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101 geodynamic modelling: how to design, interpret, and communicate numerical studies of the solid Earth

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Glossary

adiabatic heating A heat-producing mechanism that describes how the temperature of the material changes when it is compressed or when it expands (due to changes in pressure), assuming that no energy is exchanged with the surrounding material during this process (i.e., the process is adiabatic).

analogue modelling Modelling performed in a laboratory with real-world materials such as sand or silicone acting as substitutes for Earth materials (Schellart and Strak, 2016).

analytical solution Exact solution obtained by mathematically solving a system of equations.

Anelastic Liquid Approximation (ALA) An approximation to the equations of mass, momentum, and energy, commonly used in compressible mantle convection models. It assumes that lateral density variations are small relative to a reference density profile and can be neglected in the mass and energy conservation equations.

Argand number Non-dimensional number (Ar) representing the ratio of the stress arising from crustal thickness contrasts (vertical stress) to the stress required to deform the material at ambient strain rates (horizontal stress) (Houseman and England, 1986; England and McKenzie, 1982). It is commonly used in mountain building dynamics as a measure of the tendency of an orogen to collapse under its own gravitational potential energy.

benchmark A standardised test that acts as a reference against which other codes may be compared or assessed. Generally, the main aspect to compare against is code performance, but in geodynamics, model results and diagnostics can also be compared against established benchmarks.

boundary condition Boundary conditions are descriptions of (part of) the solution variables (e.g., velocity) at the boundaries of the model domain necessary to solve the system of equations. They can vary in time and space. Typical geodynamical model setups require boundary conditions for velocity and/or stress and temperature.

boundary element method (BEM) Numerical computational method of solving partial differential equations which have been formulated as integral equations over the domain boundary. It is applicable to problems for which Green's functions can be calculated.

Boussinesq approximation (BA) An approximation to the equations of mass, momentum, and energy, commonly used in incompressible models of convection or lithosphere dynamics. It assumes that density variations are so small that they can be neglected everywhere except in the buoyancy term in the momentum equation. In the buoyancy term, density may vary with respect to a constant reference temperature.

Byerlee's law A description of the shear stress that is required for rocks to slide against each other, and how much it increases with increasing normal stress or pressure, which can be expressed by the **friction coefficient**. Byerlee's law can be used to describe tectonic fracturing using **plasticity** laws, assuming that the frictional sliding of rocks against each other

occurs on preexisting micro-fractures in the rock (Burov, 2011). Originally derived from small-scale laboratory samples, it has been shown that Byerlee's law can be safely upscaled to crustal conditions Townend and Zoback (2000); something which is not straightforward for most geodynamically relevant parameters.

Cauchy boundary condition A type of boundary condition where both the Dirichlet and Neumann boundary condition are applied simultaneously by specifying both the solution and its normal derivative.

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chequerboard pressure pattern Artificial pattern of the pressure field obtained by solving the Stokes equations that resembles the colour distribution on a chequerboard, and is caused by specific numerical solution methods rather than physical processes. The discontinuous pressure field obtained with $Q1 \times P0$ elements often features this pattern before smoothing.

community benchmark Verification test that compares the results for a given physical model and model setup using different codes and numerical applications within a community to ensure cohesive results across the community.

community software A software package developed and maintained through a collaborative effort of multiple people.

compositional fields methods Eulerian numerical techniques that allow for tracking field quantities by solving an advection equation for each field usually using the same method as for solving the energy conservation equation.

diffusion creep A mechanism of viscous deformation of rocks in the Earth's interior, facilitated by the motion of imperfections in the crystal lattice - single atoms or vacancies (i.e., places in the crystal lattice where an atom is missing) - through mineral grains, which accumulate to large-scale deformation over time. Diffusion creep is assumed to be the dominant deformation mechanism in the lower mantle.

direct method Class of methods used in geodynamics to solve the linear system of equations in a finite number of operations obtained after discretising the partial differential equations. Typically robust, these methods give an exact solution barring numerical rounding errors, but are often memory intensive (Braun et al., 2008; Eijkhout, 2013).

Dirichlet boundary condition A type of boundary condition that specifies the value of the solution of an equation at the boundary, such as prescribing a zero velocity (no slip) boundary condition.

discrete element method (DEM) Family of numerical methods for computing the motion of a large number of small particles which are in contact with each other (Matuttis and Chen, 2014).

dislocation creep A mechanism of viscous deformation of rocks in the Earth's interior, facilitated by the motion of imperfections in the crystal lattice - lines of atoms or line defects - through mineral grains, which accumulate to large-scale deformation over time. This migration is highly sensitive to the stress applied to a rock. Dislocation creep is assumed to be an important deformation mechanism in the upper mantle. As the creep behaviour can be described by a power law dependence of the strain rate on the differential stress (e.g., Hirth and Kohlstedt, 2003; Karato, 2008), it is sometimes referred to as power law creep.

DOI (Digital Object Identifier) A unique and permanent digital object identifier, standardised by the International Organization for Standardization (ISO) and commonly used for scientific publications, software, data, and artwork.

drunken sailor A numerical instability that arises in models with a free surface and large density contrasts directly below it, where the chosen time step is too large to accurately reproduce changes in surface boundary elevation, which yields a sloshing behaviour.

Ekman number Non-dimensional number (Ek) representing the ratio of the viscous forces to the Coriolis forces.

equation of state The equation describing the state of a material under given physical conditions. In geodynamic models, the equation of state is commonly used to express how the density depends on temperature and pressure and sometimes other variables, such as chemical composition. This relation is needed to solve the governing equations for deformation in the Earth.

extended Boussinesq approximation (EBA) An approximation to the equations of mass, momentum, and energy, commonly used in incompressible models of convection or lithosphere dynamics. It is based on the same assumptions as the **Boussinesq approximation**, but additionally considers adiabatic and shear heating. As such, the reference temperature varies with depth.

FAIR Data principles that stand for and promote Findability, Accessibility, Interoperability, and Reusability of data.

finite difference method (FDM) Widely used numerical method that solves ordinary differential and partial differential equations by approximating the derivatives with finite differences in both space and time.

finite element method (FEM) Widely used numerical method for solving problems in geodynamics, engineering, and mathematics. The FEM subdivides a large system into smaller parts called elements and formulates the ordinary differential or partial differential equations on these, which ultimately results in a linear system of equations.

finite volume method Numerical method to solve partial differential equations in which volume integrals in a partial differential equation which contain a divergence term are converted to surface integrals using the divergence theorem. These terms are then evaluated as fluxes at the surfaces of each finite volume.

fixed-point (Picard) iteration An **iterative method** for dealing with nonlinearities in the governing equations. The method starts by guessing an approximate solution. It then improves the solution in each nonlinear iteration by using the current approximate solution to compute the solution-dependent coefficients and solving the linear system, obtaining the approximate solution for the next iteration. The process is repeated until the left-hand side and the right-hand side of the linear system match up to a given tolerance that is often called the 'nonlinear tolerance'.

free slip A type of boundary condition for the Stokes equations in which the velocity component normal to the boundary and the stress parallel to the boundary are set to zero. This combination allows for flow along, but not through, the boundary.

free surface A type of boundary condition for the Stokes equations in which the stress acting on the boundary is zero.

friction coefficient A material property that describes how much the shear stress required for plastic deformation increases with increasing normal stress or pressure. See also **Byerlee's law**.

generic modelling Modelling of a certain geodynamic system (e.g., based on a general observation) to better understand the system's general behaviour. This often includes modelling different regimes of behaviour.

geodynamics A discipline of physics concerned with forces acting on a body and the subsequent motions they produce in the Earth and other planetary bodies.

git Open source distributed **version control software** available at git-scm.com.

grain boundary sliding A mechanism of viscous deformation of rocks in the Earth's interior, facilitated by grains sliding against each other along grain boundaries. Grain boundary sliding becomes important at high temperatures and high stresses.

grid point Points in the spatial domain of the model where the numerical solution is computed. The collection of grid points make up the grid or mesh.

half-space cooling model Analytical expression for the temperature as a function of time and depth in the case that a semi-infinite constant temperature lithosphere is suddenly subjected to a different temperature at the surface (Jaupart and Mareschal, 2011).

hand of god A modelling approach where a specific feature is imposed artificially by the modeller, rather than developing self-consistently in the model (e.g., Glišović et al., 2012). Examples are prescribing plate velocities at the surface boundary, or weak zones at plate boundaries.

hello world A computer program that outputs or displays the message 'Hello, World!'. It is a simple sanity test to illustrate the basic syntax of a programming language and check that it is correctly installed and used. A parallel 'Hello world' test outputs a message from each **processor**.

hero code A code predominantly written and maintained by a single person.

IMRAD Acronym for Introduction, Methods, Results, And Discussion/conclusion, which stands for the structure of scientific articles adopted by the majority of scientific journals.

initial condition Imposed physical starting conditions required to solve time-dependent equations like the temperature and other advection equations. They specify the initial values of the solution parameter, e.g., temperature, throughout the model domain.

initial perturbation Perturbation of a field imposed by the user to trigger a physical instability (typically for buoyancy-driven models). This is often applied to the initial temperature field in the form of a harmonic perturbation or noise with a user-defined amplitude.

inner core dynamics The motion within the Earth's solid iron–nickel inner core and the forces causing this motion.

internal heating A heat-producing mechanism that is intrinsic to a specific material, and not related to its motion. In geodynamics, this would be the decay of radiogenic elements, i.e., radiogenic heat production.

iterative method A class of mathematical methods that solves a problem by starting from an initial guess, and then improving the solution iteratively, i.e. by repeatedly applying a given solution method to the problem with each new approximate solution being based on the solution of the previous step. In numerical geodynamic modelling, iterative methods are often used to solve the large linear system that arises from discretising the equations.

Knudsen number Non-dimensional number (Kn) representing the lower limit in length scale where the **Navier–Stokes equations** are relevant and the transitions to other forms of transport in micro- to nanoscale flow channels. It is defined as the ratio of the mean-free-path of molecules (i.e., the average distance travelled by a moving particle between successive impacts) to the macroscopic length scale of the pore space.

level-set method Numerical technique that allows for tracking interfaces. The basic idea is that the location of the interface is defined as the zero level set of a field ϕ defined over the domain of interest.

linear stability analysis A method that can be used to analyse the behaviour of nonlinear systems, specifically, how they evolve from a given initial condition when small perturbations are added to it. The analysis involves linearising the equations (sometimes around an equilibrium), so that they can be solved analytically.

Mach number Non-dimensional number (M) representing the ratio of the velocity of material flow to the speed of sound in a given medium.

mantle convection Thermally and/or compositionally driven slow creeping motion of Earth's solid silicate mantle forming convection currents across various scales that carry heat between the interior of the Earth and the surface.

marker-chain method Numerical technique that tracks interfaces by means of Lagrangian markers placed on them at the beginning of the simulation.

Maxwell relaxation time A characteristic time that describes the relative importance of viscosity and elasticity as the response of a material to applied stresses. On timescales that are larger than the Maxwell time, a material predominantly behaves like a viscous fluid, whereas on timescales smaller than the Maxwell time, a material behaves elastically. The Maxwell time is of the order of 450 years for the Earth's mantle.

mesh smoothing Repositioning the nodes of a mesh based on local information to improve the mesh quality.

method of manufactured solutions (MMS) General procedure for generating an analytical solution for code accuracy **verification**. The basic idea is to manufacture an exact solution for the system of equations and then use it to verify the code, without being concerned about its physical realism.

mixed boundary condition A type of boundary condition where Dirichlet, Neumann, and/or Robin boundary conditions are applied to specific parts of the same boundary, e.g. constant velocity Dirichlet conditions on the upper part of a vertical boundary mimicking plate velocity and open Neumann conditions on the mantle below.

model Simplified representation of a natural system.

model setup The result of the modeller's choice of **physical model**, the corresponding **numerical model** and the parameters defining the model domain, time, and initial and boundary conditions.

model simulation (model runs) The actual computations performed with the **numerical code**. Each simulation that starts with a different **model setup** can potentially produce different model results.

MPI (Message Passing Interface) Message-passing standard designed to function on a wide variety of parallel computing architectures. MPI is a standard commonly used to run geodynamic modelling codes in parallel on distributed memory systems.

Navier–Stokes equations Equations describing the motion of a **viscous fluid** under the influence of gravity in a more general form than the **Stokes equations**, including both viscous and inertia forces. The equations cover conservation of mass and momentum.

Neumann boundary condition A type of boundary condition that specifies the value of the derivative of the solution. Specifying the stress is a Neumann condition, as stress is related to the velocity through its derivatives.

Newton iteration An **iterative method** for dealing with nonlinearities in the governing equations (e.g., Fraters et al., 2019a). It introduces the residual $\boldsymbol{r} = \boldsymbol{A} \cdot \boldsymbol{X} - \boldsymbol{b}$ of the linear system, which needs to be minimised. This is done by finding the roots of its derivative and requires computing the Jacobian $\boldsymbol{J}$ of the residual (a matrix containing all its first-order partial derivatives with respect to the solution variables), and solving $\boldsymbol{J}\delta\boldsymbol{X} = -\boldsymbol{r}$ for $\delta\boldsymbol{X}$. Note that this implies that the linear

system is being solved for the update $\boldsymbol{\delta X}$ to the solution of the original problem in each nonlinear iteration (and not the solution itself).

Newtonian fluid A viscous fluid with a linear relation between the stress and the rate of deformation (strain rate). In geodynamic modelling, the rheology of mantle rocks is sometimes approximated as that of a Newtonian fluid, because there is a linear relation between stress and strain rate if rocks deform by **diffusion creep**.

no slip A type of **Dirichlet boundary condition** for the Stokes equations in which the velocity is fixed to zero at the boundary. It is a special case of **prescribed velocities**. This boundary condition is often used to mimic the 660 km depth discontinuity at the bottom boundary of asthenospheric-scale models.

nonlinear In a nonlinear system, the reaction or output of the system is not proportional to the input, i.e., the relation between input and output is not linear. In a system of (partial differential) equations, as considered in geodynamic modelling, this means that any of the unknown variables (in our case, velocity, pressure, temperature, and in some cases other advected quantities) appear in the equations in a form that is not of polynomial degree one (e.g., a higher polynomial degree, or a different relationship, like an exponent). This often occurs when material properties depend on the unknown variables.

numerical code Software that in the context of geodynamics solves the governing equations (usually conservation of momentum, mass, and energy) based on a **numerical model**.

numerical implementation The process of putting the physical/mathematical model into computer language as a series of numerical routines.

numerical model The representation of a mathematical or **physical model** on a computer.

numerical modelling Simplified representation of a natural system based on physical principles that is performed on a computer. This involves using numerical methods to find solutions to, or analyse, the equations that make up a mathematical or **physical model**.

Nusselt number Non-dimensional number (*Nu*) representing the relative efficiency of convective heat transport. It describes the ratio of the total heat flux in the presence of convection (i.e., heat advection and conduction combined) to the heat flux in the absence of convection (i.e., heat conduction only). Earth's mantle is characterised by $Nu \approx 10-100$, meaning that the convection of heat is much more efficient than the conduction of heat.

open boundary In the geodynamics context, a type of Neumann boundary condition for the Stokes equations in which the lithostatic pressure used to prescribe the normal component of the traction on the boundary, allowing for material entering and leaving the domain based on the over-pressure.

OpenMP (Open Multi-Processing) An application programming interface that consists of a set of compiler directives, library routines, and environment variables that support the parallelisation of codes running on **shared memory systems**.

parameter space The parameters and their range of values that are tested in a - in this case geodynamic modelling - study.

parameter study A geodynamic modelling study focused on determining the dependency of the model solution and evolution on the parameters under investigation. Typically, the value of one or more parameters is varied systematically (see **parameter space**) and the resulting model behaviour is analysed for corresponding trends.

particle-in-cell (marker-in-cell) Numerical method to solve the advection equation, which relies on individual Lagrangian particles that are tracked throughout the computational domain.

Peclet number Non-dimensional number (Pe) representing the ratio of heat diffusion to heat advection timescales in a fluid transporting mass and heat.

Peierls creep A mechanism of viscous deformation of rocks in the Earth's interior with a very strong, exponential dependence on the stress applied to a rock (also called 'low-temperature plasticity'). It is inferred to apply when creep is controlled by glide of dislocations (line defects) through mineral grains.

periodic boundary condition Type of boundary condition that does not explicitly prescribe any part of the solution. Instead, it 'links' boundaries together to approximate a larger (or infinite) system of which the model setup is merely a part: any materials or flows passing through one boundary interface re-enter the model domain through the opposite boundary interface.

physical model A conceptual **model** of a natural process or system, based on the laws of physics. These models generally use equations to approximate the natural behaviour.

physical or mathematical modelling The process of approximating a natural system or process by developing a mathematical or **physical model**. In geodynamics, the mathematical descriptions follow the laws of physics, and physical and mathematical modelling can be considered to mean the same.

plane strain assumption Assumption that the strain in the direction perpendicular to the applied stresses equals zero. It is often used in 2-D Cartesian models of the lithosphere.

plasticity Non-elastic and non-recoverable deformation of materials characterised by a yield criterion. Once local stresses reach the yield strength of a material, it starts to deform plastically. In geodynamic modelling, plasticity is commonly used to describe brittle deformation, specifically, tectonic fracture/failure in shear. There are various different failure criteria used to model brittle behaviour, such as the Mohr-Coulomb failure criterion.

plate cooling model Analytical expression for the temperature as a function of time and depth in the case of a lithosphere of finite thickness and subjected to a constant temperature at the bottom and top (McKenzie, 1967).

Prandtl number Non-dimensional number (Pr) representing the ratio of momentum diffusivity (η/ρ) to thermal diffusivity in a fluid. It depends on the properties of the fluid, namely its viscosity, specific heat, and thermal conductivity. The Prandtl

number is approximately 10^{25} for Earth's mantle. Consequently, a common approximation for mantle and lithosphere models is the 'infinite Prandtl number' approximation, which eliminates inertia effects from the governing equations.

prescribed stresses A type of **Neumann boundary condition** for the Stokes equations in which the stress at the boundary is prescribed, for example to mimic ridge push on a plate moving into the domain.

prescribed velocities A type of **Dirichlet boundary condition** for the Stokes equations in which the velocity is prescribed, for example to define the plate motions along the top the model. Also called kinematic or in-/outflow boundary conditions.

processor Electronic circuitry in a computer that executes instructions given by a computer program. Also called central processing unit (CPU).

quadtree A data structure which partitions a 2-D model domain by recursively subdividing cells into four quadrants or regions ('children'). How often each cell is subdivided can vary cell by cell, so that relevant areas are subdivided more often (leading to smaller cells). An octree is the 3-D analogue where each cell is subdivided into 8 children cells.

radial basis function method (RBF method) Numerical method based on real-valued functions whose values depend only on the distance between the input and some fixed point.

Rayleigh number Non-dimensional number (*Ra*) representing the ratio of heat conduction to heat convection timescales. For a system with given boundary conditions and geometry, a value for a critical Rayleigh number, Ra_{critical}, exists that marks the transition from pure conduction to fluid convection as the dominant mode of heat transfer.

regime diagram Commonly the synthesis of analysing the results of a **parameter study** that shows how the individual models' behaviour can be grouped into several regimes (e.g. slab retreat, slab advance and slab stagnation in a subduction model), with the studied parameters on the axes of the diagram.

remeshing Manipulating the mesh in numerical methods to improve its quality by minimising skewness and/or element aspect ratios.

replicable Results of a prior study can be duplicated with new data and tools (e.g., codes) (Bollen et al., 2015; Goodman et al., 2016). Not to be confused with **reproducible**.

reproducible Results of a prior study can be duplicated with the same data and tools (e.g., codes) (Bollen et al., 2015; Goodman et al., 2016). Not to be confused with **replicable**.

resolution test Investigation of the changes in the model outcome with varying resolution. Ideally, the model outcome (i.e., solution) converges with the differences in solution decreasing with increasing resolution (i.e., smaller grid size).

Reynolds number Non-dimensional number (*Re*) representing the ratio of inertial forces to viscous forces in a flow. (Very) Low Reynolds numbers are typical of fluid flow in the mantle.

rheology The study of the deformation of matter in response to an applied force (see Ranalli, 1995; Jaeger et al., 2007).

Robin boundary condition A type of boundary condition that consists of a linear combination of the values and derivatives of the solution.

scaling analysis A technique to simplify equations by using non-dimensional numbers that combine multiple dependent variables and characterise the physical system. The goal of scaling analysis is to obtain dynamic similarity in which non-dimensional numbers can predict the behaviour of the system (i.e., systems characterised by similar non-dimensional numbers behave similarly). Also known as dimensional analysis (Barenblatt, 1996).

scientific colour maps Scientifically derived colour gradients that are perceptually uniform (i.e., do not distort the data visually), perceptually ordered (i.e., are intuitively readable), and colour-vision deficiency friendly (i.e., universally readable) to map data values to colours (Crameri et al., 2020).

shared memory systems A computer architecture with a (large) block of memory that can be accessed by several **processors**. This allows for fast communication between the different threads of a parallel program.

shear band Narrow zones of extreme shear deformation, resulting from strain localisation. In numerical geodynamic modelling, where discrete faults cannot be represented, and **plasticity** is used to approximate brittle failure, shear bands are often interpreted as faults on crustal and lithospheric scales, resulting from coalescence of preexisting micro-cracks and fractures into a single frictional shear band (fault) at sufficiently high strains (Burov, 2011).

smoothed particle hydrodynamics method (SPH method) A mesh-free Lagrangian computational method used in mechanics of continuum media, such as solid mechanics and fluid flows, astrophysics, and ballistics. The method is based on dividing the material/fluid into a set of particles with mass that interact with each other.

software management plan A well-defined plan that describes the goals in software development and management: what software will be produced and for whom, and how will this software be managed and maintained.

sparse matrix A matrix in which most of the entries are zero, which is common for matrices obtained from discretising partial differential equations. Which numerical methods are most efficient for solving a linear system depends on the properties of a matrix, including its sparsity.

specific modelling Modelling approach that aims to reproduce and understand a specific state of a certain geodynamic system (e.g., based on a direct set of observations, or with the aim of modelling a specific geographic area).

spectral methods Numerical methods to solve ordinary or partial differential equations, generally involving the use of the fast Fourier transform. The solution is expressed as a sum of certain 'basis functions' (for example, as a Fourier series), and the coefficients in the sum are computed such that they satisfy the differential equation as well as possible.

stencil a geometric arrangement of neighbouring nodes that relate to the node of interest on which finite difference derivatives are formulated.

sticky air The low-density, low-viscosity top layer sometimes present on top of a model. This layer mimics air and allows for the formation of topography. It is often used as an approximation of a **free surface**.

Stokes equations Equations describing the motion of a **viscous fluid** under the influence of gravity. The equations are valid under the assumption that compared to viscous forces, inertia forces are small and can be neglected, which is the case for the long-term deformation of the Earth on timescales of millions of years (see also **Prandtl number**). The Stokes equations are a special case of the more general **Navier–Stokes equations**.

stress tensor A tensor, consisting of 9 components in 3D, that completely defines the stress (force per unit area). The 9 components are needed because the tensor not only defines the direction of the force acting on a surface, but also the orientation of this surface.

strong scaling A method for quantifying the parallel performance of a code. It describes how the solution time varies with the number of **processors** for a fixed problem size defined by the number of unknowns.

svn (subversion) A free, open source **version control software** from Apache Software Foundation.

test Steps or programs intended to establish the quality, performance, or reliability of a code, especially before it is taken into widespread use.

thermal diffusivity Thermal property of a material representing the rate of transfer of heat of a material from hot to cold areas, defined by the thermal conductivity divided by density and specific heat capacity at constant pressure.

thermodynamic potentials Scalar quantities used to describe the thermodynamic state of a system, e.g., the internal energy, Helmholtz free energy, Gibbs free energy, enthalpy, and the Landau potential.

Truncated Anelastic Liquid Approximation (TALA) An approximation to the equations of mass, momentum, and energy, used in compressible mantle convection models. It is based on the same assumptions as the **Anelastic Liquid Approximation**, but further assumes that changes in density due to pressure variations can be neglected in the buoyancy term in the momentum equation as well.

unit test Generally automated test to ensure that a section of an application (known as the 'unit') meets its design and behaves as intended. The unit can be an individual function or procedure, but can also extend to the whole module or object.

validation Testing of the equations against observations to confirm that the right equations are solved. Not to be confused with **verification**.

verification Testing of whether the equations are implemented and solved correctly. Not to be confused with **validation**.

version control software System responsible for managing and tracking changes to codes, enabling easier and less error-prone collaboration on codes.

viscous dissipation (shear heating) A heat-producing mechanism that describes the amount of energy released as heat due to friction when material is deformed viscously and/or plastically. Also sometimes called shear heating, as kinetic energy is transformed to heat due to shearing.

viscous fluid A material that deforms as a continuum, without the formation of gaps (e.g., bubbles), with a predominantly viscous rheology. For a viscous rheology, the stresses are proportional to the rate of deformation (strain rate) in the material, and deformation is irreversible. In geodynamic models of the mantle and lithosphere, it is often assumed that rocks deform like viscous fluids (although other deformation mechanisms also play an important role), and the **Stokes equations** can be used to describe their mass and momentum balance.

viscous isentropic relaxation timescale The time necessary to expand (or contract) regions of excess (or deficit) pressure against viscous constraints (e.g., the characteristic timescale of postglacial rebound). In the Earth, this timescale is on the order of a few hundred years for the upper mantle to a few tens of thousands of years for the lower mantle.

visualisation pitfalls Inaccurate representation of data, thus leading to miscommunication of data, by altering the impression of actual local data magnitudes and gradients, or making the data graphically inaccessible to parts of the readership.

volume-of-fluid method A Eulerian numerical technique for tracking and locating the free surface or fluid–fluid interface.

weak scaling A method for quantifying the parallel performance of a code. It describes how the solution time varies when both the number of **processors** and the problem size (the number of unknowns) are increased by the same factor. The ideal result for this scenario is a constant solution time.

weak seed Area/volume in the domain prescribed by the user to have weak mechanical properties. It ensures that the deformation initially localises on the weak seed rather than on numerical noise and/or near boundaries.