

Supplementary Information for

Structural inheritance and transient coupling govern porphyry W-Mo mineralization

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Introduction

This Supplementary Information provides methodological details and supporting analyses for the magnetotelluric imaging and thermomechanical simulations presented in the main text. Supplementary Text S1 documents the compilation of representative porphyry-related W deposits, whereas Supplementary Text S2 describes the anomaly-replacement tests. Supplementary Texts S3 and S4 provide the electrical and seismic calculations used to assess the physical state of C1, and Supplementary Text S5 describes the thermomechanical model formulation and paired-model comparison. Supplementary Figs. 1-8 and Supplementary Tables 1-3 provide the associated data-quality, model-robustness, and parameter information.

Supplementary Text S1. Compilation of representative porphyry-related W deposits worldwide

Tungsten has an average abundance of approximately 1 ppm in the bulk continental crust¹. Porphyry-related W deposits are comparatively uncommon and typically record prolonged, multistage magmatism, with principal mineralization commonly linked to late-stage magma emplacement². To place Larong in this global context, we compiled geological and geochronological constraints from representative porphyry-related W deposits worldwide that record multiple magmatic events (Supplementary Table 1). For each deposit, we recorded the lithology and age of representative pre-ore, ore-related, and post-ore intrusions, together with the lithology, age, and published evidence most directly linking the principal W or W-Mo mineralization to a specific magmatic-hydrothermal episode.

Distinct magmatic events were recognized from geochronologically distinguishable intrusive phases, mapped intrusive relationships, and crosscutting constraints. A single principal mineralizing event was defined as one temporally restricted mineralizing window or one continuously evolving cogenetic magmatic-hydrothermal system; it does not require mineralization to be associated with only one intrusive lithology or one hydrothermal pulse. Closely spaced ore-related intrusions and fluid pulses were grouped when published evidence interpreted them as components of the same evolving system. Regional magmatic events were included only where their relationship to the deposit was geologically supported and were distinguished from directly dated deposit-scale intrusions. The compilation documents the temporal association between multistage magmatism and mineralization; it does not by itself demonstrate progressive W enrichment across successive events.

Supplementary Text S2. Anomaly-replacement sensitivity tests

We assessed the sensitivity of the MT dataset to conductors C1 and C2 by replacing each feature individually and evaluating the resulting change in data misfit. The target volumes were defined from the extents of C1 and C2 in the preferred three-dimensional resistivity model (Supplementary Fig. 6). For each test, all model cells within the target volume were assigned a homogeneous resistivity of 100 $\Omega\cdot\text{m}$, whereas all other cells were held fixed. Synthetic responses were then recalculated by forward modeling without reinversion. The procedure was applied to C1 and C2 individually and to both conductors simultaneously.

The modified models were compared with the preferred model using the overall normalized root-mean-square (nRMS) misfit and station-level relative RMS increases. Relative to the preferred-model nRMS of 1.95, replacing C1 increased the nRMS to 2.06, replacing C2 increased it to 2.48, and replacing both conductors increased it to 2.64. The systematic deterioration in data fit shows that both C1 and C2 are required to reproduce the observed MT responses.

We further assessed the sensitivity of the MT dataset to the conductive connection between C1 and C2 by replacing its shallower and deeper segments separately with a homogeneous resistivity of 100 $\Omega\cdot\text{m}$. All other model cells were held fixed, and synthetic responses were recalculated by forward modeling without reinversion. The change in data fit at each station was quantified as the relative RMS increase:

$$\Delta\text{RMS}_i(\%) = 100 \times \frac{\text{RMS}_{i,\text{modified}} - \text{RMS}_{i,\text{preferred}}}{\text{RMS}_{i,\text{preferred}}},$$

where $\text{RMS}_{i,\text{modified}}$ and $\text{RMS}_{i,\text{preferred}}$ are the RMS misfits at station i for the modified and preferred models, respectively. Both replacements produced spatially coherent increases in station-level RMS

misfit, locally approaching 20% (Supplementary Fig. 7). These tests show that C1 and C2 are required by the MT dataset and support a conductive connection between them at the resolution of the MT array.

Supplementary Text S3. Estimation of hydrous silicate melt fraction

To assess whether minor interconnected hydrous silicate melt could account for the representative bulk resistivity of C1, we used the modified Archie's law for two conducting phases³:

$$\sigma_{bulk} = \sigma_{rock}(1 - \phi)^P + \sigma_{melt}\phi^m,$$

where

$$P = \frac{\log(1 - \phi^m)}{\log(1 - \phi)},$$

and

$$\rho_{bulk} = \frac{1}{\sigma_{bulk}},$$

Here, σ_{bulk} , σ_{rock} , and σ_{melt} are the bulk, solid-rock, and melt conductivities, respectively; ϕ is the melt volume fraction; and m is the Archie exponent. Electrical conductivity is expressed in S/m, and resistivity is expressed in $\Omega \cdot m$.

We derived the representative bulk resistivity of C1 from model cells with resistivities below 50 $\Omega \cdot m$ between depths of 20 and 40 km within the predefined C1 volume ($-15 \leq x \leq 27$ km and $-13 \leq y \leq 25$ km in local model coordinates). The selection contained 320 model cells and yielded a mean resistivity of 33.1 $\Omega \cdot m$. We adopted a host-rock resistivity of 2000 $\Omega \cdot m$, a reference melt resistivity of 0.2 $\Omega \cdot m$, and an Archie exponent of 1.5. The reference melt resistivity was based on the hydrous silicate-melt parameters adopted from Cui et al.⁴ at approximately 1 GPa and 900 °C.

For these reference parameters, a bulk resistivity of 33.1 $\Omega \cdot m$ corresponds to a melt volume fraction of approximately 0.033, or 3.3 vol.%. We evaluated parameter sensitivity over melt resistivities of 0.1 to 2.0 $\Omega \cdot m$ and melt fractions of 0.01 to 0.80 (1 to 80 vol.%; Fig. 3b).

We did not apply the silicate-melt mixing calculation to C2 because its shallower depth and the regional thermal constraints do not favor volumetrically significant silicate melt. Its possible conductive phases were instead evaluated from its depth, thermal setting, geometry, and alternative conduction mechanisms in the Discussion. The C1 calculation was used as an end-member test of whether minor interconnected hydrous melt could reproduce the observed bulk resistivity.

Supplementary Text S4. Equivalent-porosity estimate from regional shear-wave velocity

To provide an independent seismic constraint on the physical state of the middle–lower crust beneath Larong, we extracted a horizontal slice of shear-wave velocity (V_s) at 30 km depth from the three-dimensional Tibetan Plateau velocity model of Huang et al.⁵. The model grid node nearest to Larong (98.0°E, 30.0°N) yielded a V_s of 3.375 km/s. We adopted $V_{s0}=3.60$ km/s as the reference velocity representative of the surrounding crust at the same depth. The relative shear-wave velocity anomaly was calculated as:

$$\Delta V_s(\%) = 100 \times \frac{V_s - V_{s0}}{V_{s0}},$$

where V_s is the velocity beneath Larong and V_{s0} is the reference velocity. These values yield a relative S-wave velocity reduction of -6.25%.

We converted the observed velocity reduction to an equivalent porosity using a linear approximation to the low-porosity portion of the empirical granite velocity-porosity relationship presented by Chu et al.⁶:

$$\phi_{\text{eq}}(\text{vol. \%}) = -\frac{\Delta V_s(\%)}{k},$$

where ϕ_{eq} is the equivalent porosity and $k=1.33$ is the assumed percentage decrease in V_s per volume percent porosity. The calculated velocity reduction corresponds to an equivalent porosity of approximately 4.7 vol.%.

The regional V_s distribution and the conversion from ΔV_s to equivalent porosity are shown in Supplementary Fig. 8. The resulting equivalent porosity is of the same order as the approximately 3.3 vol.% hydrous-melt estimate obtained independently from the bulk resistivity of C1 (Supplementary Text S3). This comparison provides a first-order consistency check between the regional seismic and MT constraints. The conversion treats the observed velocity reduction as equivalent to the effect of pores containing low-velocity melt or fluid. Because V_s also depends on temperature, pressure, rock composition, seismic anisotropy, and pore geometry, ϕ_{eq} was not interpreted as a direct measurement of melt fraction or crustal porosity.

Supplementary Text S5. Thermomechanical model formulation and paired-model comparison

We used ASPECT version 3.1.0-pre to solve the conservation equations of mass, momentum, and energy under the Boussinesq approximation^{7,8}:

$$\begin{aligned}\nabla \cdot \mathbf{u} &= 0, \\ -\nabla P + \nabla \cdot (2\eta_{\text{eff}}\dot{\boldsymbol{\epsilon}}) + \rho\mathbf{g} &= 0, \\ \rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot (k\nabla T) &= Q_r + \rho H_{\text{ext}},\end{aligned}$$

where $\mathbf{u}$ is velocity, P is dynamic pressure, η_{eff} is effective viscosity, $\dot{\boldsymbol{\epsilon}} = \frac{1}{2}[\nabla\mathbf{u} + (\nabla\mathbf{u})^T]$ is the strain-rate tensor, ρ is density, $\mathbf{g}$ is gravitational acceleration, c_p is heat capacity, T is temperature, k is thermal conductivity, Q_r is volumetric radiogenic heat production, and H_{ext} is the imposed specific heating rate. Under the Boussinesq approximation, temperature-dependent density variations were retained only in the buoyancy term.

The two-dimensional Cartesian domain is 300 km wide and 120 km deep and comprises a 20-km-thick upper crust, a 40-km-thick lower crust, and 60 km of lithospheric mantle. The initial conductive geotherm increases from 273 K at the surface to 633 K at 20 km depth, 1113 K at the Moho, and 1613 K at the model base. The upper crust, lower crust, and lithospheric mantle have radiogenic heat-production rates of 1.0×10^{-6} , 0.25×10^{-6} , and 0 W m⁻³, respectively. Model geometry and prescribed forcing are shown in Fig. 4a and b, and the thermal and material parameters are summarized in Supplementary Table 3.

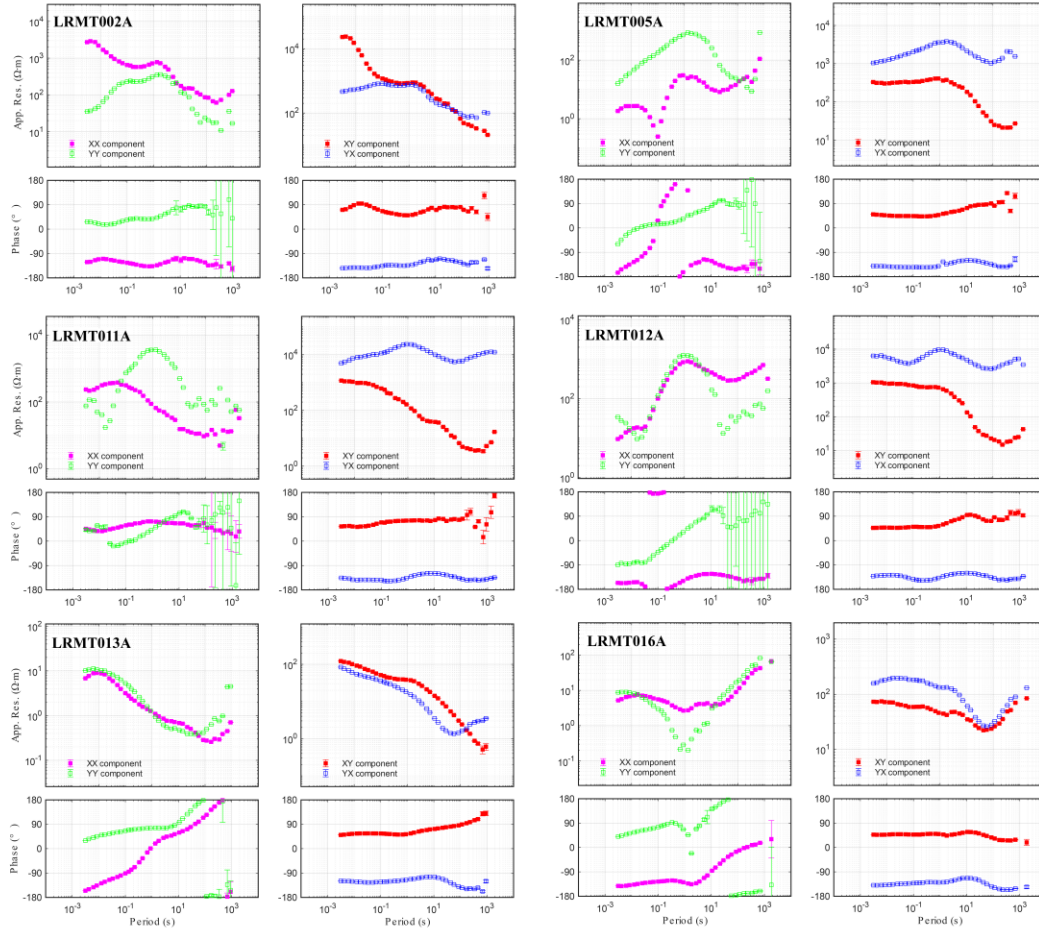
The top boundary was treated as a free surface, with surface diffusion applied to stabilize mesh deformation. Outward velocities of 1 mm/yr were imposed on each lateral boundary, corresponding to a total extension rate of 2 mm/yr. Mass balance was maintained by prescribing an upward velocity of 0.8 mm/yr along the model base. Temperatures were fixed at the upper and lower boundaries, whereas the lateral boundaries were thermally insulating. A continuous Gaussian specific heating term was imposed beneath the Moho:

$$H(x, y) = H_{\text{src}} \exp \left[- \left(\frac{(x - x_0)^2}{2s_x^2} + \frac{(y - y_0)^2}{2s_y^2} \right) \right]$$

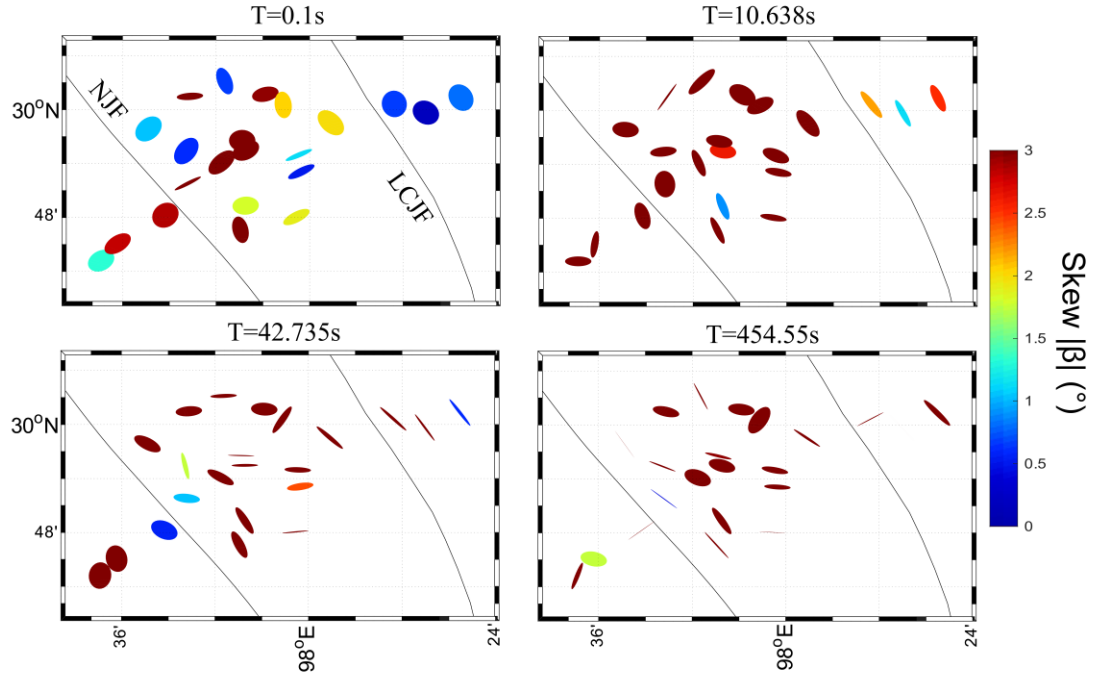
where $H_{\text{src}} = 5 \times 10^{-9} \text{ W kg}^{-1}$, $x_0 = 160 \text{ km}$, $y_0 = 45 \text{ km}$, $s_x = 20 \text{ km}$, $s_y = 12 \text{ km}$. Because the vertical coordinate is measured upward from the model base, the heat-source center corresponds to a depth of approximately 75 km. This term represents sustained thermal input rather than explicit magma generation or two-phase melt transport.

Deformation was described by a temperature-dependent viscoplastic rheology combining dislocation creep with Drucker–Prager plastic yielding. Effective viscosity was limited to between 10^{18} and $10^{26} \text{ Pa}\cdot\text{s}$. Plastic strain weakening operated between accumulated plastic strains of 0.5 and 1.5 and reduced cohesion and the friction coefficient to 25% of their initial values. Adaptive mesh refinement was concentrated in the central model region. The maximum time step was 20 kyr, and model output was saved every 0.1 Myr. Rheological, thermal, and numerical parameters are provided in Supplementary Table 3.

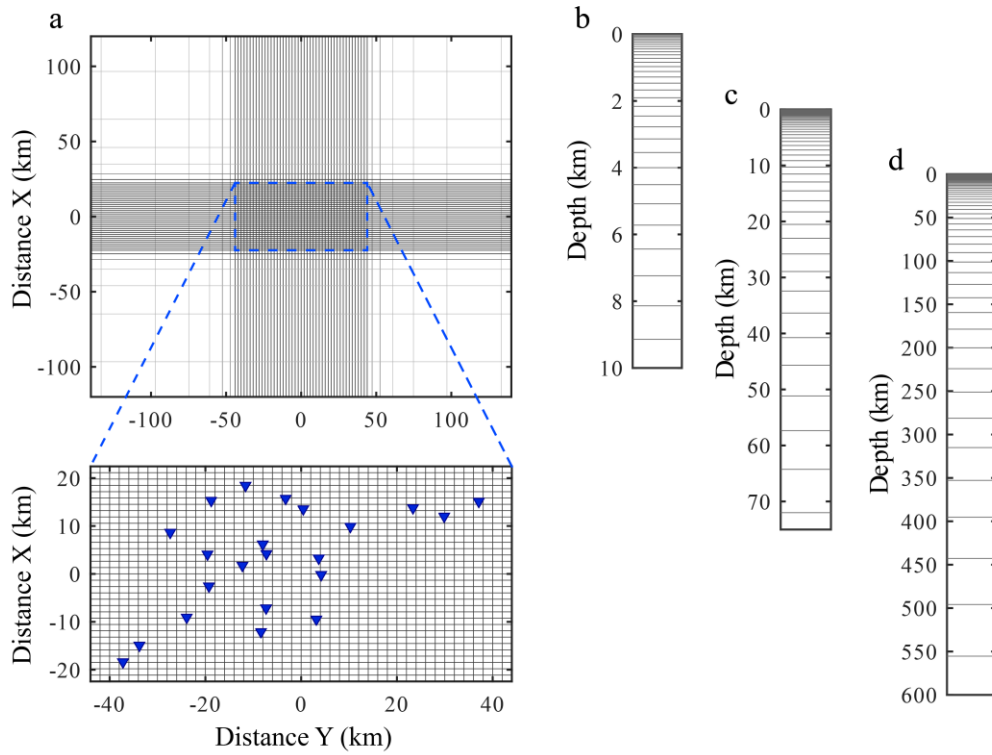
The weak-zone and reference models used identical geometry, rheology, boundary conditions, thermal forcing, and numerical settings. The only difference was the initial plastic-strain field. In the weak-zone model, an initial plastic strain of 1.5 was assigned along the idealized C1–C2–Larong geometry; the reference model had zero initial plastic strain throughout. Both models were evolved for 3 Myr, and their temperature, effective-viscosity, and velocity fields were compared at 1 and 3 Myr (Fig. 4c and d). This paired-model design isolates the mechanical influence of the prescribed weak zone on thermomechanical localization. The calculated velocities describe solid-matrix motion and should not be interpreted as magma-flow velocities.



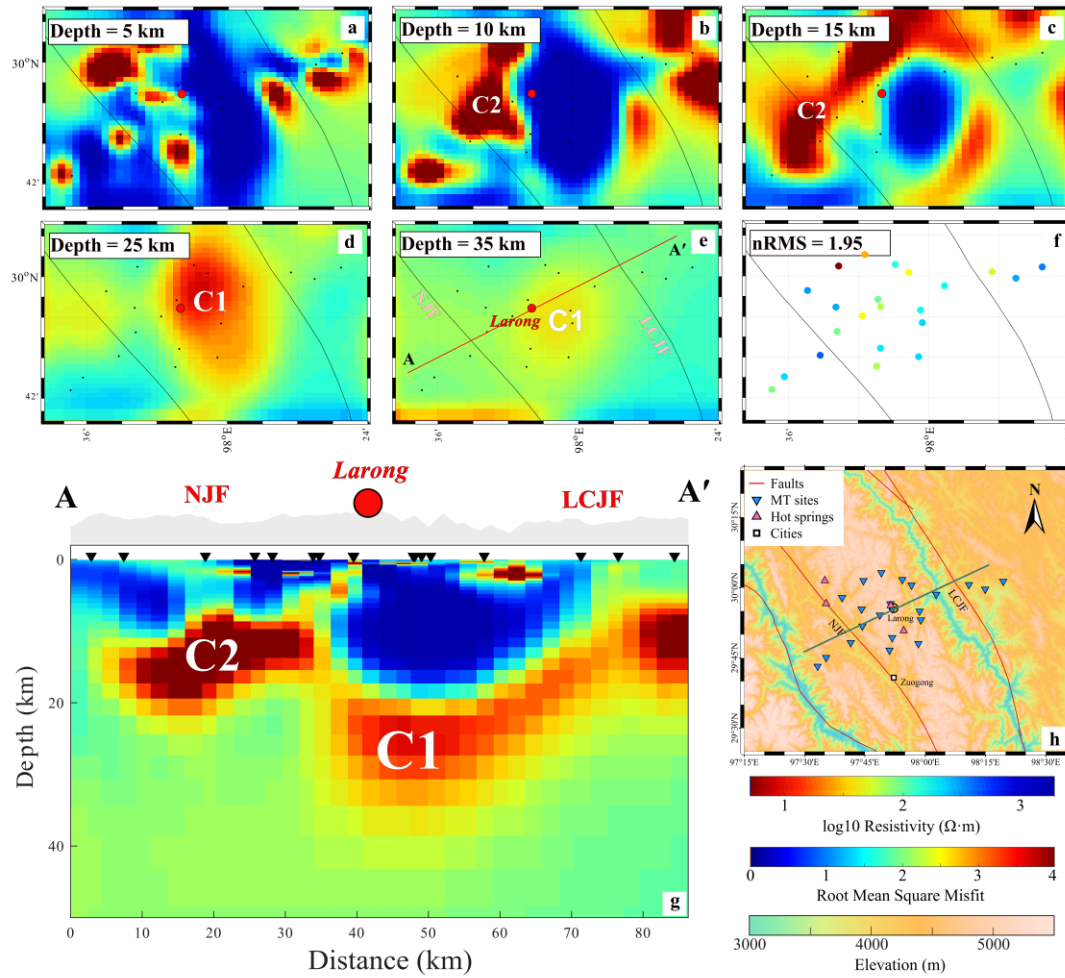
Supplementary Fig. 1 | Representative magnetotelluric impedance responses from the Larong survey. Observed apparent-resistivity and phase responses at six representative MT stations. For each station, the left panels show the diagonal impedance-tensor components Z_{xx} (magenta) and Z_{yy} (green), whereas the right panels show the off-diagonal components Z_{xy} (red) and Z_{yx} (blue). The upper and lower panels show apparent resistivity and phase, respectively, as functions of period. Error bars denote the estimated data uncertainties.



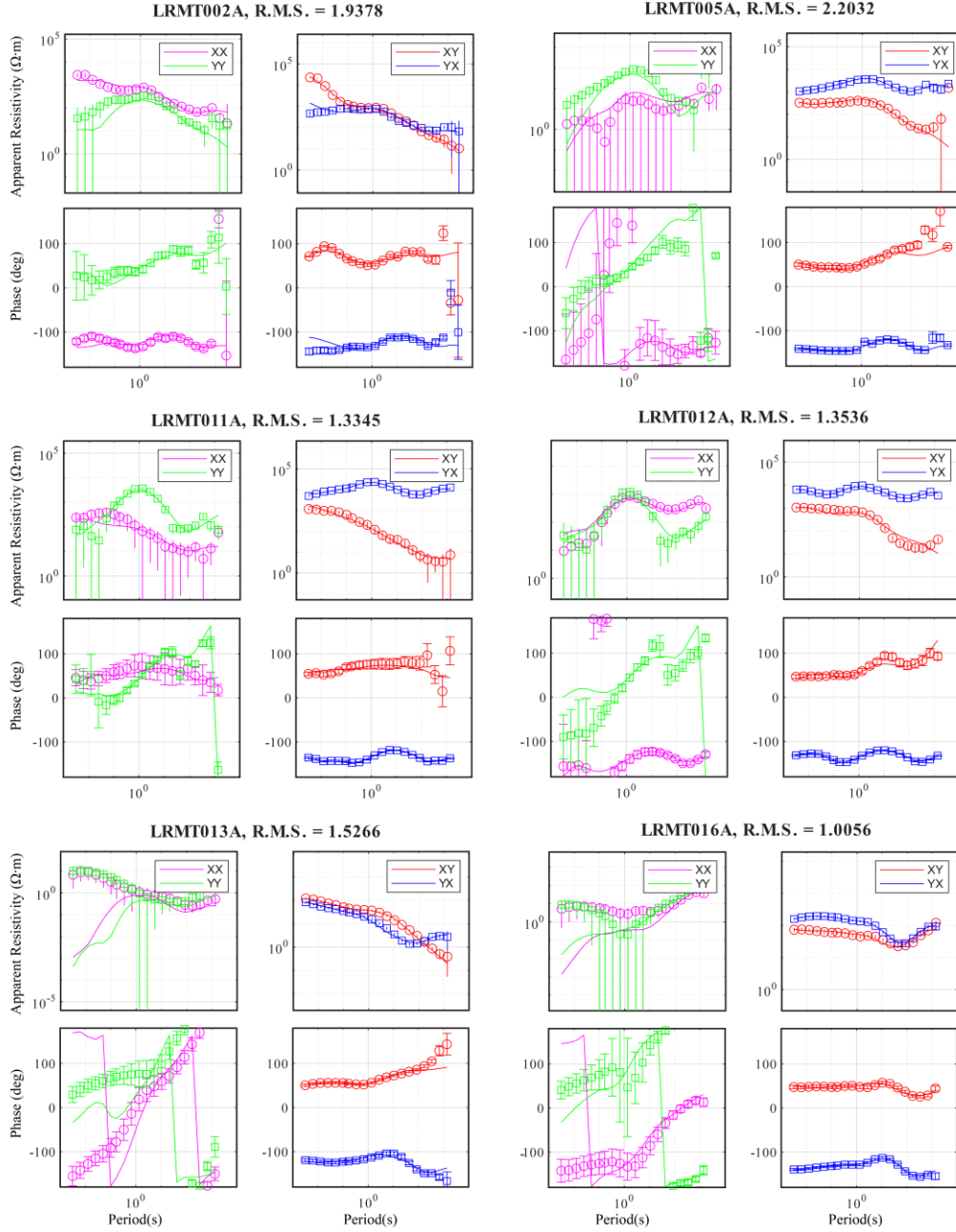
Supplementary Fig. 2 | Phase-tensor maps across the Larong MT array. Ellipse color denotes $|\beta|$ in degrees, and ellipse geometry and azimuth show phase-tensor orientation. $|\beta|$ values greater than 3° at middle to long periods indicate appreciable three-dimensional electrical effects. NJF, Nujiang fault; LCJF, Lancangjiang fault.



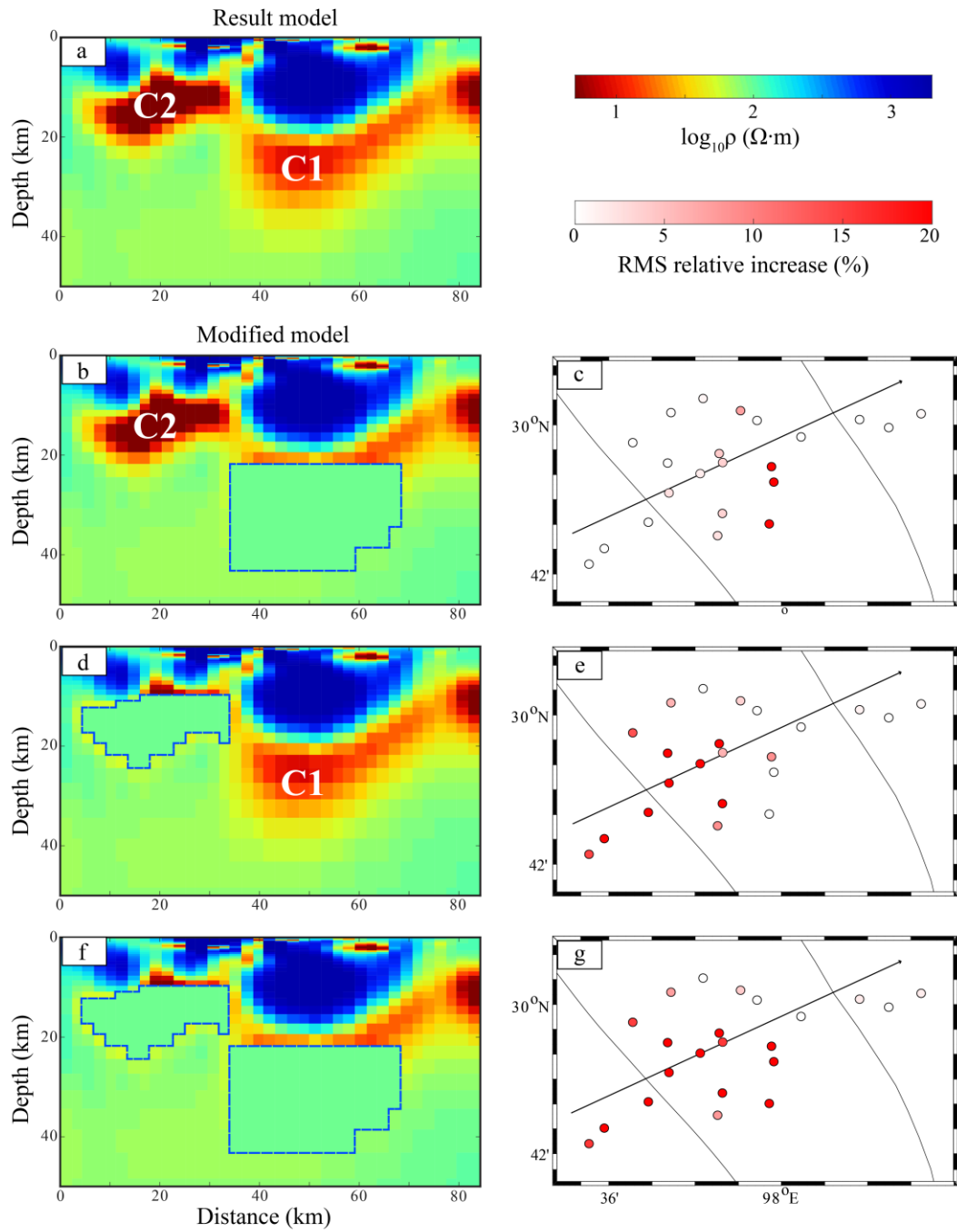
Supplementary Fig. 3 | Three-dimensional mesh used for magnetotelluric inversion. (a) Plan view of the complete horizontal mesh (upper) and an enlarged view of the refined central domain (lower). The blue dashed box in the upper panel outlines the enlarged area, and the blue inverted triangles in the lower panel mark the 22 MT stations. Horizontal cells are refined across the data-covered area and progressively enlarged toward the model boundaries. (b to d) Vertical discretization shown over progressively expanded depth intervals of 0–10, 0–75, and 0–600 km, respectively. Vertical cell spacing is finest near the surface and increases with depth.



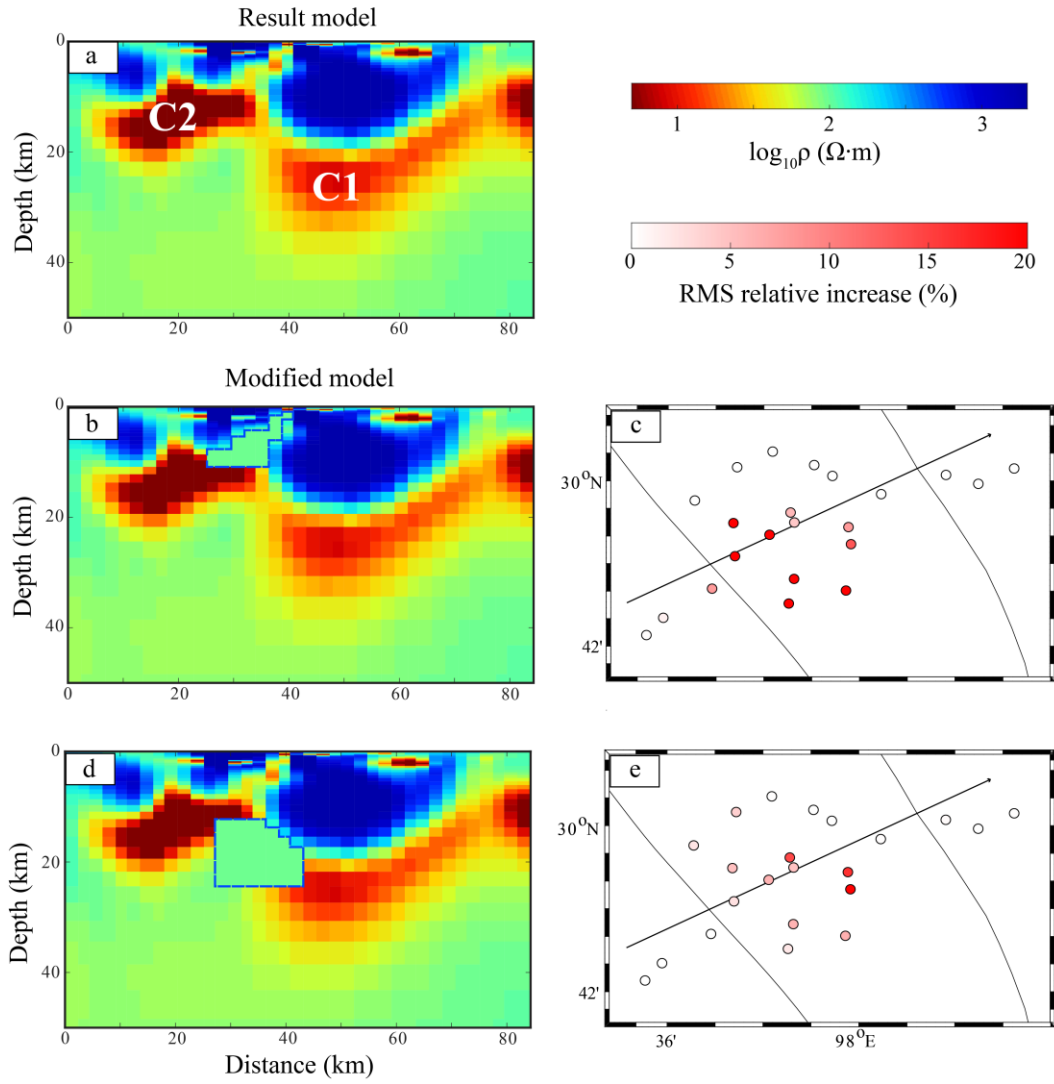
Supplementary Fig. 4 | Preferred three-dimensional magnetotelluric resistivity model and inversion misfit. (a to e) Horizontal slices through the preferred model at depths of 5, 10, 15, 25, and 35 km, respectively. The localized middle-crustal conductor C2 is labeled in (b) and (c), and the deeper middle-lower crustal conductor C1 is labeled in (d) and (e). Black dots mark MT stations, the red circle marks the Larong W-Mo deposit, and black lines denote major faults. (f) Spatial distribution of the normalized root-mean-square (nRMS) misfit at individual MT stations. The final overall nRMS misfit is 1.95. (g) Vertical resistivity section along profile A–A' showing the spatial distribution of C1 and C2 beneath Larong. Black inverted triangles mark MT stations projected onto the profile, and the red circle marks the Larong deposit. (h) Topographic map showing the location of profile A–A' and the survey configuration. Resistivity colors in (a) to (e) and (g) represent $\log_{10}\rho$, with ρ in $\Omega\cdot\text{m}$. NJF, Nujiang fault; LCJF, Lancangjiang fault.



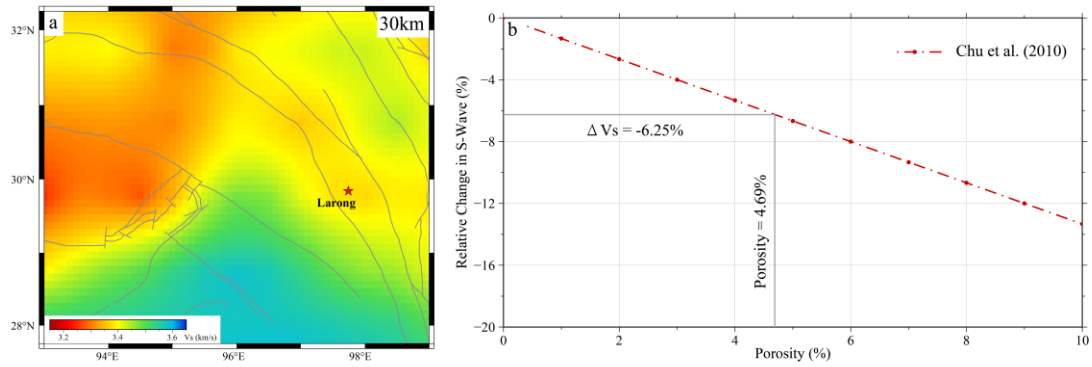
Supplementary Fig. 5 | Comparison of observed and predicted magnetotelluric responses at representative stations. Apparent-resistivity and phase responses are shown for six representative MT stations. Within each station group, the left panels show the diagonal impedance-tensor components Z_{xx} and Z_{yy} , whereas the right panels show the off-diagonal components Z_{xy} and Z_{yx} . The upper and lower panels show apparent resistivity and phase, respectively. Observed responses are plotted as open symbols with error bars, and responses predicted by the preferred three-dimensional model are shown as solid lines. Magenta, green, red, and blue denote Z_{xx} , Z_{yy} , Z_{xy} , and Z_{yx} , respectively.



Supplementary Fig. 6 | Anomaly-replacement sensitivity tests for the C1 and C2 conductors. (a) Preferred A–A' resistivity section. (b, d, and f) Modified models in which C1, C2, or both conductors were replaced by a homogeneous 100 Ω·m background; blue dashed outlines delimit the replaced model cells. (c, e, and g) Corresponding station-level relative RMS increases after forward calculation without reinversion. Circle locations mark MT stations, and warmer colors indicate greater deterioration in data fit. Resistivity colors in (a), (b), (d), and (f) represent log₁₀ρ, where ρ is in Ω·m.



Supplementary Fig. 7 | Anomaly-replacement sensitivity tests for the conductive connection between C1 and C2. (a) Preferred vertical resistivity section showing C1 and C2. (b and d) Modified models in which the shallower and deeper segments, respectively, of the intervening conductive connection were replaced by a homogeneous $100\ \Omega\cdot\text{m}$ background; blue dashed outlines delimit the replaced model cells. (c and e) Station-level relative RMS increases obtained by forward calculating the modified models without reinversion. Circle locations mark MT stations and black lines denote major faults. Resistivity colors in (a), (b), and (d) indicate $\log_{10}\rho$, where ρ is in $\Omega\cdot\text{m}$. The spatially coherent RMS increases after both replacements support a conductive connection between C1 and C2 at the resolution of the MT array.



Supplementary Fig. 8 | Regional shear-wave velocity at 30 km depth and equivalent-porosity estimate beneath Larong. (a) Horizontal slice of shear-wave velocity V_s at 30-km depth from the Tibetan Plateau velocity model of Huang et al.⁵. The red star marks the Larong deposit, gray lines denote major faults, and colors indicate absolute V_s . (b) First-order porosity estimate based on the linear relation between porosity and the relative reduction in V_s adopted from Chu et al.⁶. A local V_s of 3.375 km s^{-1} relative to a reference value of 3.60 km s^{-1} gives $\Delta V_s = -6.25\%$, corresponding to an equivalent porosity of approximately 4.69 vol.%. Gray lines mark the inferred values. This simplified end-member estimate is not unique because seismic velocity may also be affected by temperature, composition, anisotropy, and partial melt.

Supplementary Table 1 | Multistage magmatic histories and associated mineralization in representative porphyry-related tungsten deposits worldwide.

Deposit	Representative magmatic events: lithology and age	Mineralization-related lithology and age	References
Larong	Dioritic porphyry, 214.0 ± 0.7 Ma; granodiorite porphyry, 213.8 ± 1.3 Ma; biotite granite porphyry, 104.4 ± 0.9 Ma; monzogranite porphyry, 93.9 ± 1.3 Ma; biotite granite, 91.7 ± 0.5 Ma; granite aplite, 36.2 ± 0.6 Ma.	Ore-forming monzogranite porphyry, 93.9 ± 1.3 Ma; molybdenite Re–Os mineralization, 91.8 ± 0.5 Ma.	9,10
Gaojiabang	Ore-bearing granite porphyry, 150.4 ± 1.1 Ma; monzonite porphyry, 149.4 ± 1.6 Ma; post-ore Qingyang–Jiuhua intrusions, 144–127 Ma; late monzonite–granodiorite and diabase dikes, 135–127 Ma.	Granite porphyry–monzonite porphyry system at ca. 150 Ma; molybdenite Re–Os mineralization, 149.5 ± 1.4 Ma. The main W–Mo event is chiefly related to the granite porphyry.	11
Sansheng	Regional W-related magmatic–hydrothermal episodes at 250–240, 200–170, and 160–125 Ma; highly fractionated granite, 136.75 ± 0.97 Ma; monzogranite, 136.04 ± 0.75 Ma.	Highly fractionated granite–monzogranite system at ca. 136 Ma; molybdenite Re–Os, 138.6 ± 1.4 Ma; wolframite U–Pb, 137.3 ± 2.0 Ma.	12
Yangchuling	Dagangnao granodiorite, 149.8 ± 0.6 Ma; Qipancun monzogranite porphyry, 143.8 ± 0.5 Ma.	Evolved granodiorite–monzogranite porphyry system; molybdenite Re–Os mineralization, 146.4 ± 1.0 Ma. Ore bodies occur mainly near the top of the monzogranite porphyry and in its roof rocks.	13
Muguayuan	Regional Taojiang granodiorite, ca. 396 Ma; Taojiang composite pluton, 219–210 Ma; Sanxianba granodiorite porphyry, 222 ± 1 Ma; quartz porphyry, 219 ± 3 Ma.	Sanxianba granodiorite porphyry–quartz porphyry system; molybdenite Re–Os model ages of 228–223 Ma, weighted mean of 226 Ma, and isochron age of 220 ± 21 Ma.	14,15
Xingluokeng	G1 porphyritic biotite granite, 152.5 ± 1.4 Ma; G2 medium- to fine-grained biotite granite, 152.2 ± 1.2 Ma; additional concealed magmatic–hydrothermal activity, 149.5–143.5 Ma.	G2 supplied W-rich fluids and G1 was the main host; wolframite U–Pb, 150.5 ± 8.1 Ma; fluid-inclusion Rb–Sr, 147.5 ± 2.9 Ma; scheelite Sm–Nd, 142.6 ± 2.8 Ma.	16
Mount Pleasant	Granite I at ca. 370 ± 2 Ma, constrained by the coeval W–Mo event; Bailey Rock rhyolite, 363 ± 2 Ma. Granite II and Granite III represent later intrusive phases.	Fine-grained equigranular Granite I and its hornfels–stockwork system; molybdenite Re–Os ages of 370.1 ± 1.7 and 369.7 ± 1.6 Ma.	17
Lianhuashan	Regional felsic–mafic magmatism, 145–135 Ma; quartz porphyry, 137.3 ± 2.0 Ma. Other mapped intrusions are not independently dated in the cited study.	Quartz porphyry-related W mineralization; hydrothermal muscovite Ar–Ar plateau age of 133.2 ± 0.9 Ma.	19

Deposit	Representative magmatic events: lithology and age	Mineralization-related lithology and age	References
Dongyuan	Regional Jiangnan W-belt episodes at ca. 162, 150–135, and 135–125 Ma; ore-bearing granite porphyry, 148.6 ± 1.8 Ma; biotite granite, 143.5 ± 0.7 Ma.	Ore-bearing granite porphyry/porphyritic granodiorite–biotite granite system; molybdenite Re–Os mineralization, 146 ± 2.3 Ma.	20,21
Dahutang ore field	Shimensi CPBG, FPBG, FBG, and BGP phases, 147.9–138.6 Ma; early coarse-grained porphyritic two-mica granite (CPTG), 144.2–137.5 Ma; late barren CPTG, 130–128 Ma.	Two distinguishable events: BGP-related hydrothermal hornfels W–Cu–Mo mineralization, 142.0 ± 0.6 Ma; early-CPTG-related coarse quartz-vein W–Cu–Mo mineralization, 136.1 ± 0.5 Ma.	22,23

Supplementary Table 2 | Three-dimensional magnetotelluric inversion parameters.

Parameter	Values
Model grid	$54 \times 64 \times 68$ cells
Core mesh cell size	$1.32 \text{ km} \times 2.0 \text{ km}$
Starting half-space value	$100 \Omega \cdot \text{m}$
Impedance components	$Z_{xx}, Z_{xy}, Z_{yx}, Z_{yy}$
Data error floor	5% off-diagonal; 10% diagonal
Iterations	125
Final nRMS	1.95

Supplementary Table 3 | Thermomechanical model parameters.

Parameter	Symbol (unit)	Upper crust	Lower crust	Mantle
Flow law	—	wet quartzite	wet anorthite	dry olivine
Dislocation prefactor	$A \text{ (Pa}^{-n} \text{ s}^{-1}\text{)}$	8.57×10^{-28}	7.13×10^{-18}	6.52×10^{-16}
Stress exponent	n	4.0	3.0	3.5
Activation energy	$E \text{ (kJ mol}^{-1}\text{)}$	223	345	530
Activation volume	$V \text{ (cm}^3 \text{ mol}^{-1}\text{)}$	0	0	18
Density	$\rho \text{ (kg m}^{-3}\text{)}$	2700	2900	3300
Heat capacity	$c_p \text{ (J kg}^{-1} \text{ K}^{-1}\text{)}$	750	750	750
Thermal expansivity	$\alpha \text{ (K}^{-1}\text{)}$	2×10^{-5}	2×10^{-5}	2×10^{-5}
Thermal conductivity	$k \text{ (W m}^{-1} \text{ K}^{-1}\text{)}$	2.5	2.5	2.5
Radiogenic heat production	$H_r \text{ (W m}^{-3}\text{)}$	1.0×10^{-6}	0.25×10^{-6}	0
Friction angle	$\varphi \text{ (}^\circ\text{)}$	30	30	30
Cohesion	$C \text{ (MPa)}$	20	20	20

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