Using Environmental and Archaeological Samples to Build and Validate Strontium and Oxygen Isoscapes for Forensic Applications in the Peruvian Andes: Paths Forward for Identifying Victims from the Time of Violence in Peru (1980-1990s)

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LEARNING OVERVIEW

Isotopic Principles

- $^{87}Sr/^{86}Sr$ varies with bedrock age and composition (Bentley, 2006); Sr replaces Ca in enamel hydroxyapatite, so $^{87}Sr/^{86}Sr_{enamel}$ reflects geological signature of childhood diet (and by proxy, place(s) of residence)
- Oxygen isotopes vary based on altitude, latitude, temperature, and distance from the coast (Bowen et al., 2005; Fry, 2006); $\delta^{18}O$ values reflect geographically-specific drinking water consumed during tissue formation (Bowen et al., 2009; Ehleringer et al., 2008)
- Given local food and water consumption, enamel values beyond local baseline likely grew up outside the local isotopic catchment (Knudson, 2009; Knudson et al., 2016)
- Modeling "local" values from baseline materials is essential for geolocating individuals to likely geographic origins
- Isoscapes, geospatially explicit predictive models of isotope values, are used to geolocate skeletons to likely origins for O (Bowen et al., 2009; Chesson et al., 2018; Ehleringer et al., 2008; Ehleringer et al., 2010) and Sr systems (Laffoon et al., 2018; Laffoon et al., 2012); Prediction accuracy is improved by dual-isotope models (Laffoon et al. 2017)

Forensic Context

- Long term aim: Create a multi-isotope isoscape of the Peruvian Andes to aid in identifying individuals killed in the Shining Path conflict in Peru in the 1980s-1990s
- ~69,000 individuals died in the conflict
- A few thousand bodies have been exhumed (Fig. 1)

Figure 1. Exhumations in Ayacucho, Peru

HYPOTHESIS

Surface water isoscapes should yield predictions within the specified margin of error for strontium and oxygen isotopes.

METHODS

Isotope Analysis

- Water filtered, Sr separated through ion chromatography
- Archaeological enamel mechanically cleaned, drilled, and chemically prepared according to standard methods (e.g. Knudson et al. 2017; Tung et al. 2016)
- Elemental concentrations and $^{87}Sr/^{86}Sr$ ratios analyzed Keck Lab (Knudson et al., 2017; Knudson et al., 2016; Marsteller et al., 2017)
- Water analyzed for $\delta^{18}O$ at BSIRL (Tung et al., 2016)
- $\delta^{18}O‰_{dw\ SMOW} = (((^{18}O/(^{16}O_{sample})/(^{18}O/(^{16}O_{standard})) - 1) \times 1000)$ (Coplen, 1994; Craig, 1961)

Geostatistical Models and Validation

- Universal kriging with first order trend removal used due to detection of east-west trend (to satisfy stationarity assumption); spherical model type
- Dual model was co-kriged
- 20% removed from the training datasets for validation
- Interval approach used to compare enamel measurements with single and dual isoscape predictions within error (see Laffoon et al., 2017)
- For Sr, acceptable error = measurement ± 2 SD
- For O, acceptable error = measurement ± 3.1 ‰, the "minimum meaningful difference" for $\delta^{18}O$ in human enamel (Pestle et al. 2014)
- Standard model diagnostics reported (Oliver and Webster 2014)
- Validation from published and unpublished enamel

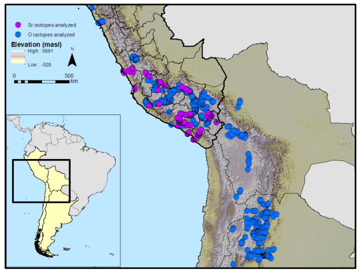

Figure 2. Surface water collection sites (N = 124 for Sr, N = 236 for O).

RESULTS: STRONTIUM ISOSCAPE

- Surface water $^{87}Sr/^{86}Sr$ values range: 0.70489 to 0.72267 (mean = 0.70766, sd = 0.0018, N = 124)
- Normally distributed (Ryan-Joiner p-value < 0.010)
- Best fit $^{87}Sr/^{86}Sr$ model (Fig. 4, Fig. 5) diagnostics: Mean < 0.001; Root-mean-square = 0.001; Mean standardized = 0.013; Root-mean-square standardized = 0.63; Average standard error = 0.003

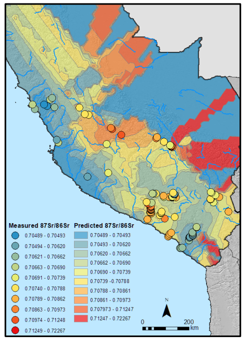

Figure 4. Water Sr isoscape.

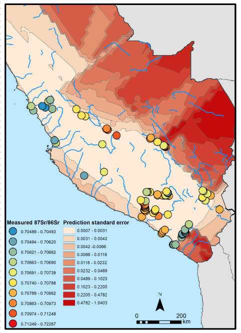

Figure 5. Prediction standard error for water Sr isoscape.

- Validation of 80% training model with 20% test set (water, n = 25) $R^2 = 0.196$
- Cross-validation with archaeological set (20% of published Andean $^{87}Sr/^{86}Sr$ values from Scaffidi and Knudson ND, n = 202), $R^2 = 0.229$
- Interval approach validation: 95.0% of archaeological samples correctly classified within ± 2 SD (SD = 0.002, mean = 0.7076, n = 205)

RESULTS: OXYGEN ISOSCAPE

- Surface water $\delta^{18}O_{dw\ SMOW}$ values ranged from -19.6‰ to -3.5‰ (mean = -11.34, sd = 4.18, N = 575)
- Normally distributed (Ryan-Joiner p-value <0.010)
- Best fit $\delta^{18}O$ model (Fig. 6, Fig. 7) (See also Zimmer-Dauphinee et al. 2020) diagnostics: Mean = -0.002; Root-mean-square = 1.168; Mean standardized = 0.003; Root-mean-square standardized = 1.054; Average standard error = 1.270

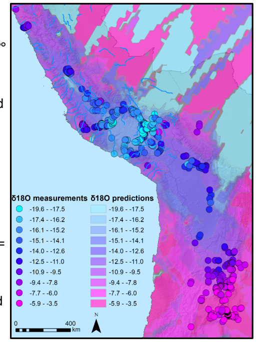

Figure 6. Water $\delta^{18}O_{dw\ SMOW}$ isoscape.

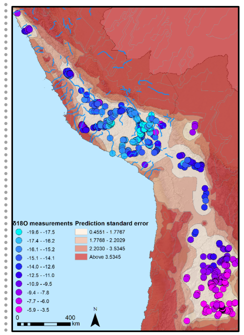

Figure 7. Prediction standard error for water $\delta^{18}O_{dw\ SMOW}$ isoscape.

- Validation of 80% training model with 20% test set (water, n =115) R2 = 0.973
- Cross-validation with archaeological set (20% of published Andean δ18O values compiled by Scaffidi and Tung, n = 115), R2 = 0.027
- Interval approach validation: 92.9% of archaeological samples correctly classified within ± 3.1 (Pestle et al. 2014) (SD = 2.48, mean = -13.86, n = 115)

RESULTS: DUAL ISOTOPE MODEL

- Co-kriged model: Same parameters as single models
- Cross-validation results are the same as reported for each individual isotope model
- Interval approach validation: 30 teeth from Uraca (Majes Valley, Peru) with paired 87Sr/86Sr and δ18O data 87Sr/86Sr: 27/30 (90.0%) of predictions fell within the measured ± 2 SD (SD = 0.002, n = 30)
- δ18O: 30/30 (100.0%) of predictions fell within the measured ± 3.1 ‰
- 27/30 (90.0%) of predictions at this site location met the criteria for both isotopes

DISCUSSION & CONCLUSION

- Excellent fit at Uraca may be explained by mixed water at intermediate elevations (500 = 1000 masl); these models may perform more poorly at higher elevations where water sources are more heterogeneous
- Future validations should attempt to validate only with most probable locals
- Oxygen isotopes continue to perform worse than strontium
- Dual-isotope model more effective at constraining likely provenience than single-isotope models
- Ongoing work: Collecting baseline samples from regions poorly represented in database, generating process-based models, and generating probability maps of likely origins

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REFERENCES AVAILABLE UPON REQUEST

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