Data Article

3-D data of thermal regime, water content, and slab dehydration in Alaska

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\textbf{ABSTRACT}

The data include the 3-D temperature field (degrees Celsius), water content (wt%), dehydration rate (wt%/km), and subduction velocity field (cm/yr) of the subducting plate, as well as the coastline and volcano distribution in Alaska. The data of the model region have dimensions of 800 × 1600 × 400 km (length × width × depth). The geometry of the subducted plate is well constrained by Slab2.0, and the plate ages are provided by Earth-Byte. The subduction velocities inside a prescribed 3-D constrained volume of the oceanic lithosphere are given based on the kinematic plate subduction modeling method and the MORVEL plate motion data. The observation of surface heat flow and Curie point depths are used to constrain the model thermal regime. The geophysical calculation is ensured after the subduction thermal regime reaches a steady state. Data are deposited in the TPDC repository, which has granted a persistent identifier https://data.tpdc.ac.cn/en/disallow/8b266d22-fea7-4259-9a5f-8ac0bd9e7869/. Data include (1) paraview_eq_USGS.vtk (earthquake catalog by IRIS, 2000-2010, Trabant et al., 2012), (2) paraview_slab.vtk (3-D thermal regime, slab water content and slab dehydration), (3) paraview_volcano.vtk (global volcanoes at NCEI, Siebert et al., 2010), and (4) paraview_map.vtk (coastline, GMT).

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Specifications Table

| Subject                        | Geophysics                                      |
|--------------------------------|-------------------------------------------------|
| Specific subject area          | Geodynamic numerical modeling                   |
| Type of data                   | Paraview vtk files data                          |
| How the data were acquired     | The data was acquired through 3-D numerical thermal modeling which was developed from originally code stag3d. An anelastic liquid approximation and the equations of conservation of mass, momentum, and energy are used in this model. Based on a three-dimensional thermomechanical model (Ji et al. [1,2]) and the collect earthquake catalog from IRIS [3], the data of the slab thermal state, water content, and slab dehydration distribution in Alaska are calculated. |
| Data format                    | Paraview data format: vtk files                  |
| Description of data collection | The data coordinates are temporarily an orthogonal coordinate system, where the origin of the coordinates is (155.0 °W, 54.9 °N), the x+ azimuth is 150 degrees clockwise from the north, the y+ azimuth is 60 degrees clockwise from the north, and the z+ direction is vertical downward, in kilometers. The data source method is a three-dimensional finite-difference numerical simulation. The geophysical calculation is ensured after the subduction thermal regime reaches a steady state. The temperature field error range is ±10 degrees Celsius, and the velocity field error range is ±0.1 cm/yr. This data can be used to further analyze the geophysical field of the subduction zone. |
| Data source location           | Country: USA-Alaska                             |
|                                | Latitude and longitude for collected data:172 °W-140 °W, 49 °N-65 °N                                      |
| Data accessibility             | TPDC repository                                  |
|                                | [https://data.tpdc.ac.cn/en/disallow/8b266d22-fea7-4259-9a5f-8ac0bd9e7869/](https://data.tpdc.ac.cn/en/disallow/8b266d22-fea7-4259-9a5f-8ac0bd9e7869/) |
| Related research article       | Qu, R., Ji, Y., Zhu, W. (2021). Variations in wedge earthquake distribution along the strike underlain by thermally controlled hydrated megathrusts. Applied Sciences, 11, 7288. [https://doi.org/10.3390/app11167268](https://doi.org/10.3390/app11167268) |

Value of the Data

- The data provide meaningful referential thermal regime, water content, and slab dehydration rate in Alaska for those who are interested.
- The data can be used to analyze the regional geophysical field of the subduction zone.
- Researchers from various disciplines of geoscience may take advantage of these data in 3-D model tests and 3-D exhibitions.
- Investigation of the 3-D hydrothermal regime could be helpful to understand the relationships between the seismic risks and subduction tectonics in Alaska.

1. Data Description

The data in Paraview format (vtk files) include the attributes of x, y, z coordinates, temperature (°C), water content (wt%), dehydration rate (wt%/km), and subduction velocity field (cm/yr) of the subducted plate and the distribution of the coastline and volcano in the model region. The coordinate data are in an orthogonal coordinate system, where the origin of the coordinates is (155.0 °W, 54.9 °N), the x+ azimuth is 150 degrees clockwise from the north, the y+ azimuth is 60 degrees clockwise from the north, and the z+ direction is vertical downward, in
kilometers. The error range of the temperature field and velocity field is ca. ±10 degrees Celsius and ±0.1 cm/yr, respectively.

The data source method is a three-dimensional finite-difference numerical modeling method. Through 3-D numerical simulation of the thermal regime and water content of the Alaskan subduction zone, it becomes feasible to incorporate the 3-D geometric data of the incoming plate, which are updated through seismic tomography (Slab2) [4], and the real subduction velocities from the MORVEL [5] and NNR-MORVEL56 [6] datasets. The age data of the subducted plate are obtained following the oceanic seafloor age, which is estimated by the trenchward model boundary based on EarthByte [7]. The model dimensions are 1600 km × 800 km × 400 km (along-arc length × across-arc length × depth) and 80 × 80 × 100 grids (Fig. 1). The incoming oceanic plate is composed of a MORB layer at the top with a thickness of 17 km underlain by an ultramafic rock layer [8]. The oceanic lithosphere thickness is estimated according to Yoshii [9]. The temperature boundary condition agrees with the plate cooling model [10]. The bottom of the slab and the perpendicular plane are prescribed as adiabatic and permeable, and the top surface is set to be a fixed temperature (0 °C) and rigid (Fig. 1).

The subduction velocities inside a prescribed 3-D constrained volume of the oceanic lithosphere are given based on the kinematic plate subduction modeling method [1,2]:

![Fig. 1. The model settings and boundary conditions for the model. The seismic events are plotted in spheres. Cones indicate active arc volcanoes [11].](image)
\[ v_x(x, y, z) = \frac{-2a(x, y)b(x, y)v_y + \sqrt{(2a(x, y)b(x, y)v_y)^2 - 4[a(x, y)^2 + 1][a(x, y)^2 + 1]v_y^2 - v_x^2}}{2[a(x, y)^2 + 1]}, \quad (1) \]

\[ v_y(x, y, z) = v_y, \quad (2) \]

\[ v_z(x, y, z) = a(x, y)v_x + b(x, y)v_y, \quad (3) \]

while

\[ a(x, y) = \frac{1}{2} \{Z(x + \Delta x, y) - Z(x - \Delta x, y)\} \cdot \frac{z_{\text{max}}}{x_{\text{max}}} , \quad (4) \]

\[ b(x, y) = \frac{1}{2} \{Z(x + \Delta x, y + \Delta y) - Z(x + \Delta x, y) + Z(x - \Delta x, y) - Z(x - \Delta x, y - \Delta y)\} \cdot \frac{z_{\text{max}}}{y_{\text{max}}}. \quad (5) \]

Here, \( v \) is the subduction velocity, and \( \Delta \) is the interval between two neighboring nodes along the axes. \( x_{\text{max}}, y_{\text{max}}, \) and \( z_{\text{max}} \) indicate the model lengths along the \( x-, y-, \) and \( z- \)axes, respectively.

According to Omori et al. [12] (MORB) and Hacker et al. [8], a P–T-wt%-facies database is established with a P–T grid interval of 0.04 GPa (1.2 km) and 5 °C. The temperature and pressure data at every P–T grid point are calculated from our 3-D thermomechanical model. The pressure (GPa) at every grid point is obtained by converting its depths (km) through PREM (preliminary reference earth model) parameters. Using the temperature and pressure provided by the numerical simulation, both each facies domain and the corresponding water content (wt%) at every grid are estimated. Through the interpolation method, the intraslab water content distribution (wt%) at various depths is then obtained.

Using the change in rock saturation water content (wt%) via a distance (km) in the subduction direction between neighboring grids, the inner-slab slab dehydration (wt%/km) is calculated. The slab is prescribed to be divided into \( >70 \) layers according to the mesh number, with the layer surface parallel to the plate interface. Then, the water content at a point on a layer surface was calculated from the water content at the grids surrounding this point through an interpolation method. Thus, the water content at each point on every layer surface is obtained. Next, the water content value difference between two neighboring points in the subduction direction is divided by the point distance (which can be derived using the horizontal distance and vertical distance), and then slab dehydration at each point on a layer can be obtained. Based on these steps, the intraslab dehydration distribution is well calculated. Slab minerals vary in saturation at each subduction stage. Thus, slab dehydration (wt%/km) reflects the efficiency of fluid production by crystalline breakdown and fluid relaxation during subduction.

### 2. Experimental Design, Materials and Methods

Aiming to investigate the in situ along-strike slab thermal variation on megathrusts and the geographically distributed hydrothermal state, a 3-D thermomechanical model was constructed based on code Stag3D [13] and the finite difference method. In this model, an anelastic liquid approximation and the equations of conservation of mass, momentum, and energy [1,2] are used:

\[ \nabla \cdot \{ \rho_s(z, T_s) \mathbf{v} \} = 0, \quad (6) \]

\[ -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} - \delta_{ij} \rho_s g \alpha_0 (T - T_s) = 0, \quad (7) \]
where $P$ is the pressure deviation from hydrostatic pressure, $\alpha_0$ is the reference thermal expansivity, $\tau_{ij}$ ($i, j = 1, 2, 3$) is the stress tensor, and $\delta_{ij}$ is the Kronecker delta. The energy equation includes the advection term, thermal diffusion term, viscous dissipation term, adiabatic heating term, and radioactive heating term. The main model parameters are tabulated in Table 1.

The viscous flow law for wet olivine [14] following laboratory experiments is included in the model. The deformation of olivine occurs by both diffusion creep ($df$) and dislocation creep ($ds$), where each mechanism accommodates a portion of the total strain rate [15]:

$$\dot{\varepsilon}_t = \dot{\varepsilon}_{df} + \dot{\varepsilon}_{ds}. \quad (9)$$

The composite upper mantle viscosity for deformation at constant stress is

$$\eta_{\text{comp}} = \frac{\eta_{df} \eta_{ds}}{\eta_{df} + \eta_{ds}}. \quad (10)$$

Here, $\eta_{df}$ and $\eta_{ds}$ represent the diffusion creep and dislocation creep viscosities for olivine. The viscosity law is

$$\eta_{df, ds} = \left( \frac{d^p}{A_0 C_{OH}^r} \right) V \left[ \frac{\dot{\varepsilon}_E^{\frac{1}{2}}} \right] \left( \frac{E_0 + P V_0}{n_o R T_a} \right), \quad (11)$$

where $\dot{\varepsilon}_E = \left( \frac{1}{2} \dot{\varepsilon}_{ij} \dot{\varepsilon}_{ij} \right)^{\frac{1}{2}}$ is given by the square root of the second invariant of the strain rate tensor reported by Ranalli [16], $A_0$ is the preexponential factor, $d$ is the grain size, $p$ is the grain size exponent, $C_{OH}$ is the OH concentration ($H/10^6Si$), $r$ is the $C_{OH}$ exponent, $n$ and $n_0$ are the stress exponents, $E_0$ is the activation energy, $V_0$ is the activation volume, $T_a$ is the temperature, including the adiabatic temperature gradient ($3 \times 10^{-4}$ K/m), $R$ is the gas constant, and $P_l$ is the lithostatic pressure [17]. The trenchward thermal structure follows the global depth and heat
(GDH1) model [10]:

$$T(z, t_{oc}) = T_m \left[ \frac{z}{d_0} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin \left( \frac{n\pi z}{d_0} \right) \exp \left( -\frac{n^2 \pi^2 \kappa t_{oc}}{d_0^2} \right) \right]$$

(12)

The time-dependent thermal boundary condition includes the initialization time. $T(z, t_{oc})$ is the temperature at depth $z$ and plate age $t_{oc}$ along the trench, $T_m$ is the lithospheric basal temperature, $\kappa$ is the thermal diffusivity, and $d_0$ is the depth for adiabatic heating. Considering that the youngest seafloor age of the trench is at least 30 Ma, the subduction duration is formulated to be at least $\geq 20$ Myr to ensure a steady thermal state with a temperature variation $<10 \, ^\circ\text{C}$ over time.

The dominant rock type in the mantle wedges and the uppermost oceanic mantle consists of ultramafic mantle rocks as harzburgite (olivine + orthopyroxene) represents, and depleted theralzolite (olivine + orthopyroxene + clinopyroxene) is considered subordinate [8]. Seismological studies support the hypothesis that harzburgite represents the principal rock type in the upper mantle. The observed P wave speeds from White et al. [18] for oceanic lower crust and mantle compared with P wave speeds for various rocks at 200 MPa [8] indicate that most oceanic uppermost mantle (suboceanic mantle) velocity measurements are best explained in terms of spinel harzburgite mantle composition. For the above reasons, in our petrological modeling approach, harzburgite is assumed to be the dominant ultramafic rock.

The surface heat flow and Curie depth are correlated, following a theoretical thermal conduction relationship:

$$Q_s = K \frac{T_c - T_0}{Z_b - Z_s} + h_r^2 H_0 \frac{Z_b - Z_s}{Z_b - Z_c} + h_r H_0 e^{-\frac{Z_s}{H_r}}$$

(13)

where $Q_s$ is the surface heat flow, $T_c$ is the Curie temperature at the Curie depth $Z_b$, $T_0$ is the temperature at the surface elevation $Z_s$, $K$ is the average thermal conductivity of the magnetic layer, $H_0$ is the heat production rate at the surface, and $h_r$ is the characteristic drop-off of heat production. The equation shows a nonlinear inverse relationship between heat flow and $Z_b$ [17]. High heat flow measurements tend to correlate with small Curie depths, and vice versa. Synthetic modeling suggests that the largest error in estimated Curie depths using the linearized centroid method will not reach 35%, and the uncertainty of the surface heat flow is expected to be $< 20$ mW/m² due to selected fractal exponent and wavenumber bands for linear regressions and observed surface heat flow in plate convergence zones.

The model is constrained by observations of surface heat flow from the global heat flow database [19] and heat flow values from Curie point depth estimates [20]. The resolution was tested and showed that the temperature variance was $< 10 \, ^\circ\text{C}$ when the mesh size exceeded $80 \times 80 \times 100$. To investigate the robustness of the model, sensitivity tests are performed, and the mantle viscosity varies from $0.9 \times 10^{20}$ Pa s to $1.1 \times 10^{20}$ Pa s and mantle density varies from 3250 kg/m³ to 3350 kg/m³. Thus, the benchmark model is presented as deviations from the reference models ($\Delta T$ and $\Delta H_2O$) at different depth levels within the subducted oceanic plate. The tests show that mantle density variations ($\pm 50$ kg/m³) induce small temperature variations of $<10 \, ^\circ\text{C}$ at depths. The model settings combine the simulation methods used in circum-Pacific convergence zones, such as the reconstruction of oceanic-continental cold subduction in Japan [1]. Based on thermomechanical models, the three-dimensional hydrothermal data of various subduction zones, including Alaska, can be obtained.

Ethics Statements

The data have no personal information or institutional references that may compromise the privacy of any parties. It is entirely anonymous; therefore, no ethical implications should be declared.
CRediT Author Statement

Yingfeng Ji: Conceptualization, Methodology, Software, Data curation, Validation, Writing – review & editing, Supervision; Rui Qu: Writing – original draft, Visualization, Investigation; Weiling Zhu: Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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