KECK GEOLOGY CONSORTIUM

21ST KECK RESEARCH SYMPOSIUM IN GEOLOGY SHORT CONTRIBUTIONS

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2007-2008 PROJECTS:

Tectonic and Climatic Forcing of the Swiss Alps
John Garver (Union College), Mark Brandon (Yale University), Alison Anders (University of Illinois),
Jeff Rahl (Washington and Lee University), Devin McPhillips (Yale University)
Students: William Barnhart, Kat Compton, Rosalba Queirolo, Lindsay Rathnow,
Scott Reynhout, Libby Ritz, Jessica Stanley, Michael Werner, Elizabeth Wong

Geologic Controls on Viticulture in the Walla Walla Valley, Washington
Kevin Pogue (Whitman College) and Chris Oze (Bryn Mawr College)
Students: Ruth Indrick, Karl Lang, Season Martin, Anna Mazzariello, John Nowinski, Anna Weber

The Árnes central volcano, Northwestern Iceland
Brennan Jordan (University of South Dakota), Bob Wiebe (Franklin & Marshall College), Paul Olin (Washington State U.)
Students: Michael Bernstein, Elizabeth Drewes, Kamilla Fellah, Daniel Hadley, Caitlyn Perlman, Lynne Stewart

Origin of big garnets in amphibolites during high-grade metamorphism, Adirondacks, NY
Kurt Hollocher (Union College)
Students: Denny Alden, Erica Emerson, Kathryn Stack

Carbonate Depositional Systems of St. Croix, US Virgin Islands
Dennis Hubbard and Karla Parsons-Hubbard (Oberlin College), Karl Wirth (Macalester College)
Students: Monica Arienzo, Ashley Burkett, Alexander Burpee, Sarah Chamlee, Timmons Erickson
Andrew Estep, Dana Fisco, Matthew Klinman, Caitlin Tems, Selina Tirtajana

Sedimentary Environments and Paleoecology of Proterozoic and Cambrian "Avalonian" Strata in the United States
Mark McMenamin (Mount Holyoke College) and Jack Beuthin (U of Pittsburgh, Johnstown)
Students: Evan Anderson, Anna Lavarreda, Ken O'Donnell, Walter Persons, Jessica Williams

Development and Analysis of Millennial-Scale Tree Ring Records from Glacier Bay National Park and Preserve, Alaska (Glacier Bay)
Greg Wiles (The College of Wooster)
Students: Erica Erlanger, Alex Trutko, Adam Plourde

The Biogeochemistry and Environmental History of Bioluminescent Bays, Vieques, Puerto Rico
Tim Ku (Wesleyan University) Suzanne O'Connell (Wesleyan University), Anna Martini (Amherst College)
Students: Erin Algeo, Jennifer Bourdeau, Justin Clark, Margaret Selzer, Ulyanna Sorokopoud, Sarah Tracy

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STRAIN ANALYSIS AND INTEGRATION: QUANTIFYING THE DEFORMATION OF THE LAGHETTI AREA, MAGGIA NAPPE, SWITZERLAND

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INTRODUCTION

Orogenic belts have long been the focus of structural studies of stresses and resulting strains of rocks involved in collisional mountain building. Plate-plate collision results in the formation of large-scale thrust faults and recumbent fold “nappes” generally referred to as fold-and-thrust belts. Post-uplift erosion can expose the crystalline basement of such structures, allowing for the direct observation of fabrics formed by ductile deformation during mountain building. Geologists have developed many techniques to identify and measure deformational patterns expressed at all scales in exposed crystalline nappes, but challenges remain leaving two important questions unanswered.

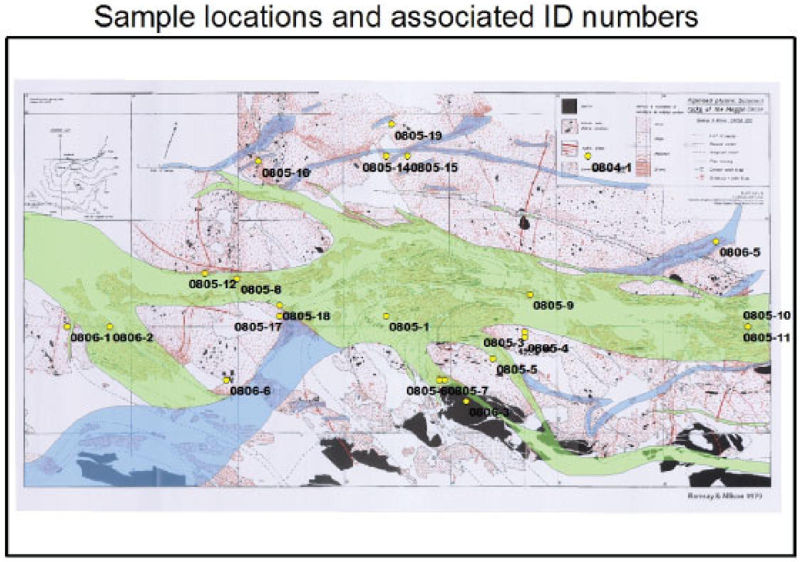
Sample locations and associated ID numbers

Figure 1: Ramsay and Allison map with sample locations and their ID numbers. Zones of shearing also shown: right handed (green), left handed (blue). Modified from Ramsay and Allison (1979).

First, while it is important to evaluate the deformation in thrust nappes at all scales, how does each technique compare in terms of the strain values produced? Second, is it possible to integrate the results from multiple strain analysis techniques at multiple scales to get an overall strain value for a large region? Integration allows local variation over a large area to be averaged providing an overall strain value that is more easily related to the large-scale tectonic stress regime.

Fieldwork was conducted in the Lepontine Alps of southern Switzerland during the summer of 2007 in the crystalline portion of the Maggia Nappe in the Pennine Zone of the Alps. Using the 1:40 map created by Ramsay and Allison (1979) of the Laghetti Area field measurements and rock samples were collected for strain analysis at three scales: 1. macroscale analysis of shear zones, 2. microscale $R_f\phi$ analysis of biotite clots, and 3. microscopic analysis of biotite LPO (Fig. 1).

LAGHETTI STRUCTURAL UNITS

Alpine deformation in the Laghetti and surrounding areas has resulted in a “predominant pattern of intersecting ductile shear zones” (Ramsay and Allison, 1979:277) occurring as conjugate sets with right- and left-handed displacement sense. Shear zones are marked by a transition from a weak to very strong planar fabric identified by the elongation of sub-rounded biotite clots to flaggy biotite ribbons. Macroscopic features such as offset aplitic dikes and deformed mafic enclaves allow for easy identification of shear zones. Both aplitic dikes and mafic enclaves of all initial orientations become thin, elongate, and subparallel to the shear zone walls (Fig. 2). Overall, the shear zones of the Laghetti area are curvy-linear ranging in width from a few centimeters to 3.5 meters. Measured shear zone orientations are highly variable with those showing left-lateral separation striking between N3E and N80E and those with right-lateral separation striking between N60E and N70W. Dip directions are variable, but all shear zones have a dip greater than 50 degrees.

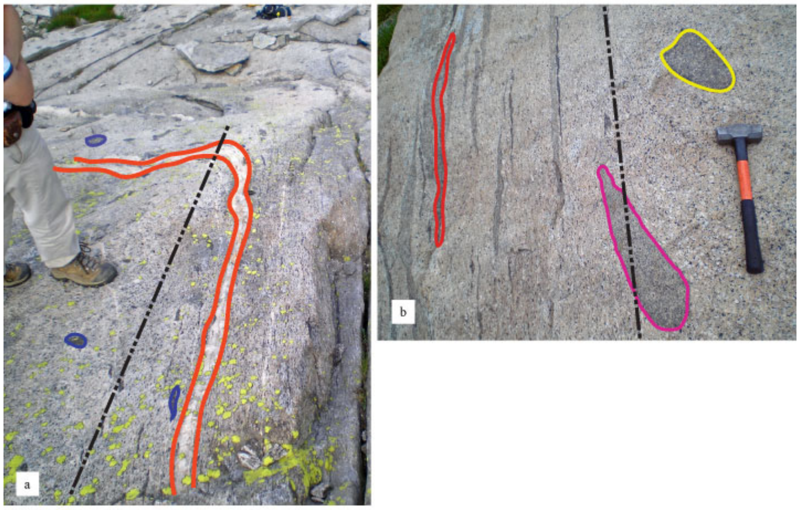

Figure 2: a) Aplite (red) dike cut by a shear zone resulting in a reorientation of the dike subparallel to the shear zone wall (dashed line). Mafic enclaves (blue) become elongate parallel to the shear zone wall. b) Example of heterogeneous strain across the margin of a shear zone (dashed line). Within a half meter, undeformed mafic enclaves (yellow) transition into long thin bands (red). Heterogeneous shearing results in a teardrop shape for those mafic enclaves at the margin of the shear zone (pink).

METHODS

Slip Vectors

While in the field, five shear zones were identified with sufficient information for slip vector calculation. At each location, four features were examined and measured: 1. the attitude of the outcrop surface, 2. the orientation of the shear zone walls, 3. the attitude of an offset dike within the undeformed wall rock, and its separation across the shear zone, and 4. the orientation of foliation in the middle of the shear zone.

In order to evaluate the displacement and slip direction along each of the measured shear zones, the structural features of interest were compiled into a schematic footwall sketch. The rakes of the outcrop surface, foliation (slip direction assumed to be perpendicular to the rake of foliation), the offset dike in the footwall and a projection of the offset dike in the hanging wall were all projected onto this surface so that the relevant relationships between them can be easily observed. Using this visual representation as a guide, simple trigonometry allows for the calculation of the displacement magnitude and direction.

Macroscopic Strain Analysis Results

Slip vector calculations show that three of the five slip vectors trend south or southwest. Three of the five slip vectors rake more than 25 degrees on the shear zone wall, indicating a significant component of dip-slip movement. Slip vector calculations for location (27,14) indicate normal dip-slip motion, which is anomalous in an inferred compressional stress regime.

Converting Slip Vectors to 3-d Strain

In order to use slip vector information in an overall strain integration calculation, slip vector information must be transformed into three principle axes of deformation and their associated stretches using *shrzone* designed by Mark Brandon (personal communication). Three-dimensional strain information calculations for four shear zones show a strong pattern of maximum shortening trending NNW-SSE with shallow plunges.

RfΦ Analysis

The mineralogical texture of the Matorello gneiss in the Laghetti Area changes based upon the degree of shearing. Specifically, biotite clots dramatically change in shape from subrounded in the unsheared wall rock to ribbon-like in the middle of the shear zones. These clots can serve as a proxy for the degree of shearing and be used to quantify strain.

RfF strain analysis assumes two initial conditions: 1. the objects analyzed are initially elliptical with random orientations in the undeformed state and 2. the objects deform homogeneously within the system of evaluation (Ramsay and Huber, 1983; Shimamoto and Ikeda, 1976). For the purposes of RfF analysis, it was assumed that the pressure conditions during crystallization under which the clots formed were uniform such that they formed as ellipsoidal objects with random orientations of the long axis.

In most of the samples collected, a foliation and lineation were identified on the basis of the alignment of minerals, the orientations of which were measured and used to guide the cutting of each sample. Three orthogonal faces were cut through each sample, one parallel to the foliation (XY face), one normal to the foliation and parallel to the lineation (XZ), and one normal to both the foliation and lineation (YZ), where X is the axis of greatest elongation, Z is the axis of greatest shortening, and Y is some intermediate value. Approximately 40 clots were digitized for each face and evaluated based on Simamoto and Ikeda's 1976 publication, and *rfpshim* (Mark Brandon, personal communication).

Biotite Lattic Prefered Orientation

Each biotite clot is composed of individual grains of biotite that are expected to reorient such that their short axis (c-axis) is parallel to the direction of greatest compressive stress. The degree to which a population of biotite grains are aligned with the direction of maximum compression can also be used to calculate strain values.

Ten samples were selected for biotite LPO analysis to produce cross-sectional strain data across individual shear zones. LPO data was collected using the electron back-scatter diffraction (EBSD) technique, sampling at 400 micron increments. Between 13 and 164 individual biotite grains were observed for each thin section.

LPO Results

The initial EBSD results show some unexpected patterns. In many cases, the c-axes are inclined nearly 45 degrees to the assumed direction of greatest observed shortening. However, many of the LPO data sets display a girdle pattern suggesting the prolate deformation expected in lineated rocks (Fig. 3).

Converting RfΦ and EBSD Data into 3-d Strain Ellipsoid Data

The RfF and EBSD data were transformed into three-dimensional data using the *strain3d* and *plstrain* programs designed by Mark Brandon (personal communication). RfF ellipse data calculated for the three faces of each sample were used to find the orientation and stretches of a single strain ellipsoid. Similarly, the c-axis orientations determined with EBSD and the degree to which the c-axes of each sample aligned (which can be used as a proxy for strain) were used to define a single strain ellipsoid for each sample.

METHOD COMPARISON

The axes of principle strain show strong patterns. The x-axes are generally ENE trending with shallow plunges indicating subhorizontal extension in the ENE-WSW direction. Z axes generally trend NNW or SSE; although the pattern is not as strong as for the x directions, most are gently plunging, indicating subhorizontal shortening in the NNW-SSE direction.

This pattern of NNW-SSE compression and ENE-WSW extension strongly parallels that expected for the large-scale orientation of the orogenic belt. Maximum shortening is perpendicular to the strike of the orogenic belt, consistent with deformation

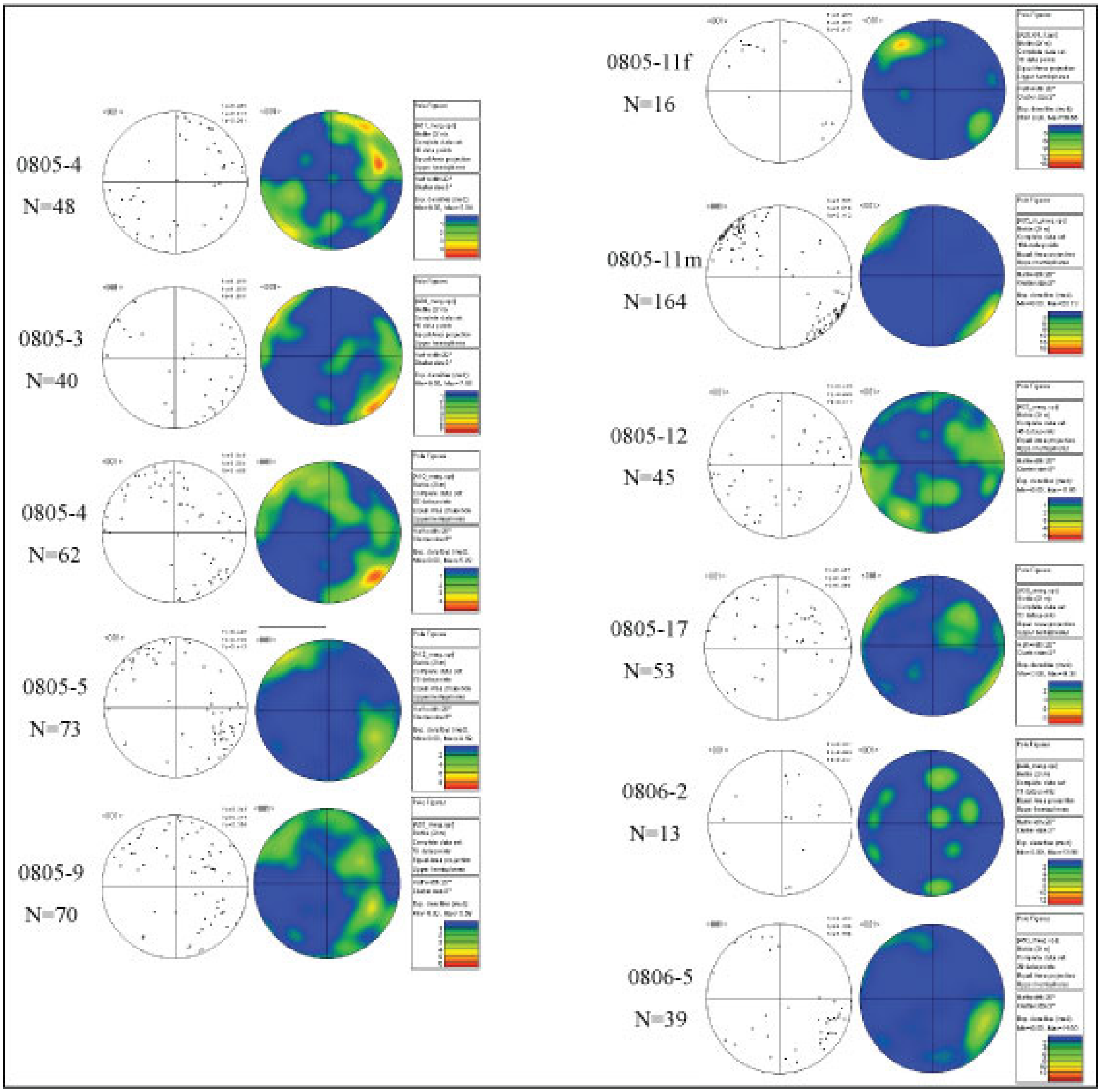

Figure 3: C-axis orientation data (scatter and contour plots) for each biotite EBSD sample. The north/south direction corresponds to the visually determined z-axis and east/west corresponds to the x direction. Note the girdle pattern for most samples inclined to the z direction. 0805-11 contained both Matorello gneiss (f) and mafic enclave (m) lithologies and was split for analysis accordingly. Notice the same orientation pattern in the mafic enclave sample indicating pervasive deformation.

during stacking of the Alpine nappes, with both the x and z axes horizontal.

As with the principle axes of strain, strain ratios calculated from all three methods are similar. Of the 27 data points, only four have X/Y and Y/Z strain ratios greater than 5. Data points are approximately evenly split between prolate and oblate deformation, but tend to lie close to the line of pure plane strain.

STRAIN INTEGRATION

Method of Integration

For the purposes of strain integration, the Laghetti map area was divided into three zones of relative de-

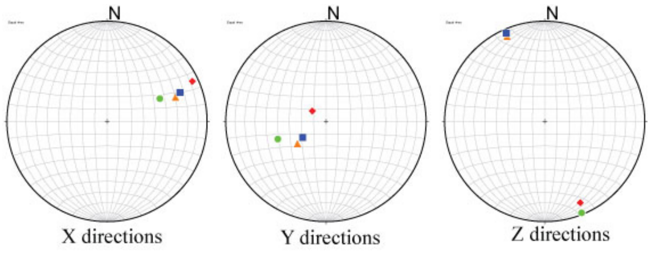

Figure 4: Composite stereonets showing x, y, and z directions for averages from zones of weak (green), intermediate orange) and strong (red) deformation as well as the weighted overall deformation (Blue).

formation: weak, intermediate, and strong, and samples were categorized accordingly. Of the 27 strain data, three are representative of weak deformation, 13 are representative of intermediate deformation intensities, and 11 represent the strong deformation characteristic of shear zones. Each data subset was then integrated with each sample weighted equally, then integrated together using the *meandefm* program (Brandon, 1996), but weighted relative to the proportion of the field area for which each value was representative: weak deformation 10%, intermediate 56%, strong 34%. These calculations do not account for any rotational deformation, assuming that rotation is minimal and does not significantly affect the results.

Results of Integration

Results for the strain integration of each deformation intensity zone show similar principle axis orientations, strengthening the claim that all of the strain expressed in the Laghetti Area is the result of the Alpine orogeny. Z directions are horizontal and parallel to the direction of inferred Alpine compression while the x directions are subhorizontal and parallel to the orogenic belt (Fig. 4).

Strain ratio results for each of the three deformation intensity zones are rather anomalous. While the X/Y ratio is least for the zone of weak deformation, the corresponding Y/Z is greater that that representing the zone of strong deformation. Additionally, both X/Y and Y/Z ratios for the zone of intermediate deformation are greater than those corresponding to the interior of the shear zones (Fig.4).

These results indicate that one or more of the methods may be underestimating strain within the zones of highest shearing. Though not necessarily evident from the Flinn plot, it is possible that the RfF method significantly underestimates the strain values for highly deformed regions of the Laghetti Area. Large stresses may cause the biotite clots not only to thin, but break apart, so what should have been digitized as one very long ribbon was digitized as two or more shorter ellipses, resulting in an underestimate of high strain areas. This phenomenon may also be the source of the consistently low Y/Z ratios for the biotite clot RfF method and the resulting prolate deformational pattern. (insert figure 4 and 5)

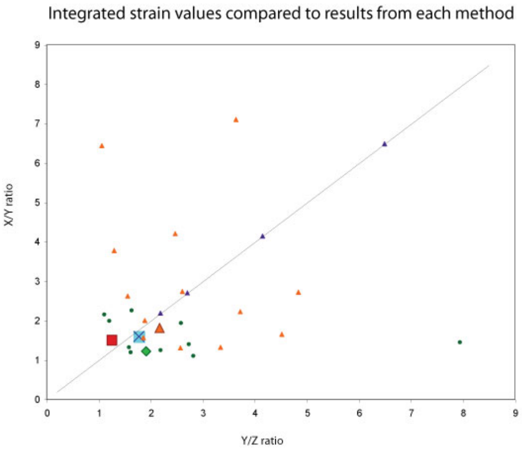

Figure 5: Strain ratio comparison for all individual methods (orange=biotite clot; green=EBSD; shear zones=purple/plane strain) with calculated averages from zones of weak (green diamond), intermediate (orange triangle), and strong (red square) was well as the weighted overall deformation (blue square). X-axis=Y/Z ratio; Y-axis=X/Y ratio

CONCLUSIONS:

Through a reinvestigation of the detailed deformation map created in 1979 by Ramsay and Allison, two general goals have been accomplished. A comparison of multiple strain quantification methods demonstrates the validity of the results gained from each and a more complete picture has been established of the deformation characteristics of the Laghetti Area, and more generally, the Maggia and other crystalline Pennine nappe units.

Slip vector analysis, biotite clot RfF, and biotite LPO, give broadly similar results when converted into three-dimensional ellipsoids. Slip vector calculations assume plane strain deformation, which may influence the final strain integration process and the biotite clot RfF analysis most likely underestimates strain in zones of high shearing, resulting in an inversion of strain ratios so that the intermediate deformation zones appear more deformed. However, biotite LPO analysis produces extremely consistent results as both X/Y and Y/Z ratios less than three with only one exception.

Individual strain analyses as well as integration indicate that shortening was taken up within the crystalline nappes during deformation in addition to along nappe boundaries. Strain integration produces the orientation results expected for nappe stacking during the Alpine orogeny; X, Y, and Z orientations are (68.4,22.6), (235.7, 66.9), and (336.5, 4.6) respectively with X stretch=1.652, Y stretch=1.037, and Z stretch=0.585.

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