Geological Society of America – Spring 2007 Cordilleran Section Meeting, Bellingham, Washington
Session: Volcanoes of the Pacific Basin and Rim – Geological and Geophysical Observations (Poster Booth 38)

Cinder Cone Analysis at Newberry Volcano, Oregon: A Synthesis of Results from the Earth Science Program for Undergraduate Research at Western Oregon University

TAYLOR, Stephen[1]; TEMPLETON, Jeffrey[1]; PIROT, Rachel[2], BUDNICK; Jeffrey[1]; DRURY, Chandra[1]; NOLL, Katherine[1]; FISHER, Jamie[1]; FALETTI, Anthony[1]; GILES, Denise[3]; and HALE, Diane[1]; (1) Earth and Physical Sciences Dept., Western Oregon University, Monmouth, OR 97361, taylors@wou.edu, (2) Dept. of Geology, Portland State University, Portland, OR 97207, (3) Dept. of Geosciences, Oregon State University, Corvallis, OR 97331

ABSTRACT

Newberry Volcano of central Oregon covers greater than 1600 sq. km and is associated with over 400 basaltic cinder cones and fissure vents (Holocene-Late Pleistocene). It is located in a complex tectonic setting that lies at the junction of the Brothers (west-northwest trending), Tumalo (north-northwest), and Walker Rim (northeast) fault zones. Digital geologic maps and 10-m DEMs were compiled with 177 single and 165 composite cones selected for spatial, morphometric, and volume analyses. The large number of cinder cones provides a robust data set from which to quantitatively test for structural controls on magma emplacement. This work represents a synthesis of results produced over the past four years by the Earth Science Program for Undergraduate Research at Western Oregon University.

Newberry cone positions and morphologic characteristics were compiled and statistically analyzed using GIS. Cone locations were further subdivided into northern (n=181) and southern (n=161) domains to test for mutually independent relations between the three fault zones. Observed cone distribution patterns were tested for randomness and spatial anisotropy using Monte Carlo simulations. Individual cone DEMs were extracted, morphometrically analyzed, and volumes calculated using a kriging-based algorithm. Statistically significant cone patterns were subsequently compared to fault trends to assess the degree to which magma emplacement was guided by regional tectonic stress fields.

The Monte Carlo-based analyses identify four significant cone alignments in the southern domain (dominant azimuth directions = 10-15, 30-35, 325-330, 355), and three in the northern (85, 310, 345). Fault segment analysis reveals three dominant azimuthal trends in the region: 310-325 (Brothers fault zone), 330-340 (Tumalo fault zone), and 45-50 (Walker Rim). In addition, cone-volume distributions show maxima oriented NW-SE, parallel to regional fault trends. The above results suggest that the Brothers and Tumalo fault zones had a detectable control on cinder-cone emplacement in both the northern and southern domains, whereas the Walker Rim is poorly correlated to significant cone distribution patterns. This study provides a framework to guide future geomorphic and geochemical analysis of cinder cones at Newberry Volcano.

INTRODUCTION

Newberry Volcano of central Oregon, is located in a complex, extensional tectonic setting at the intersection of the Basin and Range, High Lava Plains, and Cascade Volcanic Arc provinces (Fig. 1). Several major fracture systems surround and converge near Newberry, including the Brothers (W-NW trending), Tumalo (N-NW), and Walker Rim (NE) fault zones. With a volume of greater than 450 km³, Newberry is one of the largest volcanoes in the contiguous United States and is associated with over 400 basaltic cinder cones and fissure vents (Holocene-Late Pleistocene; Jensen 2002) (Figs. 2, 3, 4). Cinder cones are point-like geologic features that provide a surface record of magmatic emplacement processes through time. MacLeod and Sherrod (1988) observed that the curvilinear distribution of cinder cones and fissure vents on the flanks of Newberry trend mostly parallel to the Walker Rim and Tumalo fault zones, suggesting that these structures may form a single arc-shaped fracture zone at depth and likely serve as conduits that guide magma emplacement.

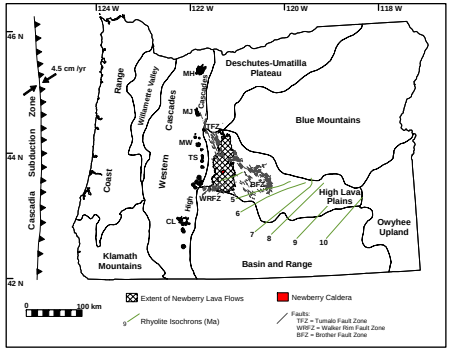


Figure 1. Generalized map of Oregon emphasizing the regional geologic and tectonic framework of Newberry Volcano. (After Walker and MacLeod, 1991).

While the structure-controlled, eruptive mechanism posited by MacLeod and Sherrod (1988) has significant merit, supporting statistical analysis of cone patterns and regional fault trends are lacking. To address this need, GIS and spatial analyses were used to quantitatively delineate Newberry vent-distribution patterns and test for structural controls on magma emplacement. The large number of cinder cones also provides an important geologic framework from which to conduct morphometric analyses, test existing erosional degradation models, and decipher controls on eruptive magnitude and frequency.

This paper presents the third installment of research on the geologic, morphologic, and spatial characteristics of basaltic cinder cones at Newberry Volcano. One of the objectives of this ongoing research is to actively engage undergraduates in quantitative applications as part of the Earth Science curriculum at Western Oregon University. The following is a synthesis of work conducted since 2001.

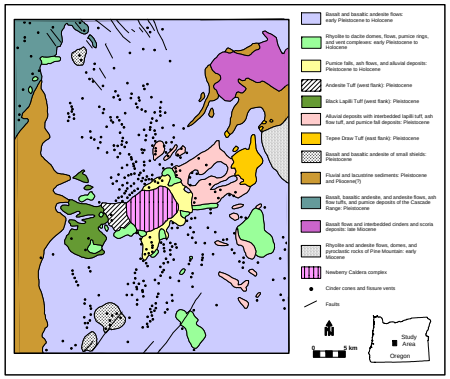


Figure 2. Generalized geologic map of Newberry Volcano (after Jensen, 2000).

GEOLOGIC SETTING

Newberry Volcano lies at the west end of the High Lava Plains about 65 km east of the Cascade Range (Fig. 1). Owing to its location, Newberry displays tectonic and compositional characteristics of the Cascade Range, High Lava Plains, and Basin and Range (MacLeod and others, 1981; MacLeod and Sherrod. 1988). The volcano is also positioned at the younger end of a sequence of rhyolite domes and caldera-forming ash-flow tuffs that decrease in age from 10 m.y. in southeastern Oregon to less than 1 m.y. near the caldera (Fig. 1).

Newberry is located in a complex, extensional tectonic setting dominated by Pliocene to Quaternary faults (MacLeod and others, 1981; MacLeod and Sherrod. 1988). Several major fault zones surround and converge near Newberry, including the Brothers fault zone, the Tumalo fault zone, and the Walker Rim fault zone (Figs. 1 and 2). The Brothers fault zone is a major W-NW trending domain of dominantly right-lateral strike slip faults that extend from southeastern Oregon to the northeast flank of Newberry (MacLeod and others, 1981; MacLeod and Sherrod. 1988). The N-NW trending Tumalo fault zone extends from the east side of the Cascades to the lower northern flanks of Newberry, where older lava flows are offset by this fault system. Along the southern flanks of Newberry, the N-NE trending Walker Rim fault zone offsets older flows (Figs. 1, 2).

The flanks of Newberry Volcano are covered mostly by basaltic andesite lava flows (Fig. 2). Cinder cones are most abundant on the north and south flanks of Newberry, less common on the east flank, and uncommon on the west flank (Figs. 3, 4). MacLeod and Sherrod (1988) interpreted cone alignments as the surface expression of dikes at depth that formed in response to regional stress fields. They observed that the apparent curvilinear distribution of cinder cones and fissure vents on the north and south flanks of Newberry trend mostly parallel to the Walker Rim and Tumalo fault zones, suggesting that these fault zones form a single arc-shaped fault zone beneath Newberry. They also posited that N-NW trending cones are relatively younger than those trending N-NE. The work presented herein provides a quantitative framework from which to evaluate this interpretation.

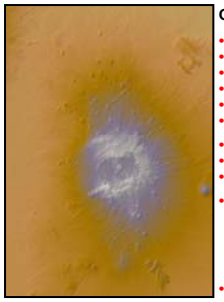


Figure 3. Atlas-relief map of Newberry Volcano.

Overview of Newberry Volcano

- Shield-shaped composite volcano
- N-S orientation, 64 km x 40 km
- Total Area > 1300 km²
- Summit Caldera Area = 44 km²
- Elevation: 1300 m – 2400 m;
- Relief ~1100 m
- Composition: Basalt to Rhyolite
- Estimated Volume = 460 km³
- >400 cinder cones and fissure vents
- Quaternary in Age
  - Normal Polarity <788,000 yrs BP
  - Tepee Draw Tuff ~500,00 yrs BP
  - West Flank Tuff ~100,000 yrs BP
  - Holocene activity: 10,000-1200 yrs
- One of largest Quaternary volcanoes

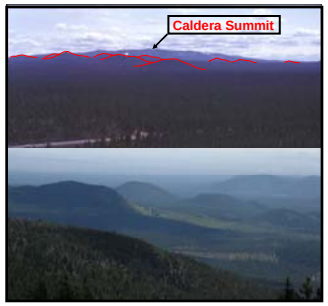


Figure 4A. Profile view of Newberry Volcano showing central caldera region and related cinder-cone field in foreground (red outlines).

Figure 4B. Aerial view of southeast cinder cone field as viewed from Paulina Peak.

CINDER CONE RESEARCH QUESTIONS

Are there morphologic groupings of ~400 cinder cones at Newberry? Can they be quantitatively documented?

Are morphologic groupings associated with age and state of erosional degradation?

Are there spatial patterns associated with the frequency, occurrence, and volume of cinder cones?

Are there spatial alignment patterns? Can they be statistically documented?

Do regional stress fields and fault mechanics control the emplacement of cinder cones at Newberry volcano?

METHODOLOGY

- Digital Geologic Map Compilation / GIS of Newberry Volcano (after McLeod and others, 1995)
- GIS analysis of USGS 10-m DEMs
  - Phase 1 Single Cones/Vents (n = 182)
  - Phase 2 Composite Cones/Vents (n = 165)
- Morphometric analyses
  - Cone Relief, Slope, Height/Width Ratio
  - Morphometric Classification
- Volumetric Analyses
  - Cone Volume Modeling
  - Volume Distribution Analysis
- Cone Alignment Analysis
  - Two-point Line Azimuth Distribution
  - Comparative Monte Carlo Modeling (Random vs. Actual)

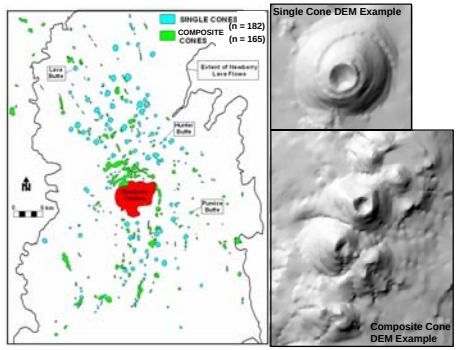


Figure 5. Map of Newberry Volcano showing classification of single and composite cinder cones. Cone outlines were digitized from map polygon "Qc" of MacLeod et al. (1995) and rendered in 3D from USGS 10-m DEMs.

MORPHOMETRIC ANALYSES: SINGLE CONES

Table 1. Explanation of Qualitative Cone Morphology Rating

1	Good-Excellent	Cone shape with vent morphology
2	Good	Cone shape with less defined vent morphology
3	Moderate-Good	Cone shape, lacks well-defined vent morphology
4	Moderate	Cone shape, no vent
5	Moderate-Poor	Cone shape, poor definition
6	Poor	Lacks cone shape
7	Very Poor	Lacks cone shape, very poorly defined morphology

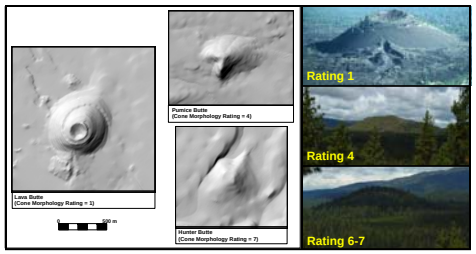
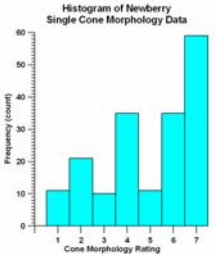


Figure 6. 10-m DEM relief maps for three select cinder cones at Newberry Volcano (map unit "Qc" of MacLeod and others, 1995). Shaded relief maps were used to visually rank each cone in the data set according to qualitative appearance of shape, slope configuration, and vent morphologies (Table 1).

Table 2. Summary of Relevant Cone Morphometry Data.

Cone Morphology Class	No.	Avg Slope (deg)		Cone Height (m)		Hco/Wco	
		Mean	Variance	Mean	Variance	Mean	Variance
Class 1	11	19.9	11.8	182.4	1344.9	0.18	0.0012
Class 2	21	18.2	10.5	124.4	2262.4	0.20	0.0073
Class 3	10	18.1	2.7	126.2	1991.0	0.19	0.0017
Class 4	35	14.9	12.1	76.2	1918.4	0.15	0.0014
Class 5	35	14.4	10.6	78.1	1682.9	0.15	0.0012
Class 6	11	11.9	13.7	59.5	1721.3	0.13	0.0025
Class 7	59	10.2	19.0	50.4	1401.3	0.14	0.0046
All Cones	182	13.6	24.2	76.4	2520.7	0.2	0.0038



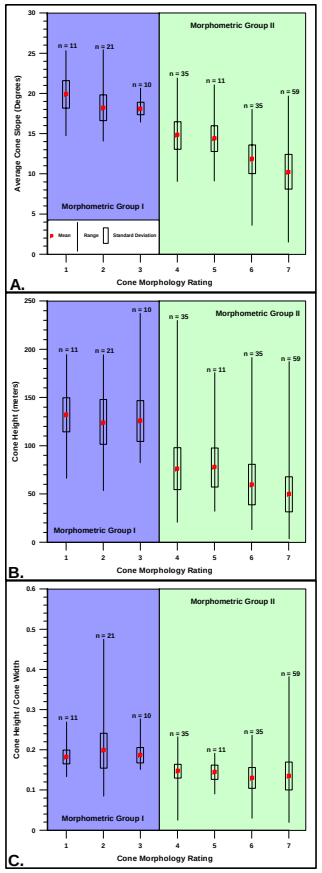


Figure 7. Whisker plots of select single-cone morphometric parameters vs. qualitative cone morphology rating. A. Whisker plot of average cone slope (degrees) vs. qualitative cone morphology rating. B. Whisker plot of cone height (meters) vs. qualitative cone morphology rating. C. Whisker plot of cone height:width ratio vs. qualitative cone morphology rating. Morphometric groupings are based on systematic t-test results at the 95% confidence level.

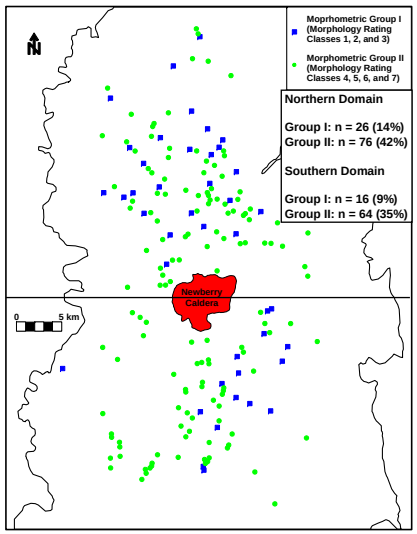


Figure 8. Map showing distribution of singles cones subdivided into the two cone populations based on morphology rating.

VOLUMETRIC ANALYSES: SINGLE AND COMPOSITE CONES

VOLUME METHODOLOGY

- **Clip cone footprint from 10-m USGS DEM (Rectangle 2x Cone Dimension)**
- **Zero-mask cone elevations, based on mapped extent from MacLeod and others (1995)**
- **Re-interpolate "beheaded" cone elevations using kriging algorithm**
- **Cone Volume = (Cone Surface – Mask Surface)**

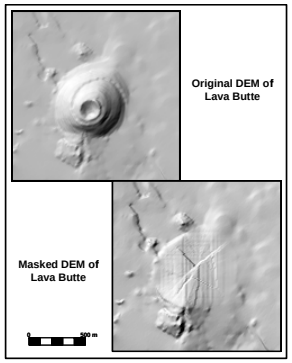


Figure 9. Shaded-relief maps illustrating the kriging-based method by which cone volumes were calculated from 10-m DEMs.

CONE VOLUME SUMMARY (SINGLE AND COMPOSITE)

Mean	4.67 x 10^7
Median	9.44 x 10^7
Mode	7.04 x 10^7
Stdev	8.29 x 10^7
Minimum	1.97 x 10^7
Maximum	4.59 x 10^7
Count	342

Cubic Meters

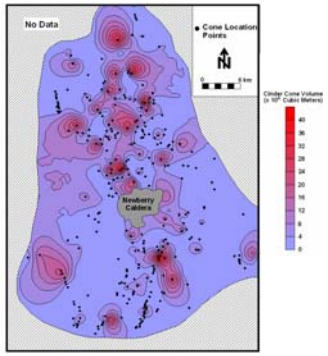


Figure 10. Contour map of select cinder cone volumes at Newberry Volcano. Volume maxima both north and south of the summit caldera are broadly co-linear with the N-NW trending Tumalo fault zone.

CONE ALIGNMENT ANALYSES: SINGLE AND COMPOSITE CONES

Observed Newberry cone alignments patterns were tested for randomness and spatial anisotropy using the "two-point" method of Lutz (1986) and the "point-density" method of Zhang and Lutz (1989). Both techniques consider cinder cone positions to represent nodal points connecting a set of lattice lines. Newberry cone positions and lattice orientations were systematically compared to simulated random point patterns (Fig. 11). Statistical filtering was used to identify anisotropic distributions and delineate cone-alignment patterns. Statistically significant cone-distribution patterns were subsequently compared to fault trends to assess the degree to which magma emplacement was guided by regional tectonic stress fields (Fig. 12).

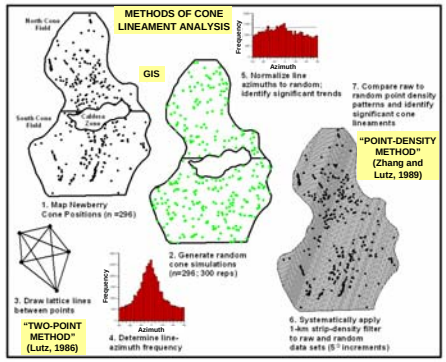


Figure 11. Diagrammatic summary of statistical procedures used to identify cinder cone alignment patterns at Newberry Volcano (after Lutz, 1986; and Zhang and Lutz, 1989).

REGIONAL FAULT-TREND ANALYSIS

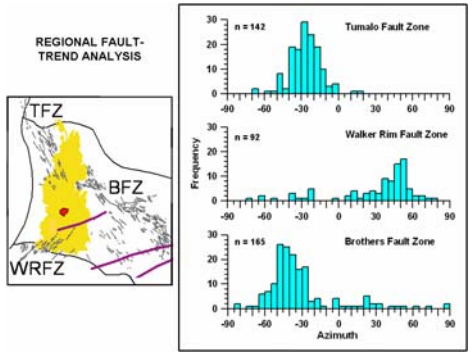


Figure 12. Location map and frequency histograms showing distribution of fault segment orientations for the Tumalo (TFZ), Walker Rim (WRFZ), and Brothers fault zones (BFZ). Modal fault azimuth orientations are 330-340, 45-55, and 310-320, respectively.

CONE TWO-POINT ALIGNMENT ANALYSIS (after Lutz, 1986)

NULL HYPOTHESIS
Distribution of Actual Cone Alignments = Random Cone Alignments

EXPECTED ALIGNMENT FREQUENCY:
$F_{EXP} = (n^*(n-1) / (2^*k))$
n = No. of Cinder Cones
k = No. of Azimuthal Bins

NORMALIZED ALIGNMENT FREQUENCY:
$F_{NORM} = (F_{EXP} / F_{AVG}) * F_{OBS}$

F_{NORM} = normalized bin frequency
F_{EXP} = expected bin frequency
F_{AVG} = average random bin frequency
F_{OBS} = observed bin frequency

CRITICAL VALUE:
$L_I = [(F_{EXP} / F_{AVG}) * F_{AVG}] + (t_{CRIT} * R_{STD})$

F_{EXP} = expected bin frequency
F_{AVG} = average random bin frequency
R_{STD} = stdev of random bin frequency
t_{CRIT} = t distribution (α = 0.05)

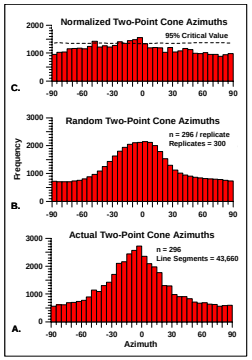


Figure 13. Frequency histograms showing the results of the two-point analysis method (Lutz, 1986) as applied to all Newberry cinder cones. A. Raw frequency distribution for line-azimuths drawn between cinder cone points (n = 296). B. Mean distribution for 300 random cone simulations (n = 296 / replicate). The strong north mode reflects the elongated N-S shape of Newberry. C. Normalized cone data, transformed to remove the shape effects. Azimuth bins with frequencies greater than the critical value are significant at the 95% confidence interval.

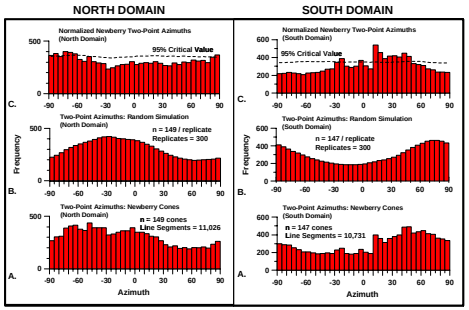


Figure 14. Results of the two-point analysis method (Lutz, 1986) as applied via dividing Newberry cones into north and south domains. Refer to Fig. 13 for discussion of techniques.

POINT-DENSITY METHOD (Zhang and Lutz, 1989)

- **1-km wide filter strips with 50% overlap**
- **Filter strip-sets rotated at 5-degree azimuth increments**
- **Tally total number of cones / strip / azimuth bin**
- **Calculate cone density per unit area**
- **Compare actual densities to random (replicates = 50)**
- **Normalize Cone Densities: D = (d – M) / S**
  D = normalized cone density
  d = actual cone density (no. / sq. km)
  M = average density of random points (n = 50 reps)
  S = random standard deviation
- **Significant cone lineaments = >2-3 STDEV above random**

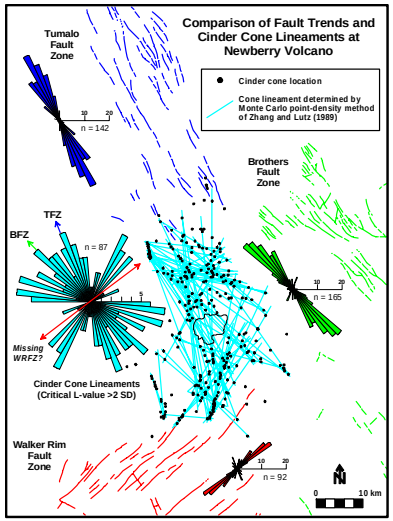


Figure 15. Summary map showing regional fault trends and results of the point density method as applied to Newberry cinder cones. Note the absence of cone-alignment trends directly parallel to the Walker Rim Fault Zone. The Monte Carlo-based analyses identify three significant cone alignments in the southern domain (dominant azimuth directions = 0, 10-35, 340-350), and three in the northern (80, 280-295, 310). Combined data from both domains strengthens the statistical significance of the 310 and 340-350 cone alignment directions.

SUMMARY AND CONCLUSION

NEWBERRY CONE MORPHOLOGY

- **Degradation Morphology Through Time (after Dohrenwend and others, 1986)**
  - **Diffusive mass wasting**
  - **Reduction of cone height and slope**
  - **Loss of crater definition**
- **Newberry Results**
  - **Group I Cones: Avg. Slope = 19-20°; Avg. Relief = 125 m; Avg. H_c/W_c = 0.19**
  - **Group II Cones: Avg. Slope = 11-15°; Avg. Relief = 65 m; Avg. H_c/W_c = 0.14**
  - **Group I = "Youthful"; more abundant in northern domain**
  - **Group II = "Mature"; common in northern and southern domains**
  - **Possible controlling factors include: degradation processes, age differences, climate, post-eruption cone burial, lava composition, and episodic (polygenetic) eruption cycles**

NEWBERRY CONE VOLUME RESULTS

- **Newberry cone-volume maxima align NW-SE with the Tumalo fault zone; implies structure has an important control on eruptive process**

NEWBERRY CONE ALIGNMENT PATTERNS

- **Newberry cones align with Brothers and Tumalo fault zones**
- **Poor alignment correlation with Walker Rim fault zone**
- **Other significant cone alignment azimuths: 10-35°, 80°, and 280-295°**
- **Results suggest additional control by unmapped structural conditions**
- **Cone-alignment and volume-distribution studies suggest that the Tumalo Fault Zone is a dominant structural control**

CONCLUDING STATEMENTS

- **This study provides a preliminary framework to guide future geomorphic and geochemical analyses of Newberry cinder cones**
- **This study frames additional questions regarding the complex interaction between stress regime, volcanism, and faulting in central Oregon**
- **This project provided an excellent opportunity to engage undergraduate Earth Science students in problem-based research.**

REFERENCES

Connor, C.B., Condit, C.D., Crumpler, L.S., and Aubele, J.C., 1992, Evidence of regional structural controls on vent distribution: Springerville volcanic field, Arizona: Journal of Geophysical Research, v. 97, p.12,349-12,359.

Dohrenwend, J.C., Wells, S.G., and Turrin, B.D., 1986, Degradation of Quaternary cinder cones in the Cima volcanic field, Mojave Desert, California: Geological Society of America Bulletin, v.97, p. 421-427.

Jensen, R.A., and Chitwood, L.A., 2000, Geologic overview of Newberry Volcano, *in* Jensen, R. A., and Chitwood, L. A., eds., What's New at Newberry Volcano, Oregon: Guidebook for the Friends of the Pleistocene Eighth Annual Pacific Northwest Cell Field Trip, p. 27-30.

Lutz, T.M., 1986, An analysis of the orientations of large-scale crustal structures: a statistical approach based on areal distributions of pointlike features: Journal of Geophysical Research, vol. 91, no. B1, p. 421-434.

MacLeod, N.S., Sherrod, D.R., Chitwood, L.A., and Jensen, R.A., 1995, Geologic Map of Newberry Volcano, Deschutes, Klamath, and Lake Counties, Oregon: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-2455, scales 1:62,500 and 1:24,000.

Settle, M., 1979, The structure and emplacement of cinder cone fields: American Journal of Science, v. 279, p. 1089-1107.

Zhang, D. and Lutz, T., 1989, Structural control of igneous complexes and kimberlites: a new statistical methoc: Tectonophysics, v. 159, p. 137-148.