Cause-and-effect of plate motion and crustal thickening using time-series analysis and data analytics

Alexander D. Farrar **Matthew J. Cracknell** **David R Cooke** **Thomas Schaap**
Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania
alex.farrar@utas.ediu.au

SUMMARY

Cordilleran orogenic systems, such as the Andes, form adjacent to oceanic-continental convergent margins due to compressional and mass transfer events, widely accepted to result from plate tectonic processes. The same tectonic processes are intrinsically related to the formation of porphyry Cu and Au deposits. However, a formal, data- driven approach that assesses the causal relationship between plate convergence parameters and orogenic uplift indicators has not been assessed. We conduct time-series and statistical analysis of published central Andean orogenic proxies since the late Cretaceous. We find that orogenic proxies statistically correlate, in some cases with temporal causality. Statistical analysis of five plate motion models for Nazca-Farallon - South America plate convergence reveals the variability between different published plate tectonic motion models.

Granger causality analysis of plate convergence motion models with orogenic proxies demonstrate that changes to convergence rate precede flat slab subduction; oscillations of tectonic stress and crustal thickening guides precede convergence rate changes, and strong bi-directional causality exists between convergence rate fluctuations and Andean exhumation and paleoelevation uplift proxies. Convergence obliquity fluctuations exhibit a causal relationship on tectonic stress and crustal thickening. These data-driven results advance our understanding of how plate convergence and orogenic processes in the central Andes interact and provide insight into tectonic preconditioning processes that are required for the formation of giant porphyry ore deposits.

Key words: Granger causality, time-series analysis, tectonics, statistics, porphyry

INTRODUCTION

Dozens of studies have generated plate tectonic models for the relative motions of the Farallon-Nazca plate (NAZ) and South American plate (SAM) and diverse research has been conducted into understanding the orogenic evolution of the central Andes, based on structural geology and basin evolution, petrology and geochronology, thermochronology, paleoelevation, seismology, and geodynamic modelling. Given the myriad different models that exist for the tectonic evolution of the central Andes, how does one decide which model(s) are most the useful for further tectonic analysis related to porphyry mineralisation processes in the central Andes?

In this study, we conduct data-driven analysis to identify and assess statistical correlation between time-series models for plate tectonics and orogenic processes in the region of the central Andes since the late Cretaceous. We compare plate motion models and orogenic proxies using the Pearson correlation coefficient (r), and we apply Granger causality, a robust method for identifying causal linkages between time-series variables that exhibit temporal lag. Granger causality has been widely employed in economic, medical, and climatic studies, however, its application in geology has remained largely unexplored. Using Granger causality, we investigate temporal linkages between plate convergence parameters and orogenic variables, and we assess their statistical correspondence. Our data-driven method identifies numerous causal linkages that yield critical insight into the relationships between plate tectonic and Cordilleran orogenic processes.

Method

Five plate tectonic motion models representing a diversity of available models for SAM-NAZ convergence (Müller et al., 2019; Pardo-Casas and Molnar, 1987; Quiero et al., 2022; Schepers et al., 2017; Somoza and Ghidella, 2012; hereafter referred to as M19, PCM87; Q22; S17; SG12; Fig. 1) were output from pyGPlates in 1 Myr age bins. Linear correlation analysis (Fig. 1b, c) of these models was conducted at 1 Myr temporal intervals. For linear correlation analysis between orogenic datasets (Boschman, 2021; Loucks, 2021; Ramos and Folguera, 2009; Stalder et al., 2020; Fig. 2f) and G-causality analysis (Fig. 3) model proxies were binned into time intervals of two-million-years, to allow for direct temporal comparison of the datasets over a consistent time series. Sr/Y, La/Yb and uplift data are positively skewed and were log10 transformed, which yielded approximately Gaussian distributions. The mean and standard deviation of convergence obliquity and convergence rate for each plate tectonic motion model, every 1 Myr was calculated for each trench sample point14 (Fig. 1b, c;). Autocorrelation and Augmented Dickey Fuller (ADF) tests were conducted on the time series datasets to detect any significant trends in the data using the python statsmodels ADF package, which they did. We applied polynomial regression to all variables to produce a set of residual data that do not contain a unit root. For Granger causality analysis, vector autoregressive modeling (VAR) was carried on a data frame consisting of the joined plate tectonic and orogenic residual models, which defined the optimal lag order for the model, which was four lags (equivalent to 8 Myr due to 2 Myr temporal bins). Lag order was automatically selected by the model based on Akaike Information Criterion (AIC), using the statsmodels VAR package in python15. We performed the G-causality test using the statsmodels grangercausalitytests package in python.

Results

Linear analysis

Convergence rate pairs SG12 - Q22 and SG12 - M19 are strongly correlated (Fig. 1d). Convergence obliquity pairs SG12 - S17, SG12 – PCM87 are strongly correlated and Q22 is strongly correlated with all other convergence obliquity models (Fig. 1e), reflecting the homogeneity of convergence obliquity models since 28 Ma. Orogenic model pairs Sr/Y - La/Y are very strongly correlated ($r > 0.8$) and low temperature thermochronology – paleoelevation; flat slab – paleoelevation are strongly correlated ($r > 0.6$). The remaining model pairs are weakly linearly correlated ($0.2 < r < 0.6$). These results are consistent with visual analysis of Fig. 2 a-e, which illustrates the cyclic nature of crustal thickening processes over the temporal range.

Granger causality

We carried out time series analysis to assess if statistically significant Granger-causal (G-causal) lags are present between variables that would not be adequately detected by linear analysis. The results (Fig. 3) show that there are many statistically significant temporal linkages between variable pairs that exhibit strong ($P < 0.05$) and weak ($0.05 \leq P \leq 0.1$) Granger causality linkages. For orogenic variables, changes in La/Yb G-cause changes in paleoelevation, flat slab and thermochronological uplift, whilst paleoelevation and thermochronological uplift G-cause La/Yb, indicating bi-directional causal linkage between these variables. Flat Slab G-causes paleoelevation and thermochronological uplift and Sr/Y G-cause thermochronological uplift, Paleoelevation and La/Y (Fig. 3).

Strong convergence rate causal linkages are demonstrated between models SG12, PCM87 and S17, which G-cause paleoelevation; SG12, PCM87 and Q22 G-cause Flat slab, SG12 G-causes thermochronological uplift and M19 G-causes Sr/Y. Paleoelevation and thermochronological uplift G-cause SG12, indicating bi-directional causal linkage. Sr/Y and La/Yb G-cause SG12 and PCM87. Flat slab weakly G-causes S17 rate. Overall, convergence obliquity exhibits less G-causal linkages than convergence rate. Nevertheless, PCM87 convergence obliquity strongly granger causes La/Yb and Sr/Y.

Conclusions

Our analysis confirms plate tectonics and orogenesis in the central Andes since the late Cretaceous is highly inter-related, defined by numerous instantaneous and temporally lagged causal linkages, some of which exhibit bi-directional feedback. The SG12 convergence rate model exhibits seven strong G-causal linkages with orogenic proxies, many of them bidirectional, which is significantly more than other plate tectonic models and leads us to conclude that SG12 is the plate motion model that best interacts with orogenic proxies (Fig. 3). Our data-driven analysis identifies a coherent and interconnected plate tectonic – cordilleran system operating the in central Andes. Subduction obliquity changes precede changes to crustal thickening (La/Yb) and tectonic stress (Sr/Y). Increasing crustal thickening and tectonic stress G-cause paleoelevation and exhumation rate to increase, and convergence rate to slow, which G-causes flat slab subduction. Decreasing convergence rate G-causes exhumation rate and paleoelevation to increase. Feedback from increasing paleoelevation and exhumation to G-cause convergence rate to further slow. Using this coherent tectonic process model, future data-driven research will examine where in this process the formation of giant porphyry ore deposits in the central Andes occurs.

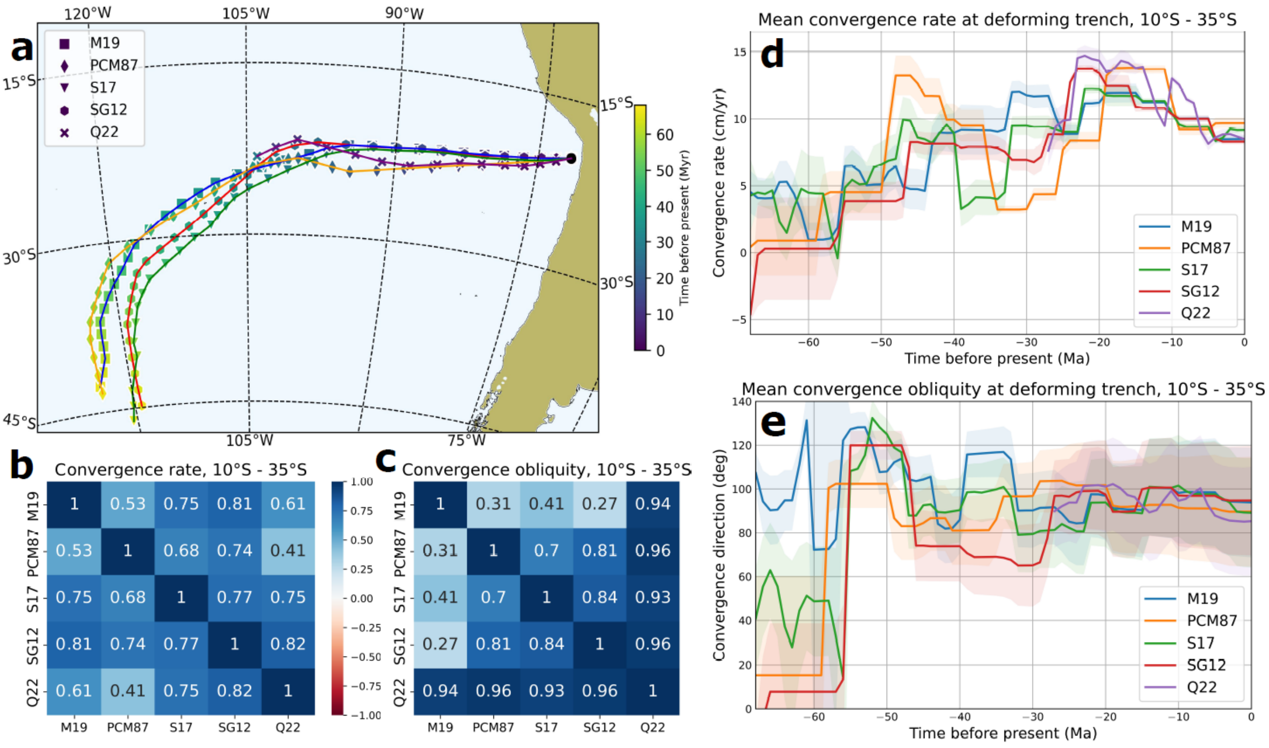

Figure 1. Convergence rate and obliquity models for NAZ – SAM since the late Cretaceous from 10° S to 35° S. Q22 model extends to 27 Ma. a Retro-projected trajectory for a point on the Nazca plate relative to South America. We selected a seed point that is currently entering the trench at 20°S and retro-projected it to 68 Ma, using the five plate models analysed in this study (see text)7, 8, 9, 10, 12. b Pearson correlation of convergence rate models, input data is rate of convergence, measured at nodes approximately every 45 km along the trench, every 1 Myr. c Linear correlation of convergence obliquity models, same parameters as for b. d Mean convergence rate per Myr along trench for each convergence model, shading represents one standard deviation of the mean. e Mean convergence obliquity per Myr along trench, shading parameters as for d.

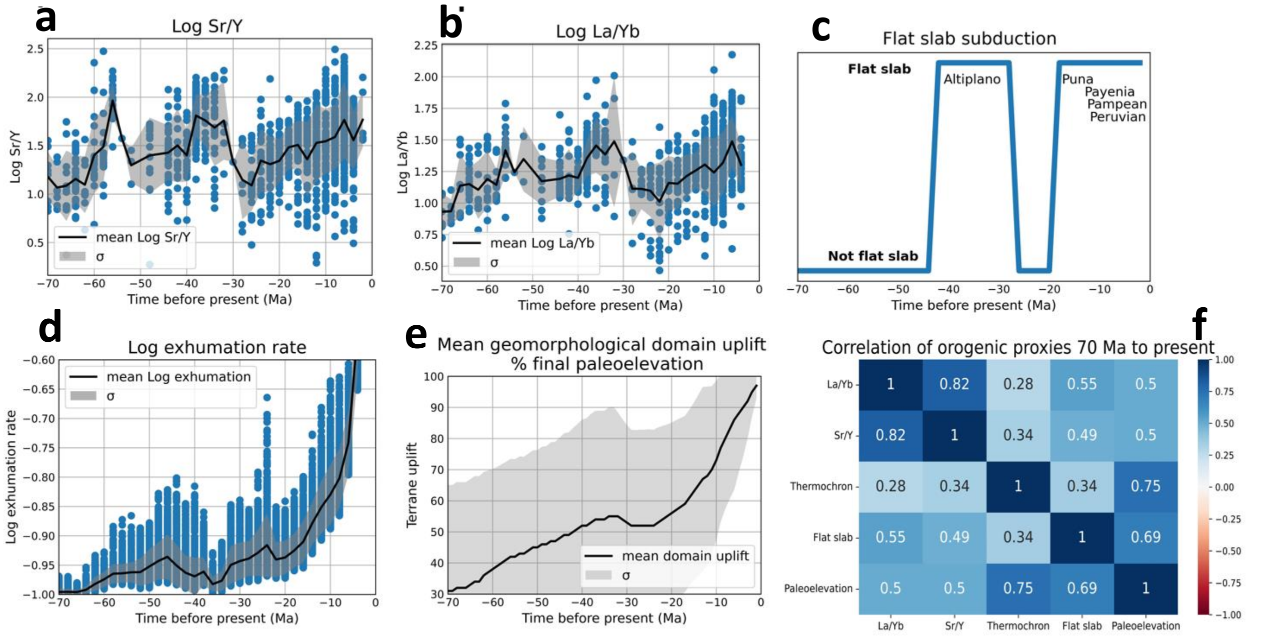

Figure 2. Orogenic indicators for the central Andes since the late Cretaceous. a Log10 transformed Sr/Y (blue points) binned into 2 Myr intervals, black line is the mean value for each 2 Myr bin, gray shading represents one standard

deviation of the mean. b Log10 transformed La/Yb, same parameters as for a. c flat slab subduction events. d log10 transformed uplift from low temperature thermochronology, same parameters as for a,b, e Mean uplift of geomorphological domains. f Pearson correlation of the means from a-e since 70 Ma.

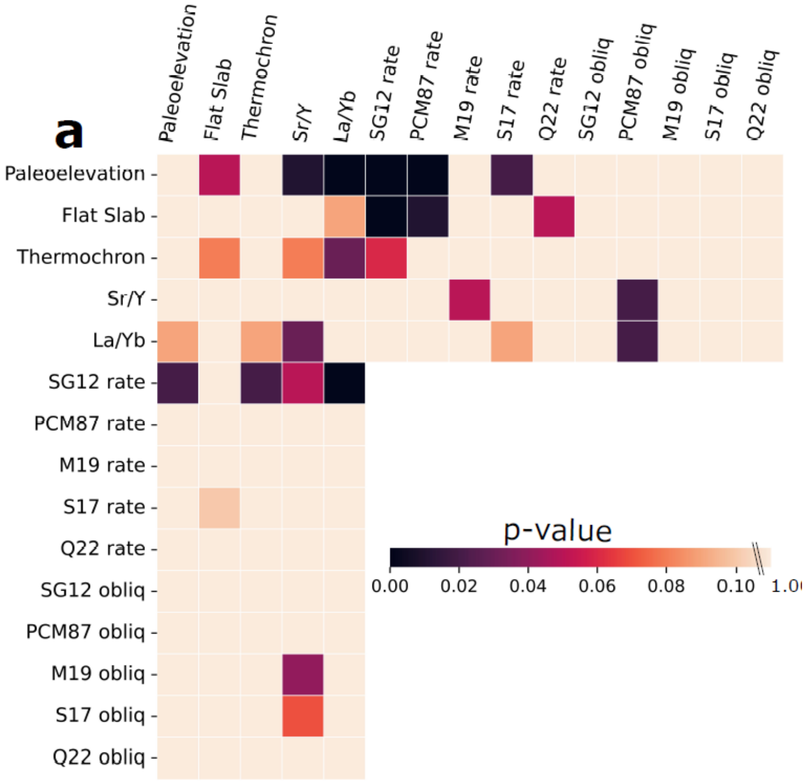

Figure 3. Granger causality matrix of plate tectonic and orogenic model pairs. The null hypothesis is that the x-axis variable does not Granger cause the y-axis variable. The null hypothesis is rejected if p-value of the F test <0.10. a p-values of variable pairs, non-background-coloured intersections represent variable pairs that exhibit statistically significant Granger causality (P<0.10).

ACKNOWLEDGMENTS

AF wishes to acknowledge a University of Tasmania travel grant that enables him to be here in person and to First Quantum minerals for sponsoring his PhD study.

REFERENCES

Boschman, L. M., 2021, Andean mountain building since the Late Cretaceous: A paleoelevation reconstruction: Earth-Science Reviews, v. 220.

Loucks, R. R., 2021, Deep entrapment of buoyant magmas by orogenic tectonic stress: Its role in producing continental crust, adakites, and porphyry copper deposits: Earth-Science Reviews, v. 220.

Müller, R. D., Zahirovic, S., Williams, S. E., Cannon, J., Seton, M., Bower, D. J., Tetley, M. G., Heine, C., Le Breton, E., Liu, S., Russell, S. H. J., Yang, T., Leonard, J., and Gurnis, M., 2019, A Global Plate Model Including Lithospheric Deformation Along Major Rifts and Orogens Since the Triassic: Tectonics, v. 38, p. 1884-1907.

Pardo-Casas, F., and Molnar, P., 1987, Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time: Tectonics, v. 6, p. 233-248.

Quiero, F., Tassara, A., Iaffaldano, G., and Rabbia, O., 2022, Growth of Neogene Andes linked to changes in plate convergence using high-resolution kinematic models: Nat Commun, v. 13, p. 1339.

Ramos, V. A., and Folguera, A., 2009, Andean flat-slab subduction through time: Geological Society, London, Special Publications, v. 327, p. 31-54.

Schepers, G., van Hinsbergen, D. J. J., Spakman, W., Kosters, M. E., Boschman, L. M., and McQuarrie, N., 2017, South-American plate advance and forced Andean trench retreat as drivers for transient flat subduction episodes: Nat Commun, v. 8, p. 15249.

Somoza, R., and Ghidella, M. E., 2012, Late Cretaceous to recent plate motions in western South America revisited: Earth and Planetary Science Letters, v. 331, p. 152-163.

Stalder, N. F., Herman, F., Fellin, M. G., Coutand, I., Aguilar, G., Reiners, P. W., and Fox, M., 2020, The relationships between tectonics, climate and exhumation in the Central Andes (18–36°S): Evidence from low-temperature thermochronology: Earth-Science Reviews, v. 210.