineation in a well developed

gneiss dome.

The Cheddar Dome exhibits a mixture of outward and inward dipping foliations that are not radial symmetric about the dome as would be expected in an ideal diapir. Foliations on the northern side of the dome (regions I, II, V, and VII) are consistent with a deep slice through a well-developed diapir (slice B in Fig. 5), where foliations dip towards the dome in both the core and mantle. The southern portion (regions III, IV, and VI) is more consistent with the shallow slice (slice A in Fig. 5) where foliations dip outwards in both regions. The current exposure of the Cheddar Dome may represent a nonhorizontal slice through a diapir, exposing a deeper section to the north and a shallower one to the south. However, the foliation patterns clearly relate to the typical southeast dip of foliation in the Central Metasedimentary Belt boundary thrust zone (CMBbtz) to the west of the Harvey-Cardiff Arch (Hanmer 1988; Hanmer and McEachern 1992). The Cheddar Dome does, however, show a lineation that is distinct. The shallowly-dipping easttrending lineation (Fig. 2) differs from the southeasttrending lineation widely reported for the CMBbtz. The prominent south-southeast dipping foliation seen in the Cheddar Dome most likely resulted from the large-scale, regional strain field of the orogenic collision. The maximum presented in Figure 1 is within thirty degrees of the orientation of the orogeny axis in Ontario (Tollo, 2004). This overprinting could have occurred in concurrence with, or after gneiss dome formation, as the regional strain field will generally be much larger than any local strain field associated with dome formation (Yin, 2004). Lineations within and outside the dome indicate stretching in the eastwest direction. Looking at infinitesimal strain, both stretching lineations and foliations tend to form perpendicular to the maximum compressive stress. If the region were undergoing pure shear from the compression of the orogeny, the maximum compressive stress remains constant, and the foliations and lineations should be aligned with the trend of the orogen. Thus, foliations should be striking at 040, approximately the same trend as mineral lineations. If instead the system were formed under simple shear, the foliation and lineation direction would rotate with progressive amounts of strain. In the case of the Cheddar Dome, the orientation of the orogen is more northerly than



Figure 5. A schematic illustration of an analogue model of diapiric dome formation, with the core below the thick line and the mantle above. Originally horizontal layers were divided into 200 segments and then drawn after deformation. The formerly horizontal lines represent foliation directions in both the core and mantle. The double arrows represent maximum elongation directions, which act as a proxy for lineation direction within the dome. In the mantle, strain is accommodated along original bedding layers, and lineations develop within that plane. Line A represents a shallow section through the dome, while B represents a deep section. (Modified from Dixon, 1975).

the attitude of foliation and lineation. This suggests that there was a component of simple shear present during the orogeny.

The Methuen Granite, which has been mapped as the core of the dome, has been dated at 1250-1240 Ma. Assuming diapirism as the mechanism of formation, domal formation is concurrent with the age of the granite. The three proposed metamorphic events tied to the orogeny occurred much later, between 1083 and 1030 Ma (Easton & Kamo, 2011). This suggests that dome emplacement occurred and its structural markers were subsequently altered by the northwestward thrusting of the orogenic collision. The strain resulting from this later orogenic stress may have rotated the dome foliations to give the appearance of different cross-section depths.

dence of deformation in the rocks, requires an explanation. The polygonal shape of the primary mineral grains can be explained if dome rocks were retained at high temperatures after deformation. Through the processes of static recrystallization and grain boundary area reduction, the internal free energy of the system is reduced and deformed grain boundaries straighten (Passchier & Trouw, 2005). The Cheddar dome was emplaced into the middle to lower levels of the orogeny into crust that was most likely raised above the geothermal gradient due to the heat of continental collision (Cosca et al., 1995). Thus it is probable that much textural evidence was lost during static recrystallization late in the orogenic cycle.

CONCLUSION

Distinct structural patterns exist in several zones of the dome. These variations in the orientation of foliation are consistent with a deep slice through a diapir in the north and a shallower slice to the south. However, the patterns of the Cheddar Dome are also reminiscent of the overprint signature and may still be reflecting its influence. Due to the relative timing of the Methuen granite emplacement and the main metamorphic events of the orogeny, the overprint signature was most likely formed after diapir emplacement. Rotation of foliations from the strain of this event may account for the lack of radially symmetric foliations and the apparent inconsistency in the depth profile of the dome.

REFERENCES

- Culshaw, N.G., 1981, Geological series, Precambrian geology of the Drag Lake area, Haliburton County, Southern Ontario; Ontario Geological Survey, Map P. 2404, scale 1:15,840, 1 sheet.
- Divi, R.R., and Fyson, W.K., 1973, Folds and Strain in Grenville Metamorphic Rocks, Bancroft, Ontario, Canada: Geological Society of America Bulletin, v. 84, p. 1607-1617.
- Dixon, J.M., 1975, Finite strain and progressive deformation in models of diapiric structures: Tectonophysics, v. 28, p. 89-124.

The lack of shear sense indicators, despite strong evi-

25th Annual Keck Symposium: 2012 Amherst College, Amherst, MA

- Easton, R.M., and Kamo, S.L., 2011, Harvey-Cardiff Domain and its relationship to the Composite arc belt, Grenville Province; insights from U-Pb geochronology and geochemistry: Canadian Journal of Earth Science, v. 48, p. 347-370.
- Gervais, F., Nadeau, L., and Malo, M., 2004, Migmatitic structures and solid-state diapirism in orothogneiss domes, eastern Grenville Province, Canada: Special Paper – Geological Society of America, v. 380, p. 359-378.
- Hanmer, S., 1988, Ductile thrusting at mid-crustal level, southwestern Grenville Province: Canadian Journal of Earth Sciences, v. 25, p. 1049-1059.
- Hanmer, S., and McEachern, S., 1992, Kinematical and rheological evolution of a crustal-scale ductile thrust zone, Central Medisedimentary Belt, Grenville orogen, Ontario: Canadian Journal of Earth Sciences, v. 29, p. 1779-1790.
- Hewitt, D.F., 1957, Geology of Cardiff and Faraday townships: Annual Report – Ontario Department of Mines, v. 66, part 3.
- Lumbers, S.B. and Vertolli, V.M., 2000, Precambrian geology, Gooderham area; Ontario Geological Survey, Preliminary Map P. 3405, scale 1:50,000, 1 sheet.
- Passchier, C.W., and Trouw, R.A.J., 2005, Microtectonics: New York, Springer, 366 p.
- Timmerman, H., Parrish, T.T., Jamieson, R.A., and Culshaw, N.G., 1997, Time of metamorphism beneath the Central Metasedimentary Belt boundary thrust zone, Grenville Orogen, Ontario; accretion at 1080 Ma? Canadian Journal of Earth Sciences, v. 34, p. 1023-1029.
- Tollo, R.P, et al., 2004, Petrologic and geochronologic evolution of the Grenville orogen, northern Blue Ridge Province, Virginia: Geological Society of America Memoir, v. 197, p. 647-677.

Van der Pluijm, B.A., Marshak, S., 2004, Earth Struc-

ture: New York, W.W. Norton, 656 p.

Yin, A., 2004, Gneiss domes and gneiss dome systems: Special Paper – Geological Society of America, v. 380, p. 1-14.