Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

A thermomechanical–Timoshenko model for estimating seismogenic thickness in the Sierra de Pie de Palo region, Central Andes

JORGE MORA

ingenierojorgemora@hotmail.com

universidad nacional de san juan https://orcid.org/0009-0007-5580-1015

Research Article

Keywords: seismogenic thickness, brittle–ductile transition, Central Andes, Sierra de Pie de Palo, Timoshenko beam, thermomechanical model, earthquake hypocenters

Posted Date: August 20th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10745077/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

A thermomechanical–Timoshenko model for estimating seismogenic thickness in the Sierra de Pie de Palo region, Central Andes

Jorge Ariel Mora
Ingeniero Civil
Investigador independiente

Abstract

The depth distribution of earthquakes provides an observational constraint on the mechanically active portion of the crust, but it is not identical to the brittle–ductile transition (BDT). This study evaluates a thermomechanical model that combines a Timoshenko-beam representation of tectonic stress with effective-stress failure and thermally activated creep to estimate a mechanically admissible seismogenic thickness in the Sierra de Pie de Palo region, Central Andes. The evaluation uses 1,247 hypocentral events from the INPRES catalogue and compares model estimates with sector-level seismicity-depth summaries. The reported model values are 38.2 km for northern Pie de Palo, 32.3 km for southern Pie de Palo, and 43.1 km for the Valle Bermejo Basin, compared with observational reference depths of 36.5, 31.0, and 46.3 km, respectively. The corresponding absolute differences are +1.7, +1.3, and -3.2 km. These results constitute a regional consistency test, not a global validation of a universal theory. The manuscript separates the BDT, the observed seismicity-depth distribution, and the model's mechanically admissible envelope; states the assumptions required for their comparison; and defines a reproducible cross-validation and sensitivity protocol for future independent tests. The angle-dependent stress term is treated as a testable parameterization rather than an established law.

Keywords: seismogenic thickness; brittle–ductile transition; Central Andes; Sierra de Pie de Palo; Timoshenko beam; thermomechanical model; earthquake hypocenters

1 Introduction

The depth range of crustal seismicity is a useful constraint on the portion of the crust that participates in brittle deformation. It should not, however, be equated without qualification with the depth of the brittle–ductile transition (BDT), because earthquake nucleation, fluid pressure, fault geometry, catalogue completeness, and hypocentral uncertainty can all affect the observed seismicity envelope. This paper evaluates a physically based model for the Sierra de Pie de Palo region rather than claiming a universal predictive theory.

The model combines a modified Timoshenko-beam stress representation, effective-stress failure, a temperature-dependent creep envelope, and a stress-partitioning term that depends on slab dip angle. The original formulation was motivated as a framework for different convergent margins, but the data presented here provide a quantitative test in one regional setting. The scientifically defensible question is therefore whether the model reproduces a prespecified regional depth statistic within uncertainty and whether each physical term improves performance relative to simpler alternatives.

The objectives are to: (1) define the model and its assumptions; (2) compare its predicted mechanically admissible thickness with sector-level seismicity-depth observations; (3) identify the limitations of interpreting hypocentral depth as BDT depth; and (4) specify an out-of-sample test and uncertainty analysis for future applications.

2 Geological and seismological setting

Sierra de Pie de Palo lies within the Central Andes of western Argentina, a region used here as a flat-slab end-member case. The seismicity observations were drawn from the public Instituto Nacional de Prevención Sísmica (INPRES) catalogue. The supplied analysis reports 1,247 high-resolution events and separates the region into northern Pie de Palo, southern Pie de Palo, and the Valle Bermejo Basin. Catalogue version, completeness magnitude, temporal window, declustering procedure, and individual location uncertainties must accompany the archived data and code at submission; they are not inferred here when absent from the supplied manuscript.

3 Model formulation

3.1 Effective stress and brittle failure

The effective normal stress is

$$\sigma_n' = \sigma_n - P_f, \tag{1}$$

where σ_n is the normal stress and P_f is pore-fluid pressure. A generic frictional failure envelope is written

$$\tau_f = C + \mu_f \sigma_n', \tag{2}$$

where C is cohesion and μ_f is the effective friction coefficient. The exact frictional law and parameter values must be stated in the machine-readable input file accompanying the submission.

3.2 Timoshenko stress representation

For a rectangular effective section, the transverse-shear correction is represented by $k_s = 5/6$. The tectonic shear contribution is written schematically as

$$\tau_T(z) = \tau_B(z) + \tau_S(z), \tag{3}$$

where τ_B is the bending contribution and τ_S is the transverse-shear contribution. The model uses an angle-dependent stress partitioning term,

$$\tau_{\mathrm{act}}(z, \phi) = \tau_T(z)\, g(\phi), \tag{4}$$

with $g(\phi) = \cos\phi$ in the current implementation. The choice of g is a hypothesis to be compared against constant, $\cos^2\phi$, and other physically bounded alternatives in future multi-region tests; it is not treated as a universal constitutive law.

3.3 Thermomechanical envelope

The ductile envelope is obtained from a temperature-dependent power-law creep relation of the general form

$$\dot{\epsilon}_{II} = A \sigma_{II}^{n} \exp\left(-\frac{Q}{RT}\right), \tag{5}$$

where A, n, and Q are rheological parameters, R is the gas constant, and $T(z)$ is the simulated temperature field. The mechanically admissible thickness h is the depth at which

the brittle and ductile envelopes intersect under the prescribed stress, thermal, and pore-pressure conditions. Initial and boundary conditions, mesh resolution, time step, convergence criterion, and all rheological values must be provided with the reproducibility package.

4 Data and evaluation protocol

The observed quantity is not called the BDT depth directly. Instead, the analysis defines a regional seismicity-depth statistic for each sector. The manuscript must specify whether that statistic is the maximum depth, a chosen percentile, the depth of the lower seismicity envelope, or another estimator. The uncertainty of the statistic must include both catalogue location uncertainty and sampling uncertainty.

The evaluation protocol is:

1. freeze the model equations and all parameter sources before evaluating the target sector;
2. define the seismicity-depth statistic and its uncertainty before comparison;
3. compute h without using the target statistic to select parameters;
4. compare the prediction with the target sector;
5. repeat after exchanging training and test sectors;
6. report the complete parameter provenance and uncertainty for every run.

A direct comparison of a model envelope with hypocentral depths is interpreted as a regional consistency test unless the parameter-freezing and cross-validation requirements are satisfied.

5 Results

The supplied analysis reports the following sector-level values.

The model is close to the reported regional reference values in the three sectors, with absolute differences of 1.3–3.2 km. This agreement is encouraging but does not establish that the model uniquely identifies the BDT: the reference quantity is derived from seismicity, and the current evidence is confined to one tectonic setting.

Table 1: Regional comparison reported in the supplied analysis. The observational column is a seismicity-depth reference and should be defined operationally in the final data supplement.

Sector	h_{model} (km)	h_{obs} (km)	Difference (km)	Relative error (%)
Northern Pie de Palo	38.2	36.5	+1.7	+4.7
Southern Pie de Palo	32.3	31.0	+1.3	+4.2
Valle Bermejo Basin	43.1	46.3	-3.2	-7.0

6 Required model comparisons and sensitivity analysis

A stronger sismological test should compare four models: (1) an observational seismicity-depth reference; (2) a temperature-only BDT estimate; (3) the thermomechanical model without the Timoshenko correction; and (4) the complete model. The same held-out sectors and the same loss function must be used for all models. Recommended metrics are mean signed error, mean absolute error, root-mean-square error, and coverage of predictive intervals.

Uncertainty should be propagated jointly for temperature, heat flow, thermal conductivity, pore pressure, cohesion, friction, rheological parameters, k_s, ϕ, and hypocentral depth. Point estimates alone are insufficient to determine whether the apparent agreement is meaningful. A Monte Carlo implementation should report the full predictive distribution of h for each sector.

The angle term should be tested using a prespecified comparison of $g(\phi) = 1$, $\cos\phi$, and $\cos^2\phi$, with any additional parameterized form constrained before evaluation. A more complex term should be retained only if it improves held-out performance without event- or sector-specific parameter revision.

7 Discussion

The principal result is regional: the reported model values are similar to the sector-level seismicity-depth references in Sierra de Pie de Palo. This supports the use of the framework as a physically motivated screening calculation in this setting. It does not demonstrate that the model predicts earthquake occurrence, that the calculated envelope is identical to the BDT, or that the same parameters transfer to other margins.

The distinction matters because earthquake depths can be influenced by catalogue completeness, location error, fluid pressure, fault orientation, stress transients, and nucleation physics. A shallow or deep seismicity boundary may therefore depart from the thermomechanical transition even when the model is physically reasonable. The final paper should

report the seismicity distribution, not only three summary numbers, and should show how the result changes with the selected observational statistic.

The flat-slab interpretation should also be limited. At $\phi \simeq 0°$, $\cos\phi \simeq 1$ in the adopted parameterization. At larger dip angles the stress projection changes, but $\cos\phi = 0$ at $90°$ does not by itself reproduce all physics of an extensional back-arc system. It marks the boundary of applicability of the present compressional representation.

The strongest future test is a pseudo-prospective regional test in which the catalogue, spatial sectors, parameter sources, and loss function are frozen before evaluation. A multi-margin comparison is then needed to assess transfer across slab dip, thermal regime, crustal composition, and fluid pressure. Until that test is completed, the model should be described as a regional physical framework and hypothesis-testing tool.

8 Conclusions

1. The thermomechanical–Timoshenko model provides a physically motivated estimate of a mechanically admissible seismogenic envelope for Sierra de Pie de Palo.

2. The supplied sector values differ from the reported observational references by 1.3–3.2 km, corresponding to 4.2–7.0% relative error.

3. The comparison is a regional consistency test, not evidence of a universal model or deterministic earthquake prediction.

4. Hypocentral depth and BDT depth must be treated as distinct quantities and compared using an explicitly defined seismicity-depth statistic with uncertainty.

5. Cross-validation, baseline models, complete equations, parameter provenance, and joint uncertainty propagation are required before claiming independent predictive performance.

6. Transfer to other subduction geometries remains a testable hypothesis requiring independent multi-margin data.

Data and code availability

The final submission should include the INPRES event catalogue subset, selection criteria, model input file, numerical code, mesh and boundary-condition files, and scripts that reproduce every table and figure. The supplied manuscript identifies a Zenodo record for code

and data; the final version must provide a verified DOI and version number and distinguish author-generated files from the original INPRES data source.

Declarations

Funding: No external funding statement was available in the supplied manuscript.

Conflict of interest: The author declares no competing interests.

Author contributions: Jorge Ariel Mora: conceptualization, methodology, analysis, writing, and visualization.

Ethics approval: Not applicable.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

Acknowledgements

The author acknowledges the Universidad Nacional de San Juan for institutional support and the Instituto Nacional de Prevención Sísmica for the public earthquake catalogue.

References

Byerlee, J. (1978). Friction of rocks. *Pure and Applied Geophysics*, 116, 615–626.

Timoshenko, S. (1921). On the correction for shear of the differential equation for transverse vibrations of prismatic bars. *Philosophical Magazine*, 41, 744–746.

Mora, J.A. (2026). Thermomechanical simulation codes, structural calculations, and regional datasets for seismogenic-thickness estimation. Zenodo. DOI and version to be verified before submission.

Instituto Nacional de Prevención Sísmica. Regional earthquake catalogue for Argentina. Public data portal; catalogue version and access date to be specified in the final submission.