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**Models of lithospheric subduction in 2D
Cartesian and spherical geometry**

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Title: Models of lithospheric subduction in 2D Cartesian and spherical geometry

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Abstract: This thesis investigates simplified two-dimensional models of lithospheric subduction in Cartesian and spherical geometries. The models were constructed with the Geodynamic World Builder and solved with the finite-element code ASPECT. They aimed to test the implementation of comparable subduction setups in both geometries and to study i) the effects of phase-transition strength and the rheology of the decoupling layer on slab dynamics in generic models, ii) sinking of the detached slab through the lower mantle, and iii) the effect of a more complex crustal structure of the Hellenic subduction.

The generic spherical models show that stronger plate coupling reduces rollback, while larger Clapeyron-slope magnitudes at the 410 km and 660 km phase transitions reduce total rollback, enhance slab buckling, and make slab motion more episodic. In the end-member case with strong phase-transitions and a strong interface, slab detachment occurs. Comparisons with Cartesian counterparts show that the geometries do not produce identical time-dependent evolution, especially during initialization and early subduction near the trench. However, the overall subduction style remains consistent across geometries. Slab sinking models show that spherical geometry can delay detachment, but the later sinking velocity of the detached slab fragment remains comparable to the Cartesian case. The Hellenic-type model confirms that additional plate-structure complexity does not change this overall conclusion. The results indicate that while spherical geometry is a useful improvement for large-domain subduction models implemented in ASPECT and GWB, the first-order effects are well captured in Cartesian models.

Keywords: subduction, lithospheric plates, mantle convection, numerical modelling, ASPECT, Geodynamic World Builder

Název práce: Modely subdukce litosféry ve 2D kartézské a sférické geometrii

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Abstrakt: Tato práce se zabývá zjednodušenými dvourozměrnými modely subdukce litosférických desek v kartézské a sférické geometrii. Modely byly vytvořeny pomocí nástroje Geodynamic World Builder a řešeny metodou konečných prvků v programu ASPECT. Jejich cílem bylo otestovat implementaci vzájemně porovnatelných subdukčních modelů v obou geometriích a prozkoumat i) vliv síly fázových přechodů a reologie oddělující vrstvy na dynamiku slabu v generických modelech, ii) klesání odtrženého slabu spodním pláštěm a iii) vliv složitější korové struktury helénské subdukce.

Generická sférická modelová sada ukazuje, že silnější mechanická vazba mezi deskami snižuje rollback, zatímco větší magnituda Clapeyronových sklonů na fázových přechodech v hloubkách 410 km a 660 km snižuje celkový rollback, zesiluje skládání slabu a vede k epizodičtějšímu pohybu desky. V krajním případě se silnými fázovými přechody a silným deskovým rozhraním dochází k odtržení slabu. Srovnání s kartézskými protějšky ukazuje, že obě geometrie neposkytují totožný časový vývoj, zejména během inicializace a rané fáze subdukce v okolí příkopu. Celkový charakter subdukce však zůstává napříč geometriemi zachován. Modely klesání slabu ukazují, že sférická geometrie může zpoždit odtržení slabu, ale následná rychlost klesání odtrženého fragmentu zůstává srovnatelná s kartézským případem. Model helénskému typu potvrzuje, že dodatečná složitost deskové stavby tento celkový závěr nemění. Výsledky naznačují, že ačkoli sférická geometrie představuje užitečné zlepšení pro rozsáhlé subdukční modely implementované v programech ASPECT a GWB, efekty prvního řádu jsou dobře zachyceny i v kartézských modelech.

Klíčová slova: subdukce, litosférické desky, plášťová konvekce, numerické modelování, ASPECT, Geodynamic World Builder

Contents

Introduction	8
1 Theoretical Background	11
1.1 Plate tectonics and subduction	11
1.2 Phase transitions	11
1.3 Rheology	13
1.4 Extended Boussinesq approximation and governing equations . . .	14
1.5 Model geometry and thermal structure of oceanic lithosphere . . .	16
2 Model description	19
2.1 Common setup of the generic reference models	20
2.2 Tamara: generic spherical model	21
2.3 Dobroslav: generic Cartesian model	26
2.4 Norbert: shorter-interface models	29
2.5 Vitek: Hellenic-type models with continental segments and a weak zone	30
2.6 Parameter sets	33
3 Numerical implementation	36
3.1 Coupling ASPECT and the Geodynamic World Builder	36
3.2 Material model and rheology	36
3.3 Initialization and restart strategy	37
3.4 Boundary conditions and driving velocity	39
3.5 Particles	40
3.5.1 Post-processing of particle output	41
3.6 Adaptive mesh refinement	42
3.7 Solver settings and output	43
4 Results	44
4.1 Tamara	44
4.1.1 Evolution of the Tamara model family	44
4.2 Dobroslav	47
4.3 Norbert	50
4.4 Vitek	53
5 Discussion	57
5.1 Simplified treatment of mantle phase transitions	57
5.2 Resolution and representation of the weak layer	57
5.3 Limited parameter-space exploration	58
5.4 Cartesian and spherical model geometry	59
Conclusion	61
Bibliography	63

A	Appendix	67
A.1	ASPECT parameter files	67
A.1.1	ASPECT parameter file for Tamara and Norbert_SPH	67
A.1.2	Changes for the Dobroslav and Norbert Cartesian model .	71
A.1.3	Changes for the Vitek_SPH model	72
A.1.4	Changes for the Vitek_CART model	74
A.2	Geodynamic World Builder files	76
A.2.1	World Builder file for Tamara and Norbert_SPH	76
A.2.2	World Builder file for Dobroslav and Norbert_CART	79
A.2.3	World Builder files for Vitek_SPH and Vitek_CART . . .	81

Introduction

Subduction is one of the fundamental processes controlling the long-term evolution of the Earth. It is responsible for the recycling of oceanic lithosphere into the mantle and plays a central role in the global transport of heat, mass, and chemical heterogeneities. Subduction zones are also among the most geodynamically active regions on Earth. They are associated with intense deformation, intermediate-depth and deep seismicity, arc volcanism, and large-scale mantle flow. Understanding the dynamics of subducting lithospheric plates is therefore essential for interpreting both surface observations and the structure of the Earth's interior [1, 2, 3].

The mechanical behaviour of the mantle depends strongly on the time scale considered. On short time scales, such as those relevant for the propagation of seismic waves, the mantle behaves as an elastic medium. On geological time scales of millions of years, however, mantle rocks deform by slow viscous flow. The viscosity of the mantle is high, with typical values on the order of 10^{21} Pa s and leads to mantle flow velocities of the order of centimeters per year. These velocities are comparable to the relative motions of lithospheric plates observed at the Earth's surface [4, 5].

Mantle flow is primarily driven by density variations caused by temperature differences. The Earth's interior remains hot, with temperatures of several thousand kelvin near the core–mantle boundary at a depth of approximately 2900 km, while the temperature decreases towards the surface. This unstable thermal structure gives rise to mantle convection. At mid-ocean ridges, hot mantle material rises, partially melts, and forms new oceanic lithosphere. As the newly formed lithosphere moves away from the ridge, it cools, thickens, and becomes denser. Eventually, in regions of convergence, an oceanic plate may sink beneath another plate and enter the mantle as a subducting slab [4, 1].

The thermal and mechanical evolution of a subducting slab is closely linked to its ability to deform and to transmit stresses. Because the slab is colder and stronger than the surrounding mantle, it may preserve its identity over large depths while undergoing bending, stretching, buckling, or interaction with phase transitions in the mantle transition zone. The resulting stress distribution is relevant for understanding the conditions under which intermediate-depth and deep earthquakes occur. At the same time, the thermal structure of the slab influences dehydration reactions, melting processes, and the generation of arc volcanism. The evolution of temperature and stress within subducting plates is therefore a key target of geodynamic studies [6, 7, 2, 8, 9].

Direct observations of subducted slabs are limited, but important constraints are provided by seismology. Seismic tomography uses differences in the travel times of seismic waves recorded at seismic stations to image variations in seismic wave speeds within the Earth [3, 10]. Since cold subducted slabs typically produce positive seismic velocity anomalies, tomographic models allow us to infer their geometry, depth extent, and interaction with the surrounding mantle. These observations provide essential constraints for numerical models, which can be used to test physical mechanisms that cannot be studied directly from observations alone [2, 3, 10].

Numerical modelling of mantle convection provides a way to investigate the long-term evolution of subduction systems under controlled physical assumptions. Such models solve the equations describing the conservation of mass, momentum, and energy, together with appropriate constitutive relations for the rheology of mantle and lithospheric materials. They make it possible to study how slab geometry, temperature, viscosity, phase transitions, boundary conditions, and other model parameters affect the deformation and stress state of subducting plates. For this reason, numerical models have become an important tool for connecting geological and geophysical observations with the underlying dynamics of the mantle [5, 11, 2, 7].

A wide range of numerical codes [11, 12, 13, 14] is used in the geodynamic community, differing in geometry, discretisation method, treatment of rheology, and numerical implementation. In this thesis, the models are constructed using ASPECT [15, 16, 17, 18], an open-source software package for modelling mantle convection and lithospheric dynamics. ASPECT is based on the finite element method and provides a flexible framework for solving geodynamic problems in different geometries. An important advantage of ASPECT is adaptive mesh refinement, which allows the numerical resolution to be increased in regions where it is most needed. This is particularly useful for subduction modelling, where deformation, strong temperature gradients, and stress localisation often occur in relatively narrow and moving regions.

The initial geometry of the models is defined using the Geodynamic World Builder. This tool allows complex geodynamic structures, such as lithospheric plates, slabs, and thermal anomalies, to be prescribed in a systematic and reproducible way [19, 20, 21]. In subduction models, the initial geometry and thermal structure of the slab strongly influence the subsequent evolution of the system. The combination of ASPECT and the Geodynamic World Builder therefore provides a suitable framework for constructing simplified yet physically meaningful models of subduction.

Many regional subduction models are formulated in Cartesian geometry, often in two dimensions [22, 23, 24, 25, 26]. This approach is computationally efficient and allows the first-order physical processes controlling slab deformation to be investigated in a simplified setting. However, subduction takes place on a spherical planet, and the curvature of the Earth may affect the geometry and deformation of slabs, especially when processes are considered over distances of hundreds to thousands of kilometres. Spherical geometry can therefore represent an important extension of Cartesian models and may influence the predicted evolution of temperature, viscosity structure, and slab morphology [27, 11, 28].

This thesis focuses on the implementation and comparison of two-dimensional subduction models in Cartesian and spherical geometries. The models are developed using ASPECT together with the Geodynamic World Builder to explore the capabilities of these tools for studying subduction dynamics. Particular attention is given to slab morphology, viscosity structure, plate velocities, rollback, and slab sinking. Although the stress field is not analysed as a primary output, the models use a stress- and strain-rate-dependent rheological formulation, so the effective viscosity reflects the mechanical state of the deforming lithosphere and mantle. We present here the comparison of spherical and Cartesian models in three setups: *i)* generic slab models that test effects of the strength of the shallow plate interface

and the magnitude of the Clapeyron slopes at the 410 km and 660 km phase transitions [2, 29], *ii*) models focused on slab break-off and sinking through the lower mantle [30, 10], and *iii*) models tailored to the Hellenic subduction with a complex structure of subducting plate crust [23].

1 Theoretical Background

1.1 Plate tectonics and subduction

The theory of plate tectonics provides the basic framework for understanding the large-scale evolution of the Earth's surface and upper mantle. Although the idea of continental drift had been discussed earlier, the modern concept of plate tectonics developed mainly during the 1960s. An important step was the work of Tuzo Wilson [31] who contributed to the view that the Earth's outer shell is divided into several relatively rigid plates moving over a weaker underlying layer. These plates may carry continents, ocean basins, or both.

Plate tectonics is supported by a wide range of geological and geophysical observations. Geological structures, fossil distributions, and evidence of past glaciations indicate that continents that are now widely separated must once have been connected or located in different climatic zones. Further support comes from magnetic anomalies on the ocean floor. The characteristic pattern of alternating magnetic stripes on both sides of mid-ocean ridges records reversals of the Earth's magnetic field and provides evidence for seafloor spreading. Paleomagnetic data also make it possible to reconstruct past positions of continents and plate motions.

According to plate tectonics theory, the lithosphere is divided into a number of relatively rigid lithospheric plates. These plates move over the asthenosphere, which behaves as a weak, viscous layer on geological time scales. Lithospheric plates may consist of oceanic lithosphere, continental lithosphere, or a combination of both. Their relative motion gives rise to three main types of plate boundaries: divergent, convergent, and transform boundaries.

At divergent boundaries, such as mid-ocean ridges, plates move away from each other and new oceanic lithosphere is formed. Hot mantle material rises beneath the ridge, cools, and becomes part of the newly created plate. Since the total surface area of the Earth remains approximately constant, the creation of new lithosphere must be balanced by the recycling of older lithosphere elsewhere. This occurs mainly at convergent plate boundaries, where one plate may sink beneath another and return into the mantle. The process by which one plate is forced beneath another is called subduction.

A central assumption of plate tectonics is that plates behave approximately as rigid bodies, while deformation is concentrated along their boundaries. Plate boundaries are therefore regions of intense tectonic activity, including earthquakes, volcanism, mountain building, and lithospheric deformation. Subduction zones are particularly important because they represent the main locations where oceanic lithosphere is recycled into the mantle and where strong mechanical and thermal interactions occur between the descending slab, the overriding plate, and the surrounding mantle.

1.2 Phase transitions

The Earth's mantle is composed of minerals whose stability depends on pressure and temperature. As pressure and temperature increase with depth, mantle minerals undergo changes in crystal structure. These transformations are

known as phase transitions. They are often accompanied by changes in density and by the release or absorption of latent heat.

Although the mineralogical composition of the mantle is complex, many geodynamic models describe the main phase transitions using the olivine component, one of the dominant constituents of the upper mantle. In this simplified description, the most important transitions occur in the mantle transition zone, at depths of approximately 410 km and 660 km. The transition near 410 km is associated with the transformation of olivine to its high-pressure phase wadsleyite, while the transition near 660 km is associated with the transformation of ringwoodite into bridgmanite and ferropericlase. Another transition, from wadsleyite to ringwoodite, occurs near 520 km, but its density contrast is usually less dynamically important and it is often neglected in simplified mantle-flow models.

Phase transitions are important in numerical models because they modify the density of the material and therefore affect buoyancy forces. In addition, phase transitions are not fixed at a single depth. Their equilibrium condition is described in pressure-temperature space by the Clausius–Clapeyron relation. Its slope,

$$\gamma = \frac{dp}{dT} = \frac{\Delta S}{\Delta V} = \frac{L}{T\Delta V}, \quad (1.1)$$

relates changes in equilibrium pressure to changes in temperature along the phase boundary. Here, γ is the Clapeyron slope, p is pressure, T is temperature, ΔS is the entropy change across the phase transition, ΔV is the corresponding volume change, and L is the latent heat of the transition. Since pressure increases with depth in the mantle, the sign and magnitude of γ determine how the phase boundary is deflected in thermally anomalous regions, such as cold subducting slabs.

The transition near 410 km is exothermic and has a positive Clapeyron slope. In a cold subducting slab, this transition therefore occurs at lower pressure, and consequently at a shallower depth, than in the surrounding warmer mantle. The transition near 660 km is endothermic and has a negative Clapeyron slope. In this case, the transition in a cold slab is shifted to higher pressure and greater depth.

These deflections produce local density anomalies. At the 410 km transition, the phase change in the cold slab occurs earlier than in the surrounding mantle, so denser material is present above the average transition depth. This positive density anomaly tends to enhance the downward motion of the slab. At the 660 km transition, the opposite situation occurs: the phase transition is delayed in the cold slab, and relatively less dense material may persist below the average transition depth. This negative density anomaly may resist the descent of the slab into the lower mantle and can contribute to slab stagnation, folding, or temporary slowing in the mantle transition zone.

In numerical models, phase transitions are usually represented as finite-width regions rather than infinitely sharp discontinuities. Although the equilibrium condition of a phase transition is defined in pressure-temperature space, the ASPECT input files used in this thesis prescribe the transition positions and widths in terms of depth. The progress of each transition is described by a phase function Γ , which changes smoothly from 0 before the transition to 1 after the transformation is complete:

$$\Gamma = \frac{1}{2} \left[1 + \tanh \left(\frac{\Delta z}{\Delta z_0} \right) \right], \quad (1.2)$$

where Δz_0 controls the finite depth interval over which the transition occurs. In the present models, this width is set to 15 km for the 410 km and 660 km phase transitions. The quantity Δz measures the signed distance from the local, temperature-dependent phase boundary and can be written schematically as

$$\Delta z = z - z_{\text{transition}}(T), \quad (1.3)$$

where z is depth and $z_{\text{transition}}(T)$ is the depth of the phase boundary at the local temperature. The reference transition depths are prescribed as 410 km and 660 km, but their local position is shifted according to the Clapeyron slope. For a positive Clapeyron slope, warmer material requires higher pressure to undergo the transition, so the phase boundary is shifted to greater depth, while colder material shifts it to shallower depth. For a negative Clapeyron slope, the sense of this deflection is reversed.

In subduction models, phase transitions are therefore important not only because they change the density of mantle material, but also because their depth depends on temperature. A cold slab crossing the mantle transition zone deflects the phase boundaries and produces buoyancy anomalies that can either promote or hinder its descent. The corresponding density and latent heat contributions are included in the governing equations through the extended Boussinesq approximation, described in Section 1.4.

1.3 Rheology

Rheology describes the relation between stress and deformation. On geological time scales, mantle rocks can be approximated as highly viscous fluids, with a viscosity that depends on temperature, pressure, strain rate, stress, composition, and other material properties. In subduction zones, this dependence is particularly important because cold lithospheric plates are much stronger than the surrounding mantle, while deformation is often localized in narrow regions.

In the upper mantle, the deformation of mantle and lithospheric material can be described by diffusion creep, dislocation creep, and a stress-limiting mechanism. Diffusion creep is a linear, Newtonian deformation mechanism, whereas dislocation creep is nonlinear and follows a power-law relation. The stress limiter approximates strongly nonlinear deformation in regions where stresses would otherwise become unrealistically high.

The total strain rate tensor is written as the sum of the strain rates associated with the individual mechanisms,

$$\dot{\epsilon}_{ij} = \dot{\epsilon}_{ij}^{\text{diff}} + \dot{\epsilon}_{ij}^{\text{disl}} + \dot{\epsilon}_{ij}^y. \quad (1.4)$$

Since the strain rates are additive, the combined effective viscosity is given by the harmonic sum of the partial viscosities,

$$\eta_{\text{eff}} = \left(\frac{1}{\eta_{\text{diff}}} + \frac{1}{\eta_{\text{disl}}} + \frac{1}{\eta_y} \right)^{-1}. \quad (1.5)$$

For diffusion creep, the viscosity is given by an Arrhenius-type relation,

$$\eta_{\text{diff}} = \frac{1}{A_{\text{diff}}} \exp \left(\frac{E_{\text{diff}} + pV_{\text{diff}}}{RT} \right), \quad (1.6)$$

where A_{diff} is the pre-exponential factor, E_{diff} is the activation energy, V_{diff} is the activation volume, p is pressure, R is the gas constant, and T is temperature. Since diffusion creep is Newtonian, the viscosity does not depend on strain rate.

For dislocation creep, the viscosity depends on the second invariant of the strain-rate tensor and is written as

$$\eta_{\text{disl}} = \frac{1}{A_{\text{disl}}^{1/n}} \dot{\epsilon}_{II}^{\frac{1-n}{n}} \exp\left(\frac{E_{\text{disl}} + pV_{\text{disl}}}{nRT}\right), \quad (1.7)$$

where A_{disl} , E_{disl} , and V_{disl} are the dislocation creep parameters, n is the stress exponent, and $\dot{\epsilon}_{II}$ is the second invariant of the strain-rate tensor. For $n > 1$, the effective viscosity decreases with increasing strain rate.

The stress-limiting mechanism is described by

$$\eta_y = \tau_y \dot{\epsilon}_y^{-1/n_y} \dot{\epsilon}_{II}^{1/n_y - 1}, \quad (1.8)$$

where τ_y is the stress limit, $\dot{\epsilon}_y$ is the reference strain rate, and n_y is the stress-limiter exponent. This mechanism reduces the viscosity in regions of high stress and limits the maximum stress that the material can support.

The resulting viscosity field is highly heterogeneous. Cold lithospheric plates reach high viscosities and may remain mechanically coherent during subduction, whereas the surrounding mantle is warmer and weaker. Localized weakening, for example along plate boundaries or in prescribed weak layers, allows relative motion between neighbouring plates.

1.4 Extended Boussinesq approximation and governing equations

The models are based on an incompressible extended Boussinesq formulation with additional thermal terms. In this formulation, the flow is assumed to be incompressible, so that density variations do not enter the mass conservation equation. The material compressibility is set to zero in the material model. Density variations are, however, retained where they affect buoyancy and in the thermal energy equation. The temperature equation is solved using the **real density** formulation in ASPECT, so that the density entering the thermal equation is evaluated from the material model rather than replaced by a constant reference density. Additional thermal effects associated with adiabatic heating, viscous dissipation, and phase transitions are included. This distinguishes the formulation used here from the classical Boussinesq approximation, in which these additional heating terms are usually neglected.

The conservation of mass is expressed as

$$\nabla \cdot \mathbf{v} = 0, \quad (1.9)$$

where $\mathbf{v}$ is the velocity field. Since mantle flow occurs at very low Reynolds numbers, inertia is neglected and the momentum equation reduces to the Stokes equation. After subtracting a reference hydrostatic state, the momentum balance can be written in buoyancy form as

$$-\nabla \pi + \nabla \cdot \boldsymbol{\sigma} + \Delta \rho \mathbf{g} = \mathbf{0}, \quad (1.10)$$

where π is the reduced pressure, $\boldsymbol{\sigma}$ is the deviatoric stress tensor, $\Delta\rho$ is the density perturbation relative to the reference state, and $\mathbf{g}$ is the gravitational acceleration. The reduced pressure π represents the pressure remaining after the reference hydrostatic contribution has been absorbed into the buoyancy formulation. It should therefore be distinguished from the full thermodynamic pressure p , which enters pressure-dependent material laws, such as the rheological creep laws, and the thermodynamic description of phase transitions.

The energy equation is written as

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) - \rho c_p (\mathbf{v} \cdot \nabla) T + \rho \alpha T \mathbf{v} \cdot \mathbf{g} + \boldsymbol{\sigma} : \nabla \mathbf{v} + Q_L, \quad (1.11)$$

where ρ is the local density evaluated from the material model, c_p is the specific heat capacity at constant pressure, T is temperature, k is thermal conductivity, and α is the coefficient of thermal expansion. The terms on the right-hand side describe heat conduction, advection, adiabatic heating or cooling, viscous dissipation, and latent heat, respectively. No radiogenic heat production is included in the present models, so the corresponding internal heating term is set to zero.

The latent heat contribution due to phase transitions is written as

$$Q_L = \sum_k \frac{\gamma_k \delta \rho_k T}{\rho_0} \frac{D\Gamma_k}{Dt}, \quad (1.12)$$

where γ_k is the Clapeyron slope, $\delta \rho_k$ is the density change associated with the k -th phase transition, and Γ_k is the corresponding phase function. The ratio $\delta \rho_k / \rho_0$ represents the relative density contrast of the transition, where ρ_0 is a reference density at reference temperature T_{ref} used to scale the phase-transition contribution. The material derivative of the phase function is defined as

$$\frac{D\Gamma_k}{Dt} = \frac{\partial \Gamma_k}{\partial t} + \mathbf{v} \cdot \nabla \Gamma_k. \quad (1.13)$$

The sign of the latent heat term is controlled by both the Clapeyron slope and the local rate at which material passes through the phase transition, represented by $D\Gamma_k/Dt$.

Compositional fields C are advected with the flow according to

$$\frac{\partial C}{\partial t} + (\mathbf{v} \cdot \nabla) C = 0. \quad (1.14)$$

Such fields are used to distinguish different materials or regions of the model.

The density perturbation contains thermal, compositional, and phase-transition contributions,

$$\Delta\rho(T, p, C) = -\rho_0 \alpha (T - T_{ref}) + \Delta\rho_C + \sum_k \delta \rho_k \Gamma_k, \quad (1.15)$$

where T_{ref} is the reference temperature, $\Delta\rho_C$ is the compositional density contrast, and the last term represents density changes associated with phase transitions. Pressure does not enter the density through elastic compressibility, because the compressibility is set to zero. It enters the density perturbation indirectly through the phase functions Γ_k , because the position of each phase transition is determined in pressure-temperature space.

The deviatoric stress tensor is related to the strain-rate tensor by

$$\boldsymbol{\sigma} = 2\eta\dot{\boldsymbol{\epsilon}}, \quad (1.16)$$

where η is the effective viscosity. As discussed in the rheological description above, this viscosity may depend on temperature, pressure, composition, and the second invariant of the strain-rate tensor. The strain-rate tensor is defined as

$$\dot{\boldsymbol{\epsilon}} = \frac{1}{2} [\nabla \mathbf{v} + (\nabla \mathbf{v})^T]. \quad (1.17)$$

Therefore,

$$\boldsymbol{\sigma} = \eta [\nabla \mathbf{v} + (\nabla \mathbf{v})^T]. \quad (1.18)$$

In component form this relation is

$$\sigma_{ij} = 2\eta\dot{\epsilon}_{ij} = \eta \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right). \quad (1.19)$$

The second invariant of the deviatoric stress tensor is defined as

$$\sigma_{II} = \left(\frac{1}{2} \boldsymbol{\sigma} : \boldsymbol{\sigma} \right)^{1/2} = \left(\frac{1}{2} \sum_{i,j} \sigma_{ij} \sigma_{ij} \right)^{1/2}. \quad (1.20)$$

The second invariant of the strain-rate tensor is defined analogously as

$$\dot{\epsilon}_{II} = \left(\frac{1}{2} \dot{\boldsymbol{\epsilon}} : \dot{\boldsymbol{\epsilon}} \right)^{1/2}. \quad (1.21)$$

Together, these equations describe slow incompressible mantle flow driven by thermal, compositional, and phase-transition-related buoyancy. The temperature equation is solved using the real-density formulation, while adiabatic heating, viscous dissipation, and latent heat are retained. Radiogenic heat production is not included in the present models. The mechanical response is coupled to the rheological model through the effective viscosity.

1.5 Model geometry and thermal structure of oceanic lithosphere

The governing equations introduced above can be solved in different geometrical approximations. In mantle and lithosphere dynamics, this choice is not merely a technical detail. It determines how distances, directions, boundary shapes, and volume elements are represented. It also determines the direction of gravity and the way in which a plate or slab moving over large distances is embedded in the model domain. For this reason, the geometry of the computational domain may affect the predicted evolution of a subducting slab, especially when the model extends over several thousand kilometres or reaches into the lower mantle.

The simplest representation is Cartesian geometry. In two dimensions, the model is described by a rectangular box with a horizontal coordinate and a vertical coordinate. Gravity is usually prescribed as a constant vector pointing vertically downward. This geometry is a local approximation to the Earth and is well suited

for idealized studies in which the horizontal extent of the model is small compared to the radius of the planet. It is computationally convenient, straightforward to interpret, and useful for isolating the first-order influence of material parameters, phase transitions, or boundary conditions.

However, subduction is a planetary-scale process. Over distances of thousands of kilometres, the curvature of the Earth becomes important. A spherical shell geometry represents depth by the radial coordinate and horizontal distance by an angular coordinate. If R is the outer radius of the model and r is the local radius, the depth is

$$d = R - r. \quad (1.22)$$

A horizontal angular interval $\Delta\phi$ corresponds to an arc length

$$s(r) = r\Delta\phi. \quad (1.23)$$

Thus, the same angular interval represents a shorter physical distance at depth than at the surface. In contrast, a Cartesian box assigns the same horizontal length to a given interval at all depths. Spherical geometry also changes the direction of gravity, which is radial rather than vertical in a fixed Cartesian direction. These differences are the reason why the Cartesian and spherical models in this thesis are compared separately rather than treated as exactly equivalent descriptions of the same domain.

A full three-dimensional spherical model would be the most complete geometrical representation, but it is computationally expensive and introduces along-strike variations that are not always needed for the questions studied here. A useful intermediate choice is a two-dimensional spherical sector. In ASPECT this is implemented as the **chunk** geometry. In two dimensions, the **chunk** can be understood as a vertical slice through a cylinder. It retains the radial structure of the Earth and the curvature of the surface, while still allowing the problem to be treated as a two-dimensional cross-section.

In addition to the shape of the computational domain, the initial thermal structure of the oceanic lithosphere is an important part of the model geometry. Oceanic plates form at mid-ocean ridges and cool conductively as they move away from the ridge. Their temperature therefore depends on both depth and thermal age. For a plate moving with a spreading velocity u , the age at a surface distance x from the ridge is approximately

$$t \approx \frac{x}{u}. \quad (1.24)$$

The resulting thermal structure controls the thickness, density, and strength of the incoming plate and therefore strongly influences the subsequent evolution of the slab.

A common approximation is the half-space cooling model. In this model, the mantle is treated as a cooling half-space with a fixed surface temperature T_s and an interior temperature T_m . For a plate of age t , the temperature at depth d can be written as

$$T(d, t) = T_s + (T_m - T_s) \operatorname{erf} \left(\frac{d}{2\sqrt{\kappa t}} \right), \quad (1.25)$$

where κ is the thermal diffusivity. The characteristic thermal thickness therefore increases approximately as $\sqrt{\kappa t}$. This model captures the observed cooling of young

and intermediate-age oceanic lithosphere, but it predicts continuous thickening with age and does not by itself impose a limiting plate thickness.

Plate cooling models [32] often describe older oceanic lithosphere. These models introduce a finite thickness of the cooling plate and approach a steady-state geotherm at large ages. In practice, this prevents the lithosphere from thickening indefinitely and provides a more stable representation of old oceanic plates in long-domain subduction models. The choice between a half-space cooling model and a plate model determines how old and how thick the incoming oceanic lithosphere is at the trench.

In all model families considered here, the oceanic plates are initialized using the GWB plate model. The exact values of spreading velocity, thermal diffusivity, thermal conductivity, and lithospheric thickness used in each model family are given in Chapter 2.

2 Model description

In this thesis, subduction is investigated using a set of two-dimensional numerical models constructed with ASPECT and initialized with the Geodynamic World Builder (GWB). The models are not intended to represent a single progression from a simple to a complex case. Instead, they form four related model families, each of which is designed to answer a slightly different question. The two generic reference families are Tamara and Dobroslav, which are used to compare the behavior of a generic subduction system in spherical and Cartesian geometry. The third model family, Norbert, uses the same generic subduction setup but assumes that the extent of the weak crust is initially limited to 1300 km left from the trench. That ensures slab break-off after these 1300 km of slab were subducted, followed by free sinking through the (lower) mantle. Such a setup can then be used to study slab sinking velocities [30] and compare them in Cartesian and spherical geometry. The fourth model Vitek applies the same modelling strategy to a more realistic plate configuration inspired by the Hellenic subduction zone and is again implemented in both spherical and Cartesian geometry.

The four model families are referred to by the working names Tamara, Dobroslav, Norbert, and Vitek. Tamara is the generic spherical reference model. Dobroslav is its Cartesian counterpart. Norbert consists of two comparable shortened-interface models, one spherical and one Cartesian, designed to study the descent of a detached slab. Vitek consists of two comparable Hellenic-type models, one spherical and one Cartesian, with continental lithospheric segments and an overriding-plate weak zone. The overview of the model families is written down in Table 2.1. This naming convention is used only for clarity when discussing the model sets and does not imply different governing equations.

Name	Geometry	Main purpose	Main geometrical modification
Tamara	spherical chunk	generic spherical reference model	curvature included
Dobroslav	Cartesian box	generic Cartesian reference model	straight 2-D box geometry
Norbert	spherical chunk and Cartesian box	sinking of a detached slab fragment	shortened weak_layer in two comparable geometries
Vitek	spherical chunk and Cartesian box	application to a realistic plate structure	continental stripes and weak zone in two comparable geometries

Table 2.1 Overview of the model families used in this thesis.

2.1 Common setup of the generic reference models

Tamara and Dobroslav are designed as two coordinate representations of the same idealized subduction system. The model domain contains an overriding plate, a subducting plate, an initially prescribed slab, and the surrounding mantle. A weak crustal decoupling layer is prescribed along the whole surface of the subducting plate and the initial subducted slab tip. In both generic reference models, the initial thermal and compositional structure is prescribed by `GWB`. The oceanic plates are initialized with the `GWB plate model` [32], and the slab temperature is computed with the `GWB mass conserving` temperature model [33] using the same plate model as the reference thermal structure. The shared thermal and slab-temperature parameters used in the generic reference models are summarized in Table 2.2.

Parameter	Value
Surface temperature	273 K
Mantle potential temperature	1573 K
Specific heat capacity	1250 J kg ⁻¹ K ⁻¹
Thermal expansion coefficient	2×10^{-5} K ⁻¹
Thermal diffusivity	10 ⁻⁶ m ² s ⁻¹
Thermal conductivity	3.0 W m ⁻¹ K ⁻¹
Oceanic-plate thermal model	<code>GWB plate model</code>
Spreading velocity of subducting and overriding plates	0.05 m yr ⁻¹
Slab-temperature model	<code>GWB mass conserving model</code>
Subducting velocity in slab-temperature model	0.05 m yr ⁻¹

Table 2.2 Shared thermal and slab-temperature parameters of the generic reference models Tamara and Dobroslav.

The initial slab geometry is prescribed directly in `GWB` and is summarized in Table 2.3. A schematic view of this initial slab geometry is shown in Figure 2.1. In the generic models, the slab consists of two segments. The first segment is 200 km long and bends from a horizontal orientation to a dip angle of 25°. Along this segment, the thermal thickness decreases from 150 km to 120 km. The second segment is 180 km long, continues at a constant dip angle of 25°, and has a constant thermal thickness of 120 km. The `GWB` slab feature is allowed down to a maximum depth of 1000 km.

Slab segment	Length and dip	Thermal thickness
Bending segment	200 km, 0°–25°	150–120 km
Constant-dip segment	180 km, 25°	120 km

Table 2.3 Initial slab geometry used in the generic reference models.

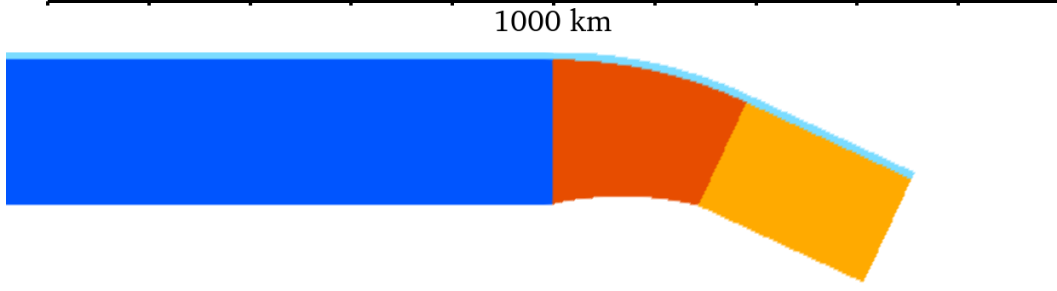


Figure 2.1 Schematic representation of the initial slab geometry prescribed in GWB. The dark blue region represents the incoming subducting plate, while the initially prescribed slab consists of a 200 km long bending segment, shown in red, followed by a 180 km long constant-dip segment, shown in orange. The light blue layer marks the shallow `weak_layer` located on top of the subducting plate and along the upper surface of the slab. The black scale bar has a total length of 1000 km.

The models include phase transitions at depths of 410 km and 660 km. The corresponding density jumps are 273 kg m^{-3} and 341 kg m^{-3} , and the transition width is 15 km. The reference Clapeyron slopes are

$$\gamma_{410} = 2.0 \times 10^6 \text{ Pa K}^{-1}, \quad \gamma_{660} = -2.5 \times 10^6 \text{ Pa K}^{-1}. \quad (2.1)$$

Additional model sets use different pairs of Clapeyron slopes, as described in Section 2.6. The weak crustal material associated with the shallow lubrication layer contains an artificial transition at 150 km depth. This transition has zero Clapeyron slope and zero density jump, so it does not add an extra buoyancy force. It is used only to replace the shallow weak interface material by the mantle material below the plate interface where the lubrication is no more needed. The phase transition parameters in the generic reference models are summarized in Table 2.4.

Transition depth	Density jump	Width	Reference Clapeyron slope
150 km	0	–	0
410 km	273 kg m^{-3}	15 km	$2.0 \times 10^6 \text{ Pa K}^{-1}$
660 km	341 kg m^{-3}	15 km	$-2.5 \times 10^6 \text{ Pa K}^{-1}$

Table 2.4 Phase-transition parameters used in the generic reference models. The 150 km transition is an artificial transition in the `weak_layer` material and does not represent a mantle phase transition.

2.2 Tamara: generic spherical model

Tamara is the generic spherical reference model. It uses the ASPECT `chunk` geometry and represents a two-dimensional sector of a cylindrical annulus. The model extends from the surface to a depth of 2000 km, with an outer radius of 6371 km and an inner radius of 4371 km. The full model domain is shown in the Figure 2.2. The angular extent of the model domain is 90° , from 45° to 135° .

When surface distances in the spherical model are compared to the Cartesian reference model, the angular width of 90° corresponds to approximately 10000 km.

Quantity	Value
Geometry	ASPECT <code>chunk</code>
Longitude interval	45° – 135°
Outer / inner radius	6371 km / 4371 km
Model depth	2000 km
Trench position	90°
Overriding plate	45° – 90°
Subducting plate	90° – 135°
Overriding-plate ridge	46°
Subducting-plate ridge	135°
Hot corner/ridge region near the lower-longitude boundary	44° – 46°
Hot corner/ridge region near the higher-longitude boundary	134° – 135°
Shallow lubrication layer on subducting plate	90° – 132°
Near-ridge part of subducting plate without lubrication layer	132° – 135°
Initial slab position	starts at 90° and dips towards the overriding plate

Table 2.5 Geometrical setup of the Tamara model family.

The overriding plate occupies the interval 45° – 90° . Its `plate model` ridge is located at 46° , close to the lower-longitude side of the model domain. This means that the overriding plate is thermally youngest close to the lateral boundary and becomes progressively older towards the trench.

The subducting plate occupies the interval 90° – 135° and uses a `plate model` ridge at 135° . It is divided into two GWB features. The main part of the subducting plate extends from the trench at 90° to 132° and contains the shallow lubrication layer. The short near-ridge interval from 132° to 135° is prescribed without this layer, so that the weak interface material is not placed directly at the ridge. The close-up of the initial state is shown in Figure 2.3.

The two upper lateral corners are treated by additional narrow hot ridge regions. One is prescribed around the lower-longitude boundary, between 44° and 46° , and the other at the higher-longitude boundary, between 134° and 135° . These regions are initialized with a linear high-temperature structure in the shallowest 50 km. They prevent the formation of unrealistically cold and strong lithosphere directly at the side boundaries and make the ridge ends of the model thermally consistent with the intended plate geometry.

The initial tip is inserted at longitude 90° . Its geometry is the generic slab geometry summarized in Table 2.3: a 200 km long bending segment followed by a 180 km long constant-dip segment, as shown in Figure 2.1. The slab temperature is computed with the GWB `mass conserving` temperature model, using the generic

`plate model` as the reference temperature model. The same ridge position as for the subducting plate, 135° , is used in the slab temperature model. The main geometrical parameters defining the Tamara model family are summarized in Table 2.5. The initial thermomechanical structure of the Tamara model is shown in Figures 2.2 and 2.3.

The purpose of Tamara is to illuminate the effect of spherical geometry. The surface of the model is curved, gravity is radial, and the slab descends through a sector of a cylindrical annulus rather than through a rectangular box. At the same time, the trench position, initial slab dip, slab thickness, thermal parameters, and material parameters are kept close to those of the Cartesian reference model Dobroslav. Differences between Tamara and Dobroslav can therefore be interpreted primarily as consequences of the geometry and of the different coordinate system.

Tamara is used for the largest parameter sweep in this thesis. Nine model sets are produced by combining three pairs of Clapeyron slopes with three values of the lubrication-layer prefactor. The full set of tested combinations is given in Section 2.6.

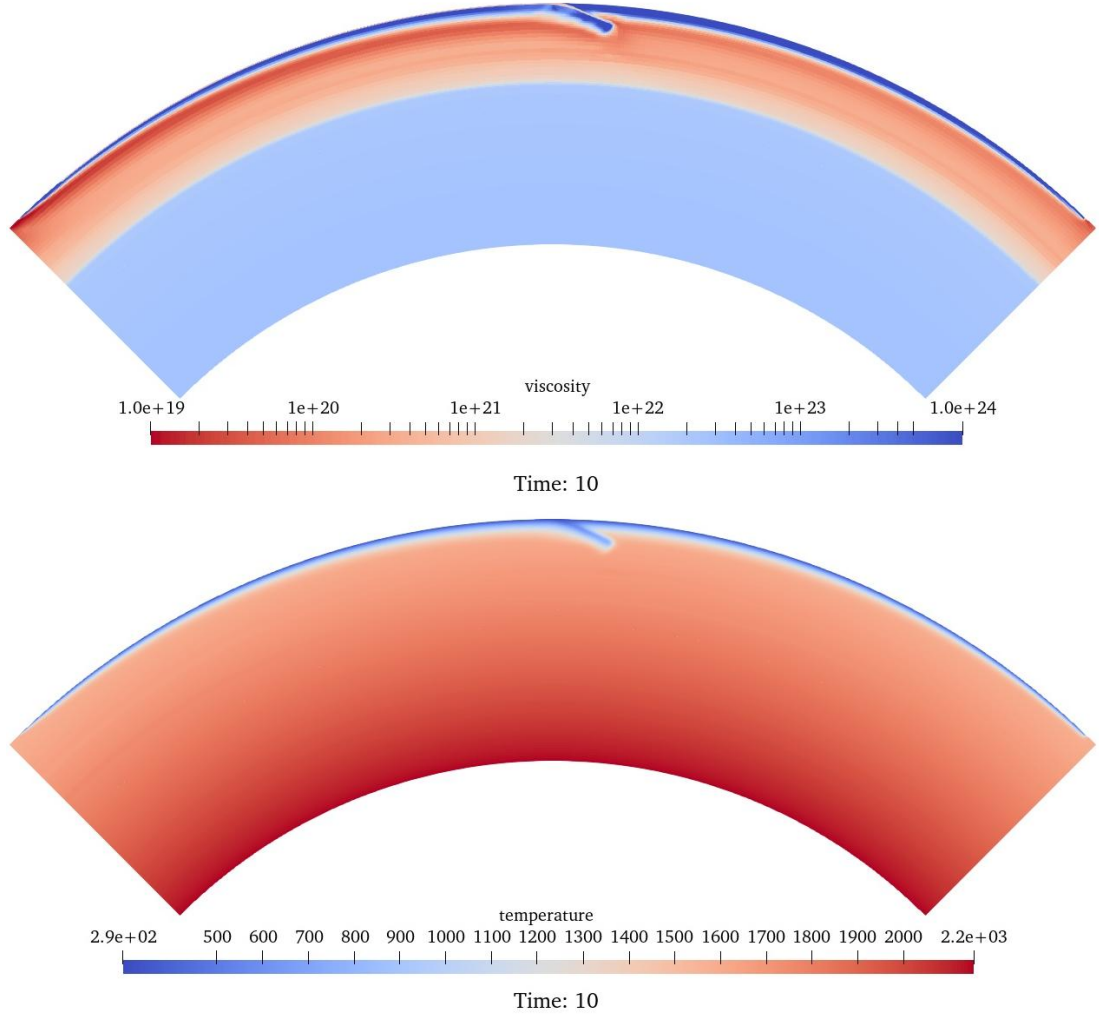


Figure 2.2 Initial thermomechanical structure of the Tamara model after 10 Myr of the initialization stage. The upper panel shows the viscosity field in the whole spherical model domain (2000 km deep), while the lower panel shows the corresponding temperature field. Viscosity is shown on a logarithmic scale in Pa s and temperature in K. The full spherical model domain is shown in both panels. The domain is a 90° -wide spherical chunk spanning longitudes 45° – 135° and radii 4371–6371 km, corresponding to a depth range of 0–2000 km and to approximately 10000 km along the surface.

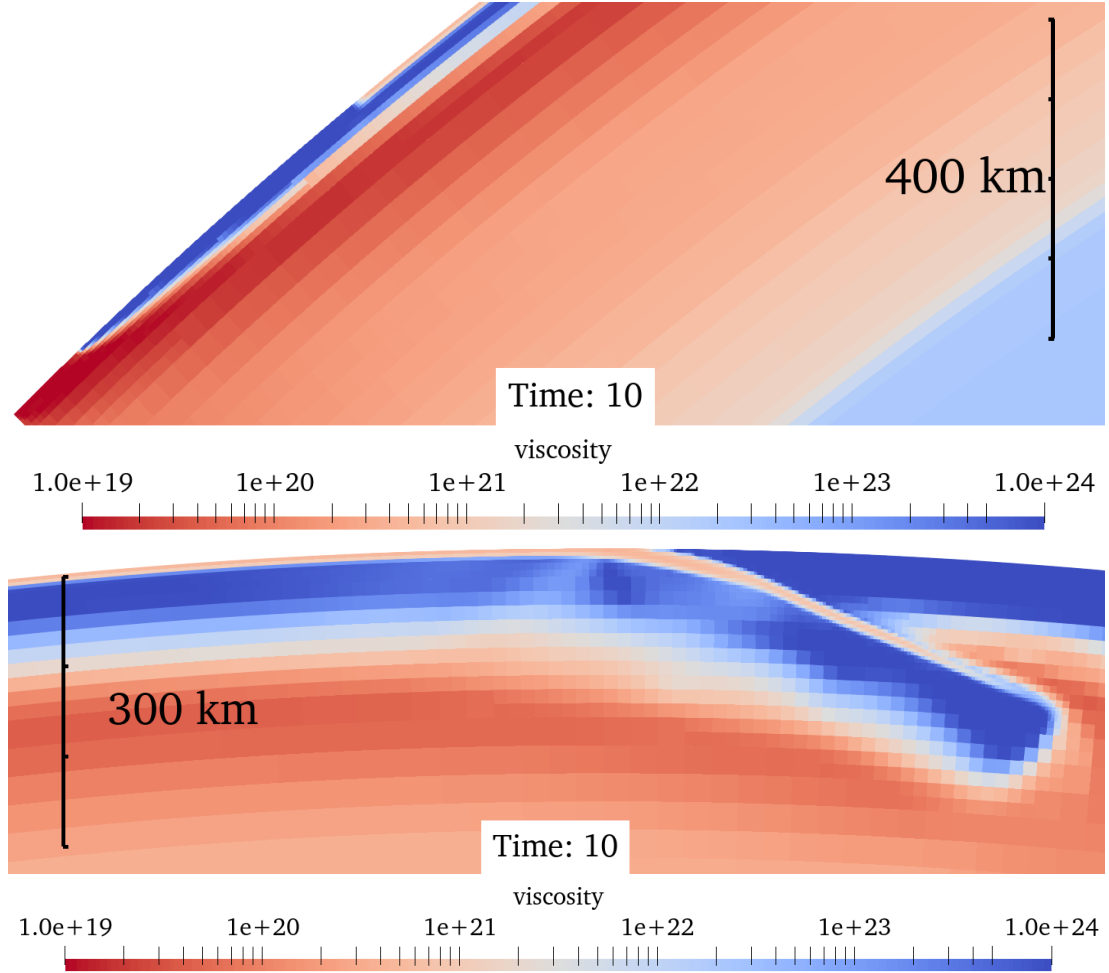


Figure 2.3 Close-up views of the viscosity field in the Tamara model after 10 Myr of the initialization stage. The upper panel shows the near-surface structure close to the upper left corner of the spherical domain, while the lower panel shows the central part of the model around the trench and the shallow slab interface. The panels illustrate the location of the low-viscosity interface and the viscosity contrast between the cold lithosphere, the weak layer, and the surrounding mantle. The black scale bar has a total length of 400 km in the upper panel and 300 km in the lower panel. The same logarithmic viscosity scale, ranging from 10^{19} to 10^{24} Pa.s, is used in both panels.

2.3 Dobroslav: generic Cartesian model

Dobroslav is the Cartesian counterpart of Tamara. It is formulated in a two-dimensional Cartesian box that is 10000 km wide and 2000 km deep. The horizontal coordinate x measures distance along the surface, and the vertical coordinate y is measured upward from the bottom of the box. In the text, depths are always reported downward from the surface.

Quantity	Value
Geometry	Cartesian box
Horizontal extent	0–10000 km
Vertical extent	0–2000 km, with y measured upward from the bottom
Trench position	$x = 5000$ km
Subducting plate	$x = 0$ –5000 km
Overriding plate	$x = 5000$ –10000 km
Subducting-plate ridge	$x = 0$ km
Overriding-plate ridge	$x = 9900$ km
Hot corner/ridge region near the left boundary	$x = -100$ –100 km
Hot corner/ridge region near the right boundary	$x = 9900$ –10100 km
Main subducting-plate feature	$x = 300$ –5000 km, with lubrication layer
Near-ridge part of subducting plate without lubrication layer	$x = 0$ –300 km
Initial slab position	starts at $x = 5000$ km and dips towards the right

Table 2.6 Geometrical setup of the Dobroslav model family.

The trench is initially located in the centre of the model domain at $x = 5000$ km. The subducting plate occupies the left side of the domain, while the overriding plate occupies the right side. The overriding plate extends from the trench to the right boundary, between $x = 5000$ and 10000 km. Its `plate model` ridge is located at $x = 9900$ km, close to the right boundary. This makes the overriding plate thermally youngest near the right side of the model and progressively older towards the trench.

The subducting plate extends from the left boundary to the trench and uses a `plate model` ridge at $x = 0$ km. It is split into two GWB features. The main part extends from $x = 300$ km to the trench and contains the shallow lubrication layer. The short near-ridge part extends from $x = 0$ to 300 km and is prescribed without this layer. This prevents the weak interface material from being placed directly at the ridge.

The two upper lateral corners are treated by additional narrow hot ridge regions. The left hot ridge region extends from $x = -100$ to 100 km, and the right one extends from $x = 9900$ to 10100 km. These regions are initialized with a linear high-temperature structure in the shallowest 50 km. They prevent the formation of unrealistically cold and strong lithosphere directly at the lateral

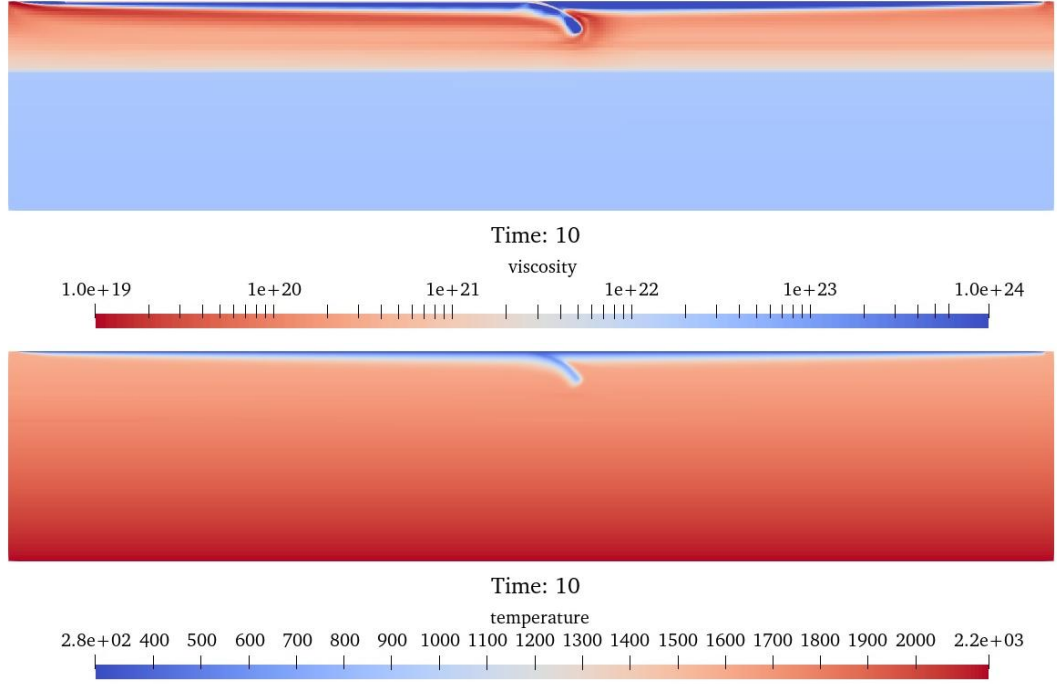


Figure 2.4 Viscosity and temperature fields of the Dobroslav model after 10 Myr of the initialization stage. The upper panel shows viscosity in the full Cartesian model domain and the lower panel shows temperature. This state represents the common thermomechanical configuration from which the Dobroslav model variants are compared. Viscosity is given in Pa s and temperature in K. The full Cartesian model domain is shown in both panels. The domain is 10000 km wide and 2000 km deep.

boundaries and make the ridge ends of the model thermally consistent with the intended plate geometry.

The initial slab is inserted at the trench. In Cartesian coordinates, its trace at the surface is located at $x = 5000$ km, and the slab dips towards the right, i.e. towards the overriding plate. Its geometry is the generic slab geometry summarized in Table 2.3: a 200 km long bending segment followed by a 180 km long constant-dip segment. The temperature of the slab is computed using the `GWB mass conserving` temperature model, with the `plate model` as the reference thermal model. The same ridge position as for the subducting plate, $x = 0$ km, is used in the slab temperature model. The main geometrical parameters defining the Dobroslav model family are summarized in Table 2.6. The initial thermomechanical structure of the Dobroslav model is shown in Figures 2.4 and 2.5.

Dobroslav is used for three model sets. In these sets, the lubrication-layer prefactor is kept fixed at the reference value and the Clapeyron slopes of the 410 km and 660 km phase transitions are varied. This provides a Cartesian reference for the phase-transition sensitivity of the slab dynamics.

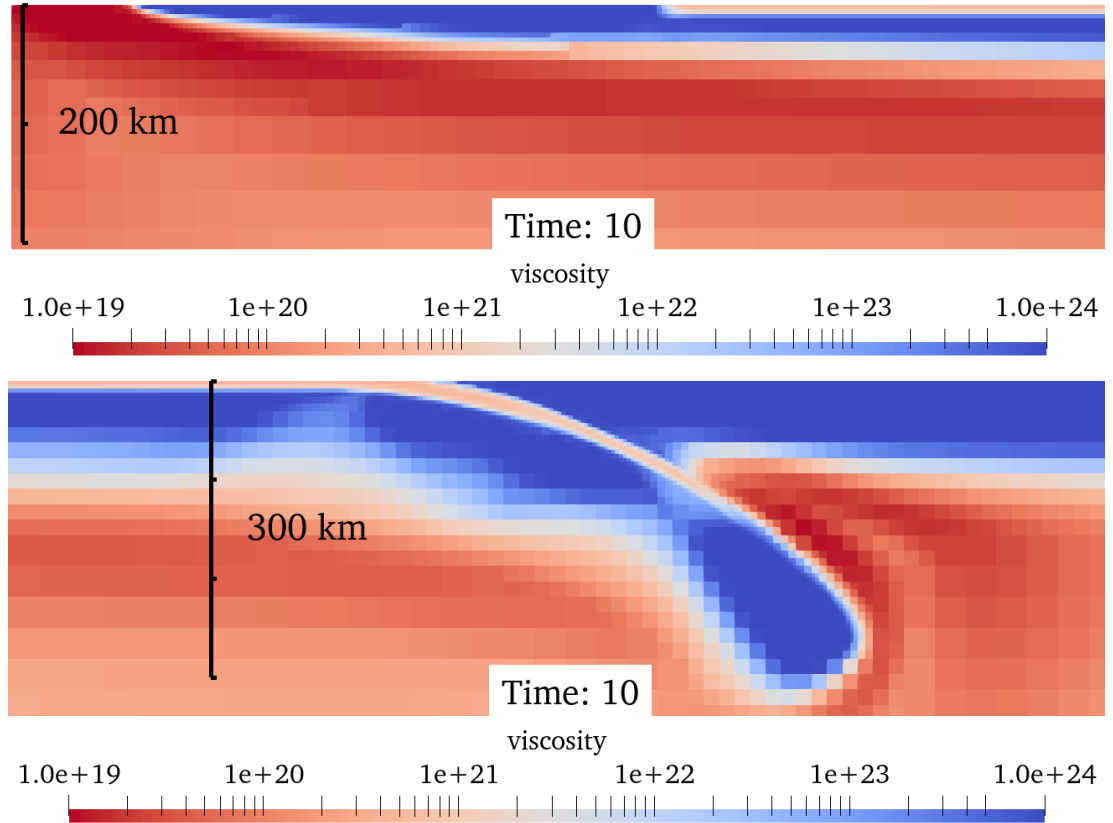


Figure 2.5 Close-up views of the viscosity field in the Dobroslav model after 10 Myr of the initialization stage. The upper panel shows the upper left corner of the Cartesian domain, while the lower panel shows the central part of the model around the trench and the shallow slab interface. The panels highlight the localization of the low-viscosity weak layer and the viscosity contrast between the cold lithosphere and the surrounding mantle. The black scale bar has a total length of 200 km in the upper panel and 300 km in the lower panel. The same logarithmic viscosity scale, ranging from 10^{19} to 10^{24} Pa s, is used in both panels.

2.4 Norbert: shorter-interface models

Norbert is a family of targeted models designed to study the free descent of a slab fragment after break-off enforced by a shorter weak decoupling interface. The setup is motivated by models in which the sinking speed of subducted lithosphere is used to constrain the viscosity structure of the mantle [30]. Norbert family consists of two geometrically comparable models: a spherical version, denoted `Norbert_SPH`, and a Cartesian version, denoted `Norbert_CART`. The purpose of using both coordinate representations is to test whether the sinking and deformation of the slab fragment are robust with respect to the model geometry.

The model setup follows the generic reference models. The oceanic plates are initialized with the `GWB plate model` using the reference spreading velocity of 0.05 m yr^{-1} . The initial slab temperature is computed with the `GWB mass conserving` temperature model, with the same subducting velocity as in the generic models (0.05 m yr^{-1}). The prescribed initial slab geometry is also the same as in generic models: the slab starts at the trench, consists of a 200 km bending segment followed by a 180 km constant-dip segment, reaches a dip of 25° , and is prescribed in `GWB` down to a maximum depth of 1000 km.

The main modification is the shorter shallow weak interface represented by the compositional field `weak_layer`. In Tamara and Dobroslav, this layer covers most of the subducting surface plate. In Norbert, it is kept only in the near-trench part of the subducting plate. The rest of the subducting plate is initialized without the shallow weak interface material. The resulting initial viscosity structure is shown in Figure 2.6. The geometrical differences between the Norbert models and their corresponding generic reference models are summarized in Table 2.7. This setup is intended to promote the evolution of a slab fragment that would break-off once the weak decoupling layer is consumed.

Quantity	Norbert_SPH	Norbert_CART
Corresponding reference model	Tamara	Dobroslav
Near-trench part with <code>weak_layer</code>	$90^\circ\text{--}102^\circ$	$x = 3666.7\text{--}5000 \text{ km}$
Subducting plate without <code>weak_layer</code>	$102^\circ\text{--}135^\circ$	$x = 0\text{--}3666.7 \text{ km}$
Length of shortened <code>weak_layer</code>	$12^\circ \approx 1333 \text{ km}$	1333.3 km
Overriding-plate ridge	42° , outside the model domain	$x = 10333.3 \text{ km}$, outside the model domain
Additional hot ridge region	$134^\circ\text{--}135^\circ$, near the subducting-plate ridge	$x = -100\text{--}100 \text{ km}$, near the subducting-plate ridge

Table 2.7 Geometrical modifications in the Norbert model family relative to the generic reference models. Only parameters that differ from the corresponding generic setups are listed.

In the spherical version, the shortened `weak_layer` extends from the trench at 90° to 102° . In the Cartesian version, the comparable interval extends from $x = 3666.7 \text{ km}$ to the trench at $x = 5000 \text{ km}$. With the same surface-distance

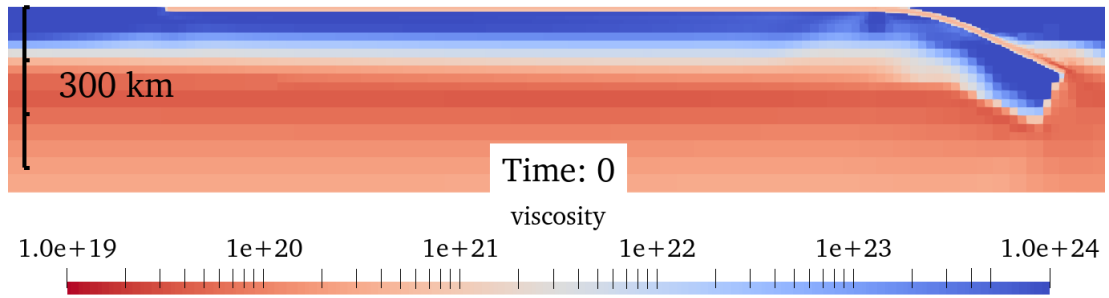


Figure 2.6 Initial viscosity field of the Norbert model. The figure highlights the shortened shallow **weak_layer**, which is restricted to the near-trench part of the incoming plate and to the top of the initially prescribed slab. The black scale bar has a total length of 300 km. Viscosity is shown on a logarithmic scale ranging from 10^{19} to 10^{24} Pa s.

scaling used for the generic spherical models, $90^\circ \approx 10000$ km, the 12° spherical interval corresponds to approximately 1333 km, matching the Cartesian interval.

In both coordinate versions, the slab starts at the trench and dips towards the overriding plate. Norbert_SPH is therefore directly comparable to Tamara, while Norbert_CART is directly comparable to Dobroslav. The comparison between Norbert_SPH and Norbert_CART then isolates the effect of model geometry on the evolution of the detached slab.

2.5 Vitek: Hellenic-type models with continental segments and a weak zone

Vitek is the application model family used to test the modelling strategy in a more realistic plate configuration inspired by the Hellenic subduction zone. Subduction of the African plate beneath the Aegean, associated with numerous intermediate-depth earthquakes, has been extensively studied using seismic methods and numerical modelling [34]. The setup is based on the Hellenic-slab model of Lohani et al. [23], which was developed in our department. Their model includes alternating oceanic and continental lithospheric segments in the subducting plate and a localized weak zone in the overriding plate and was implemented in a 2D Cartesian geometry in the geodynamic code StagYY. Based on a parametric study, they concluded that the observed cessation of seismicity at 200 km depth may be attributed to the presence of the dry continental stripes present at the subducting African plate [35]. The aim of the Vitek model family is not to reproduce this model exactly, but to implement a similar conceptual setup in ASPECT and to compare its Cartesian and spherical representations. We take the rheological and phase transition parameters of the preferred model of Lohani et al. [23], and we use them in a spherical version, denoted **Vitek_SPH**, and a Cartesian version, denoted **Vitek_CART**. Both versions contain the same conceptual plate configuration: a subducting plate with alternating oceanic and continental lithospheric segments, a shallow **weak_layer** on the subducting plate and slab interface, and a localized **weak_zone** in the overriding plate that allows for extension of the overriding plate and trench rollback.

The purpose of the two Vitek geometries is analogous to the spherical–Cartesian

comparison made for the generic and slab-sinking setups. The spherical version keeps the native ASPECT `chunk` geometry, whereas the Cartesian version expresses the same Hellenic-type structure in a straight two-dimensional box.

The shared thermal, plate-model, and slab-temperature parameters of the Vitek model family are summarized in Table 2.8.

Quantity	Value
Coordinate versions	two: <code>Vitek_SPH</code> and <code>Vitek_CART</code>
Surface temperature	273 K
Mantle potential temperature	1573 K
Specific heat capacity	1250 J kg ⁻¹ K ⁻¹
Thermal expansion coefficient	2×10^{-5} K ⁻¹
Thermal diffusivity	6.79×10^{-7} m ² s ⁻¹
Thermal conductivity	2.9 W m ⁻¹ K ⁻¹
Thermal model of oceanic plates	<code>GWB_plate_model</code>
Spreading velocity of the subducting plate	0.06 m yr ⁻¹
Spreading velocity of the overriding plate	0.10 m yr ⁻¹
Slab-temperature model	<code>GWB_mass_conserving_model</code>
Reference model for slab temperature	<code>GWB_plate_model</code>
Subducting velocity in slab-temperature model	0.06 m yr ⁻¹
Coupling depth	100 km
Forearc cooling factor	0
Initial slab geometry	200 km bending segment and 180 km constant-dip segment
Final slab dip in the prescribed geometry	25°
Maximum GWB slab depth	1000 km
Parameter sweep	none

Table 2.8 Common thermal, plate-model, and slab-temperature setup of the Vitek model family.

In the spherical version, the model domain extends from 45° to 135° and from the surface to a depth of 2000 km. The trench is located at 81°. The subducting plate extends from the trench towards the ridge at 135°, and the overriding plate occupies the interval between 45° and the trench. In the Cartesian version, the comparable box is 10000 km wide and 2000 km deep, and the trench is located at $x = 6000$ km. The coordinate conversion used for the Cartesian version is

$$x = \frac{135^\circ - \phi}{90^\circ} 10000 \text{ km.} \quad (2.2)$$

Thus, the subducting-plate ridge at 135° corresponds to $x = 0$, while the 45° boundary of the spherical chunk corresponds to $x = 10000$ km. The Cartesian model therefore has the same surface-distance scaling as the spherical model, but the horizontal coordinate increases in the opposite direction to longitude.

The corresponding geometrical parameters of the spherical and Cartesian Vitek versions are summarized in Table 2.9.

Quantity	Vitek_SPH	Vitek_CART
Geometry	ASPECT chunk	Cartesian box
Model domain	45°–135°, 6371–4371 km radius	0–10000 km horizontally, 2000 km depth
Trench position	81°	$x = 6000$ km
Overriding plate	45°–81°	$x = 6000$ –10000 km
Subducting plate	81°–135°	$x = 0$ –6000 km
Near-trench part with weak_layer	81°–132°	$x = 333.3$ –6000 km
Near-ridge part without weak_layer	132°–135°	$x = 0$ –333.3 km
Subducting-plate ridge	135°	$x = 0$ km
Overriding-plate ridge	0°	$x = 15000$ km
Initial slab position	starts at 81° and dips towards the overriding plate	starts at $x = 6000$ km and dips towards the overriding plate
Overriding-plate weak zone	77.4°–78.3°	$x = 6300$ –6400 km
Gravity direction	radial	vertical

Table 2.9 Geometrical correspondence between the two Vitek model versions.

Vitek therefore does not replace the **GWB plate model** by a different oceanic cooling model. Instead, the ridge positions and velocities used inside the **plate model** are changed relative to the generic and Norbert setups. The subducting-plate ridge remains at 135° in the spherical model ($x = 0$ km in the Cartesian model), but the trench is shifted from 90° to 81°. The ridge-to-trench distance of the subducting plate is therefore increased from approximately 5000 km in the generic setup to approximately 6000 km in Vitek. With the subducting-plate spreading velocity and the slab-temperature subducting velocity both set to 0.06 m yr^{-1} , this corresponds to an oceanic age of about 100 Myr at the trench. The temperature of the slab is computed with the same mass-conserving approach as in the generic models, but using the Vitek-specific thermal conductivity and plate-model velocities listed in Table 2.8.

Four continental lithospheric segments are inserted into the subducting plate. They are represented thermally by **GWB continental plate** features with a linear geotherm. No separate continental-crust density or rheological law is introduced. The shallow **weak_layer** marker is retained in the uppermost part of these segments, and hydration is not modelled explicitly. The continental segments therefore differ from the surrounding oceanic lithosphere primarily by their position, width, and imposed thermal thickness.

The positions, widths, and thermal thicknesses of the continental segments are listed in Table 2.10.

The overriding plate contains a localized weak zone. In the spherical version it

Segment	Longitude interval	Cartesian interval	Width	Thermal thickness
Drama/Getic	84.00°–88.68°	$x = 5146.7\text{--}5666.7$ km	520 km	120 km
Pelagonian	91.38°–93.36°	$x = 4626.7\text{--}4846.7$ km	220 km	120 km
Gavrovo–Tripolitza	98.22°–101.10°	$x = 3766.7\text{--}4086.7$ km	320 km	120 km
Africa	106.95°–129.45°	$x = 616.7\text{--}3116.7$ km	2500 km	150 km

Table 2.10 Continental lithospheric segments prescribed in the Vitek model family. The Cartesian intervals are obtained from the spherical longitudes using the same surface-distance scaling as in Table 2.9.

is placed between 77.4° and 78.3° , and in the Cartesian version the same feature lies between $x = 6300$ km and $x = 6400$ km. It is therefore located approximately 300–400 km from the trench on the overriding side. The weak zone extends down to a depth of 80 km and is represented by the compositional field `weak_zone`. Its density and phase-transition structure are the same as those of the surrounding mantle, but its maximum viscosity is limited to 1.5×10^{22} Pa s. It therefore acts as a localized rheological weakening of the overriding plate, not as a compositional density anomaly and not as a second slab-interface layer.

The resulting initial viscosity fields of both Vitek model versions are shown in Figure 2.7.

2.6 Parameter sets

The generic model families Tamara and Dobroslav are used for a controlled parameter study. The main parameters varied in the generic models are the Clapeyron slopes of the 410 km and 660 km phase transitions and, in the spherical model Tamara, the rheological prefactor controlling the shallow lubrication layer. The tested Clapeyron-slope pairs are listed in Table 2.11. The middle pair is treated as the reference case. The tested lubrication prefactors are listed in Table 2.12.

Case	γ_{410}	γ_{660}
Low-magnitude pair	1.0×10^6 Pa K ^{−1}	-1.5×10^6 Pa K ^{−1}
Reference pair	2.0×10^6 Pa K ^{−1}	-2.5×10^6 Pa K ^{−1}
High-magnitude pair	3.0×10^6 Pa K ^{−1}	-3.5×10^6 Pa K ^{−1}

Table 2.11 Tested Clapeyron-slope pairs for the 410 km and 660 km phase transitions.

For Tamara, nine model sets are used. These combine the three Clapeyron-slope pairs with three values of the lubrication-layer prefactor. For Dobroslav, three model sets are used. The lubrication-layer prefactor is kept fixed at the reference value and only the Clapeyron-slope pair is varied.

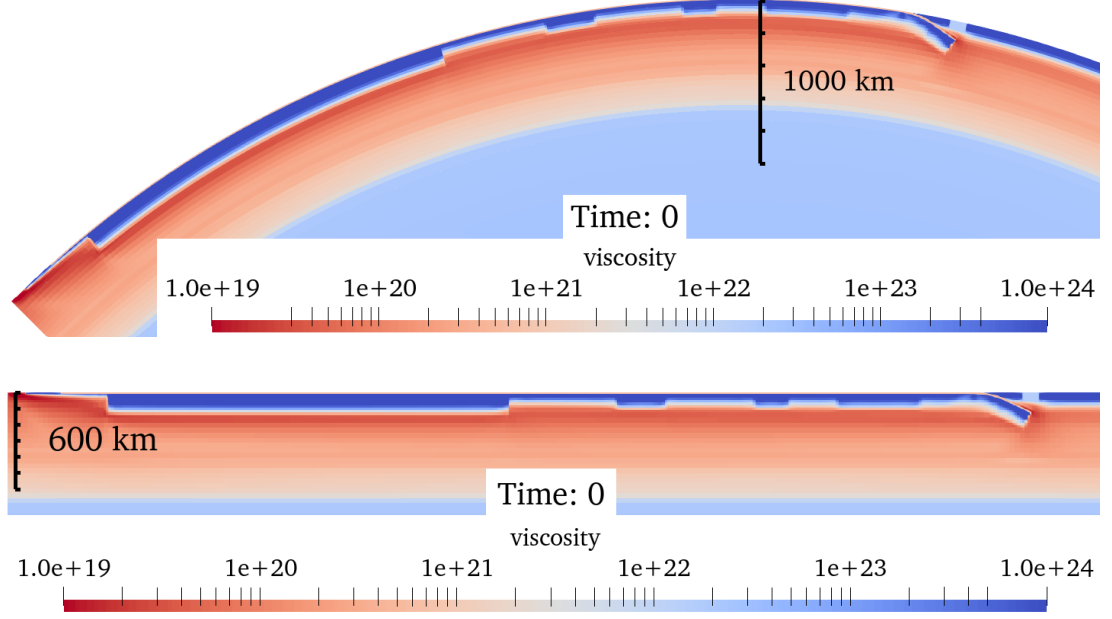


Figure 2.7 Initial viscosity fields of the Vitek_SPH and Vitek_CART models. The upper panel shows the spherical model and the lower panel shows the Cartesian model. Both panels show the initial Hellenic-type plate configuration, including the subducting plate, continental lithospheric segments, shallow **weak_layer**, and the overriding-plate **weak_zone**. The black scale bars have lengths of 1000 km in the spherical panel and 600 km in the Cartesian panel. Viscosity is shown on a logarithmic scale ranging from 10^{19} to 10^{24} Pa.s.

The varied lubrication parameter is the first dislocation-creep prefactor of the **weak_layer** material and is denoted here by A_{lub} . The corresponding rheological description has stress exponent $n = 1$ and zero activation energy and activation volume. It therefore prescribes constant-viscosity in the shallow plate interface, with a nominal viscosity of

$$\eta_{\text{lub}} \approx A_{\text{lub}}^{-1}. \quad (2.3)$$

Larger values of A_{lub} therefore correspond to a weaker lubrication layer. In SI units, a dislocation-creep prefactor with $n = 1$ has dimensions $\text{Pa}^{-1} \text{s}^{-1}$.

Case	A_{lub}	Nominal η_{lub}
Weak/reference interface	$10^{-20} \text{ Pa}^{-1} \text{s}^{-1}$	10^{20} Pa s
Intermediate interface	$5 \times 10^{-21} \text{ Pa}^{-1} \text{s}^{-1}$	$2 \times 10^{20} \text{ Pa s}$
Strong interface	$10^{-21} \text{ Pa}^{-1} \text{s}^{-1}$	10^{21} Pa s

Table 2.12 Lubrication-layer prefactors tested in the Tamara model family. The nominal viscosities correspond to $\eta_{\text{lub}} \approx A_{\text{lub}}^{-1}$ for the shallow **weak_layer** branch. All listed values lie within the imposed viscosity cutoffs.

Families Norbert and Vitek are not used for the parameter study. Norbert is a targeted shortened-interface model represented by one spherical and one Cartesian coordinate version. Vitek is an application model represented by the spherical–Cartesian pair Vitek_SPH and Vitek_CART; both versions contain the same continental segments and overriding-plate **weak_zone**. They use the

reference Clapeyron-slope pair listed in Table 2.11 and the reference shallow-interface prefactor listed in Table 2.12.

3 Numerical implementation

3.1 Coupling ASPECT and the Geodynamic World Builder

The initial temperature and composition fields are generated by GWB. In the input files, the geometry is described by a set of GWB features: mantle layers, oceanic plates, continental plates, ridge regions, and a subducting-plate feature. These features are evaluated at the beginning of the ASPECT run and are used as the initial temperature and initial composition models. The temperature field from GWB is also used at the fixed-temperature boundaries through the initial-temperature boundary model.

This approach has two advantages. First, it makes the initial geometry reproducible. The location of the trench, the thickness of the plate, the shape of the slab, and the position of the weak compositional layer are all defined explicitly in the GWB file. Second, it allows the same conceptual geometry to be implemented both in Cartesian and in spherical coordinates. The generic Cartesian and spherical models are therefore not constructed independently; they are two coordinate representations of the same idealized subduction system.

A practical detail is that the same compositional field name, `weak_layer`, is used in the ASPECT parameter files for the shallow weak interface layer. It marks the weak layer on the top of the subducting plate and along the top of the slab. In the GWB files, this layer is prescribed from 10 km above the surface to a depth of 7.5 km. The extension above the surface is kept intentionally, because it ensures that the layer intersects the top boundary cleanly and does not disappear due to small geometrical or interpolation differences at the surface.

In Dobroslav, Tamara, and Norbert there is one compositional field: `weak_layer`. In Vitek there are two compositional fields, `weak_layer` and `weak_zone`. The second field is used only in the weak zone of the overriding plate. Its density differential is set to zero, so it does not add an imposed buoyancy anomaly. Its role is rheological: it marks the region where the upper viscosity cutoff is reduced and resulting low viscosity allows for the extension of the overriding plate.

An overview of the ASPECT parameter files and Geodynamic World Builder input files is provided in Appendices A.1 and A.2, respectively. The complete versions of these files, together with the particle input files, are included as electronic supplementary material.

3.2 Material model and rheology

The models use the ASPECT `compositing` material model. In this setup, viscosity is computed by the `visco plastic` material model, while density, thermal expansivity, specific heat, thermal conductivity, compressibility, entropy derivatives, and reaction terms are taken from the `latent heat` material model. This combination makes it possible to use a composite viscous rheology and, at the same time, include density jumps and latent-heat effects associated with mantle phase transitions.

The viscous flow law is set to **composite**. It combines diffusion creep, dislocation creep, and a stress-limiting mechanism. The background mantle is represented by three rheological branches corresponding to upper-mantle, transition-zone, and lower-mantle material. Unless a material-specific upper cutoff is prescribed, viscosity is bounded between 10^{19} and 10^{24} Pa s. The minimum strain rate is 10^{-22} s $^{-1}$ and the reference strain rate is 10^{-15} s $^{-1}$.

Stress limiting is represented using the ASPECT power-law stress limiter. In this formulation, the stress-limiting viscosity is controlled by a prescribed yield stress, a reference strain rate, and the stress-limiter exponent n_y . In the present models, the maximum yield stress is set to 200 MPa, the reference strain rate is 10^{-15} s $^{-1}$, and the stress-limiter exponent is $n_y = 10$. The cohesion is set to a very large value, 2×10^{30} Pa, so that the Drucker–Prager frictional envelope does not control yielding; instead, the limiting stress is effectively given by the imposed maximum yield stress. Harmonic averaging is applied to the viscosity at material interfaces.

The material-specific rheological modifications are summarized in Tables 3.1 and 3.2. The most important special material is **weak_layer**, which contains an additional shallow rheological branch above the artificial transition at 150 km depth. This branch has stress exponent $n = 1$ and zero activation energy and activation volume. Its viscosity is therefore independent of temperature, pressure, and strain rate. The strength of this branch is controlled by the first dislocation-creep prefactor of the **weak_layer** material, denoted A_{lub} . For $n = 1$, the corresponding nominal viscosity is of order $\eta_{\text{lub}} \approx A_{\text{lub}}^{-1}$. The tested values of A_{lub} are listed together with the parameter sets in Section 2.6.

The phase transitions at 410 km and 660 km are specified consistently in both the **visco plastic** and **latent heat** subsections. In the latent-heat model, the density jumps are assigned to the corresponding material phases. For **weak_layer**, the artificial transition at 150 km has zero density jump and zero Clapeyron slope. It therefore does not introduce an additional buoyancy force; it only separates the shallow lubrication branch from the deeper mantle-like rheology. In Vitek, the **weak_zone** material has the same phase-transition structure as the background mantle and is weakened only through its reduced upper viscosity cutoff.

3.3 Initialization and restart strategy

Each model is computed in two stages. The first stage is an initialization run. During this stage, a prescribed velocity is applied at the top boundary on the subducting-plate side of the trench. This velocity drives the incoming plate towards the trench and allows the initially prescribed slab to develop into a mechanically consistent subduction configuration. The initialization stage is run to 10.2 Myr.

During the initialization stage, the lubrication-layer prefactor was kept fixed in all model variants. The shallow branch of the **weak_layer** material used $A_{\text{lub}} = 10^{-21}$ Pa $^{-1}$ s $^{-1}$, corresponding to a nominal lubrication-layer viscosity of approximately 10^{21} Pa s. The different values of A_{lub} listed in Table 2.12 were therefore applied only in the restart stage. This ensures that the parameter comparison starts from a common initialized subduction configuration.

Material	Branch	ρ kg m ⁻³	Diffusion creep ($A_{\text{diff}}, E_{\text{diff}}, V_{\text{diff}}, m$)	Dislocation creep ($A_{\text{disl}}, n, E_{\text{disl}}, V_{\text{disl}}$)
background, weak_zone	0–410 km	3300	($10^{-9}, 335, 4.0 \times 10^{-6}, 1$)	($31.5 \times 10^{-18}, 3.5, 480, 1.1 \times 10^{-5}$)
background, weak_zone	410–660 km	3573	($10^{-9}, 335, 4.0 \times 10^{-6}, 1$)	($31.5 \times 10^{-18}, 3.5, 480, 1.1 \times 10^{-5}$)
background, weak_zone	> 660 km	3914	($1.3 \times 10^{-16}, 200, 1.1 \times 10^{-6}, 1$)	($6.51 \times 10^{-30}, 1, 530, 1.3 \times 10^{-5}$)
weak_layer	0–150 km	3300	($10^{-9}, 335, 4.0 \times 10^{-6}, 1$)	($A_{\text{lub}}, 1, 0, 0$)
weak_layer	150–410 km	3300	($10^{-9}, 335, 4.0 \times 10^{-6}, 1$)	($31.5 \times 10^{-18}, 3.5, 480, 1.1 \times 10^{-5}$)
weak_layer	410–660 km	3573	($10^{-9}, 335, 4.0 \times 10^{-6}, 1$)	($31.5 \times 10^{-18}, 3.5, 480, 1.1 \times 10^{-5}$)
weak_layer	> 660 km	3914	($1.3 \times 10^{-16}, 200, 1.1 \times 10^{-6}, 1$)	($6.51 \times 10^{-30}, 1, 530, 1.3 \times 10^{-5}$)

Table 3.1 Material-specific rheological branch parameters used in the visco-plastic material model. The diffusion-creep parameters are listed as ($A_{\text{diff}}, E_{\text{diff}}, V_{\text{diff}}, m$) and the dislocation-creep parameters as ($A_{\text{disl}}, n, E_{\text{disl}}, V_{\text{disl}}$). Activation energies are given in kJ mol⁻¹ and activation volumes in m³ mol⁻¹. During the initialization stage, all model variants use $A_{\text{lub}} = 10^{-21}$ Pa⁻¹ s⁻¹; the listed values are applied in the restart stage.

Parameter	Value
Viscous flow law	composite
Minimum viscosity	10^{19} Pa s
Maximum viscosity of background and weak_layer	10^{24} Pa s
Maximum viscosity of weak_zone in Vitek	1.5×10^{22} Pa s
Minimum strain rate	10^{-22} s ⁻¹
Reference strain rate	10^{-15} s ⁻¹
Grain size	1 m
Yield mechanism	limiter
Maximum yield stress	200 MPa
Stress limiter exponent	10
Cohesion	2×10^{30} Pa
Angle of internal friction	11.53695903°
Material averaging	harmonic average only viscosity
Viscosity averaging scheme	geometric

Table 3.2 Global rheological settings used in the visco-plastic material model.

The second stage is a restart run. It is started from a checkpoint of the initialization run using `Resume computation = true`. In this stage, the prescribed top-boundary velocity is removed, and at all boundaries we prescribe impermeable free-slip. The model then evolves under its internal buoyancy, rheology, and interaction with the phase transitions. The restart stage is run to 100 Myr.

This two-stage strategy is used because a self-consistent subduction model is sensitive to the initial condition. A slab inserted at the trench is initially a geometrical object prescribed by GWB. If the surface plate is not driven during the early stage, the slab may either detach too early, fail to establish a stable subduction interface, or produce a transient response dominated by the artificial initial geometry. The initialization run reduces this dependence by creating a state in which the slab, the weak interface, and the surrounding mantle flow have adjusted to each other. The restart run then provides the dynamically relevant part of the calculation, where the slab evolves without continued kinematic forcing from the surface.

3.4 Boundary conditions and driving velocity

During the initialization stage, subduction is driven kinematically by a prescribed velocity applied at the top boundary on the subducting-plate side of the trench. The bottom and side boundaries are treated as free slip. In the restart stage, the imposed top-boundary velocity is removed and the top boundary is also included among the tangential velocity boundaries. The models then evolve only under their internal buoyancy forces, rheology, and interaction with phase transitions.

In the Cartesian models, the velocity function is written in Cartesian coordinates. The vertical velocity component is zero, while the horizontal velocity component is prescribed only on the subducting side of the trench,

$$v_y = 0, \quad v_x = \begin{cases} 0.025 \text{ m yr}^{-1}, & x < x_{\text{tr}}, \\ 0, & x \geq x_{\text{tr}}. \end{cases} \quad (3.1)$$

Here x_{tr} denotes the trench position. In Dobroslav and Norbert_CART, the trench is located at $x_{\text{tr}} = 5000$ km. In Vitek_CART, the trench is shifted to $x_{\text{tr}} = 6000$ km. The imposed horizontal velocity drives the subducting plate towards the trench and has a magnitude of 0.025 m yr^{-1} , corresponding to 2.5 cm yr^{-1} .

In the spherical models, the velocity function is written in spherical coordinates and spherical unit vectors are used. The radial velocity component is zero, while the azimuthal component is prescribed only on the subducting side of the trench,

$$v_r = 0, \quad v_\phi = \begin{cases} -0.025 \text{ m yr}^{-1}, & \phi > \phi_{\text{tr}}, \\ 0, & \phi \leq \phi_{\text{tr}}. \end{cases} \quad (3.2)$$

The negative sign of v_ϕ drives the subducting plate towards decreasing longitude, i.e. towards the trench. In Tamara and Norbert_SPH, the trench is located at $\phi_{\text{tr}} = 90^\circ$. In Vitek_SPH, the trench is shifted to $\phi_{\text{tr}} = 81^\circ$. In the ASPECT input files, these angular thresholds are written in radians as $\phi > 1.57$ for the generic spherical models and $\phi > 1.4137$ for Vitek.

The thermal boundary condition is prescribed at the top and bottom boundaries. Both use the initial-temperature boundary model, so the boundary temperatures are consistent with the GWB-generated initial temperature field. Outside the hot ridge/corner regions, the surface temperature is 273 K. In the narrow ridge/corner regions, the uppermost 50 km is initialized with a linear high-temperature structure with $T = 1573$ K at the top. At the bottom boundary, the temperature follows the initialized mantle adiabat and is approximately 2150 K at a depth of 2000 km. The lateral boundaries have zero horizontal derivative of temperature.

3.5 Particles

Passive particle tracers are used to follow selected material points during the model evolution. They are initialized from an ASCII file and are advected by the computed velocity field using the Runge-Kutta (RK2) integration scheme. The interpolation scheme is set to `cell average`. The particles carry the properties `pT path`, velocity, position, and initial position. They are written in both ASCII and VTU formats every 1 Myr.

The particles do not influence the Stokes solve, the temperature equation, or the composition equation. Their purpose is diagnostic. They make it possible to track where selected points of the slab move, how fast they sink, and which pressure–temperature paths they experience. This is particularly important for Norbert, where the goal is to follow the descent of a detached or partly detached slab fragment through the mantle. In the Vitek model, particles are also useful for comparing the later position of slab material with the initial location of the trench and the continental segments.

A technical detail is important in the spherical models. Although the model geometry and the GWB features are described using spherical coordinates, ASPECT requires the coordinates in the particle ASCII file to be Cartesian. Therefore, particle positions for the spherical models are generated by first choosing the intended angular and radial locations and then converting them to Cartesian coordinates. When the trench in Vitek is shifted from 90° to 81° , the particle positions are rotated by the same angular offset so that they remain consistent with the new trench position. This keeps the diagnostic particles in the intended position relative to the slab and the incoming plate. The initial positions of particles in Cartesian models are shown in Figure 3.1 and described in Table 3.3.

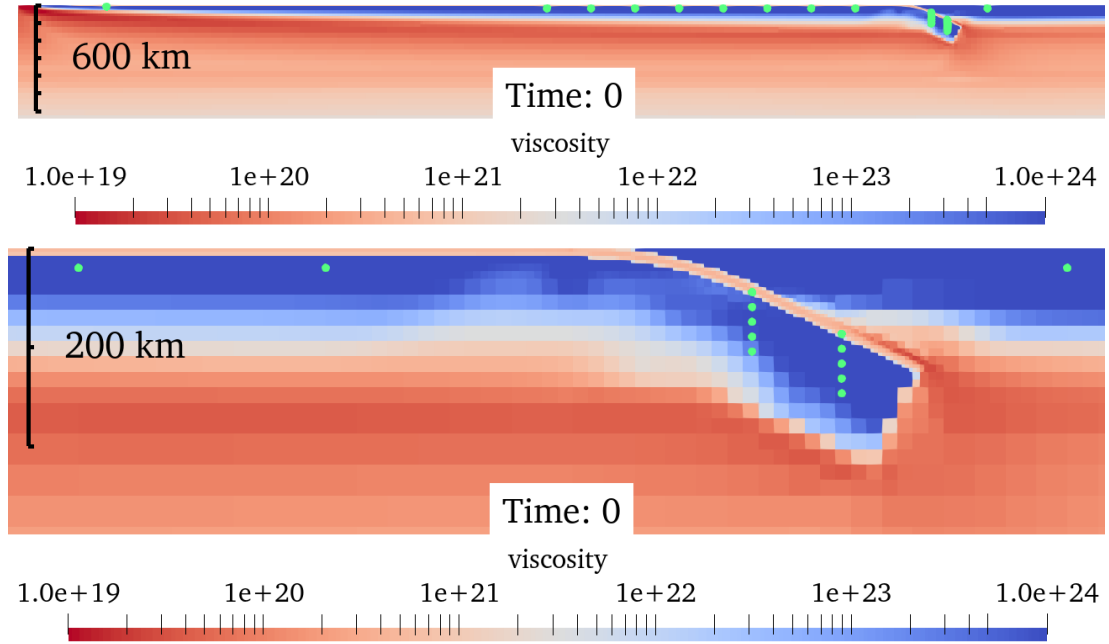


Figure 3.1 Initial particle positions in the Cartesian model Dobroslov. The upper panel shows the left part of the model domain with all particles, whereas the lower panel provides a close-up of the central region containing the slab. Particle locations are indicated by green dots.

Particle index	Initial position / role
0	Subducting plate near the ridge, at 10 km depth.
1	Overriding plate marker, 500 km behind the trench, at 20 km depth.
2–9	Incoming-plate markers at 20 km depth, 250–2000 km before the trench.
10–11	Main markers on the initially prescribed slab, at approximately 105 km and 147 km depth.
12–15	Markers above particle 10, spaced by 15 km, at approximately 45–90 km depth.
16–19	Markers above particle 11, spaced by 15 km, at approximately 87–132 km depth.

Table 3.3 Initial positions and roles of particles in the Cartesian models.

3.5.1 Post-processing of particle output

The raw ASPECT particle output is not used directly in the analysis figures. It is first processed by small Python scripts, which sort the particle records by particle number and by output time and convert the velocity components into a form that can be compared between Cartesian and spherical models. The scripts are not part of the numerical model itself; they are used only for reproducible data processing after the ASPECT runs have finished. Their complete versions are included as electronic supplementary material.

The script `particle_sort.py` is used for the spherical chunk models. It reads all particle files written by ASPECT in the directory `output/particles`, extracts the output index from the file name, and assigns time using the prescribed particle-output interval of 1 Myr. Because ASPECT writes particle velocities in Cartesian components, the script converts them to radial and tangential components according to

$$v_r = \frac{xv_x + yv_y}{\sqrt{x^2 + y^2}}, \quad v_\phi = \frac{-yv_x + xv_y}{\sqrt{x^2 + y^2}}. \quad (3.3)$$

The resulting velocities are converted from m s^{-1} to cm yr^{-1} . The output is a set of files in the directory `sorted_particles`: one file for each particle and one combined table containing all particles.

The script `particle_sort_cart.py` performs the same task for the Cartesian models. To keep the output format compatible with the spherical models, the Cartesian horizontal velocity is stored as v_ϕ and the vertical velocity as v_r , with v_r positive upward. This convention makes it possible to use the same plotting script for both geometries, while preserving the interpretation of surface-parallel and vertical/radial motion.

The script `plot_particles.py` is a small plotting utility for the sorted particle tables. The user specifies the model folders, particle ids, and the columns to be plotted, for example temperature, pressure, radial velocity, tangential velocity, or particle position as a function of time. The script saves both the figure and the data actually used in the figure. This is useful for checking the reproducibility of particle-track plots and for comparing selected particles between different model families.

3.6 Adaptive mesh refinement

All models use adaptive mesh refinement. The initial global refinement level is 5, followed by four initial adaptive refinement steps. The solvers are skipped during the initial refinement stage, so the mesh can adapt to the prescribed initial temperature and composition fields before the first Stokes solve. During the time-dependent calculation, mesh refinement is performed every 10 time steps.

The refinement strategy combines minimum and maximum refinement functions with refinement based on viscosity and on a composition threshold. The purpose of the minimum and maximum refinement functions is to guarantee sufficient resolution in the shallow part of the model and around the subducting plate. In the Cartesian model, the functions are written in terms of x and y . The highest refinement is prescribed in the upper 30 km on the subducting side of the model, with lower but still elevated refinement levels in the upper 100 km and upper 700 km.

In the spherical models, the refinement functions are written in terms of radius r and longitude ϕ . The highest refinement is prescribed close to the surface on the subducting side of the trench. For Tamara and Norbert, this means $r > 6341$ km and $\phi > 90^\circ$. In Vitek, the longitude threshold is shifted to $\phi > 81^\circ$, following the shifted trench. Additional refinement is prescribed down to radii corresponding approximately to depths of 100 km and 700 km. This ensures that the weak interface, the shallow slab, and strong thermal and viscosity gradients are resolved more finely than the surrounding mantle.

The composition-threshold refinement is applied to the compositional fields with a threshold of 0.1. In the generic models, this applies to the single field `weak_layer`. In Vitek, the threshold is applied to both `weak_layer` and `weak_zone`. This helps to refine the mesh around both the slab interface and the overriding-plate weak zone.

3.7 Solver settings and output

The nonlinear solver scheme is `iterated Advection and Stokes`. The maximum number of nonlinear iterations is 20 and the nonlinear solver tolerance is 10^{-5} . The Stokes linear solver tolerance is 10^{-5} , while the temperature and composition solver tolerances are both 10^{-12} . The CFL number is 0.5 and the maximum time step is 40000 yr. Checkpoints are written every 10 time steps, which allows the restart stage to continue from the driven initialization run.

The heating model includes adiabatic heating, constant heating, shear heating, and latent heat. The simplified adiabatic heating formulation is used. The constant radiogenic heating rate is set to zero, so the models do not include internal radioactive heat production. Gravity has a constant magnitude of 9.81 m s^{-2} . It is vertical in Dobroslav and radial in Tamara, Norbert, and Vitek.

The postprocessing output includes velocity, temperature and heat flux statistics (average and maximum value in each time step), depth averages, visualization output, and particles. Visualization files are written in VTU format every 1 Myr. The output variables include material properties, strain rate, stress, shear stress, stress second invariant, principal stress, temperature anomaly, adiabat, and heating terms. In spherical models, spherical velocity components are also written. These fields are used to analyse slab morphology, sinking velocity, viscosity structure, stress localization, and the thermal state of the slab.

4 Results

4.1 Tamara

4.1.1 Evolution of the Tamara model family

The Tamara model family represents the generic spherical reference setup of this thesis. All nine models develop a stable subduction configuration after the initialization stage, with a continuous subducting plate, a localized shallow `weak_layer`, and a slab descending into the mantle. This confirms that the GWB-based initial geometry can be used to construct a self-consistent spherical subduction model in ASPECT and provides a controlled framework for testing the effects of various parameters.

The first parameter tested in this thesis is the lubrication-layer prefactor A_{lub} . According to equation 1.6, smaller values of A_{lub} correspond to a higher nominal viscosity and therefore to a stronger plate interface. The models show that rollback decreases with decreasing A_{lub} . In other words, a stronger interface couples the subducting and overriding plates more efficiently and makes trench retreat less effective. The reference-interface case, which has the largest tested value of A_{lub} , therefore generally allows the most mobile trench, while the strong-interface cases show more limited rollback (cf. left, middle and right columns in Figure 4.1).

The second varied parameter is the magnitude of the Clapeyron slopes at the 410 km and 660 km phase transitions. Increasing this magnitude does not simply accelerate subduction. Instead, it reduces the overall rollback and makes the slab evolution more strongly controlled by the transition zone. The stronger phase transitions both enhance the downward acceleration of the slab near the 410 km discontinuity and increase the resistance to its further descent near the 660 km discontinuity, leading to a more compressed and strongly deformed slab geometry.

This difference is visible in the viscosity snapshots in Figure 4.1. At 20 Myr, the models are still relatively similar and the slab geometry is not far from the initialized configuration. At later times, the slab reaches the transition-zone region and the parameter dependence becomes clearer. With increasing magnitude of the Clapeyron-slopes, the slab becomes more folded. This buckling reflects the mechanical response of the cold, viscous slab to the phase-transition forces: the slab continues to be pulled downward, but its penetration and motion are partly resisted by the transition zone, so the plate weakens through the strain-rate dependent power-law stress limiter and begins to fold instead of sinking smoothly.

The same process is also reflected in the subducting plate velocities shown in Figure 4.2. The velocity curves are not smooth, but show distinct peaks and intervals of slower motion. This episodic behaviour is consistent with the buckling observed in the viscosity field. The stronger the interaction with the phase transitions, the more pronounced this episodicity becomes. The high Clapeyron-slope cases therefore tend to show sharper velocity peaks and more irregular time evolution than the low-magnitude cases.

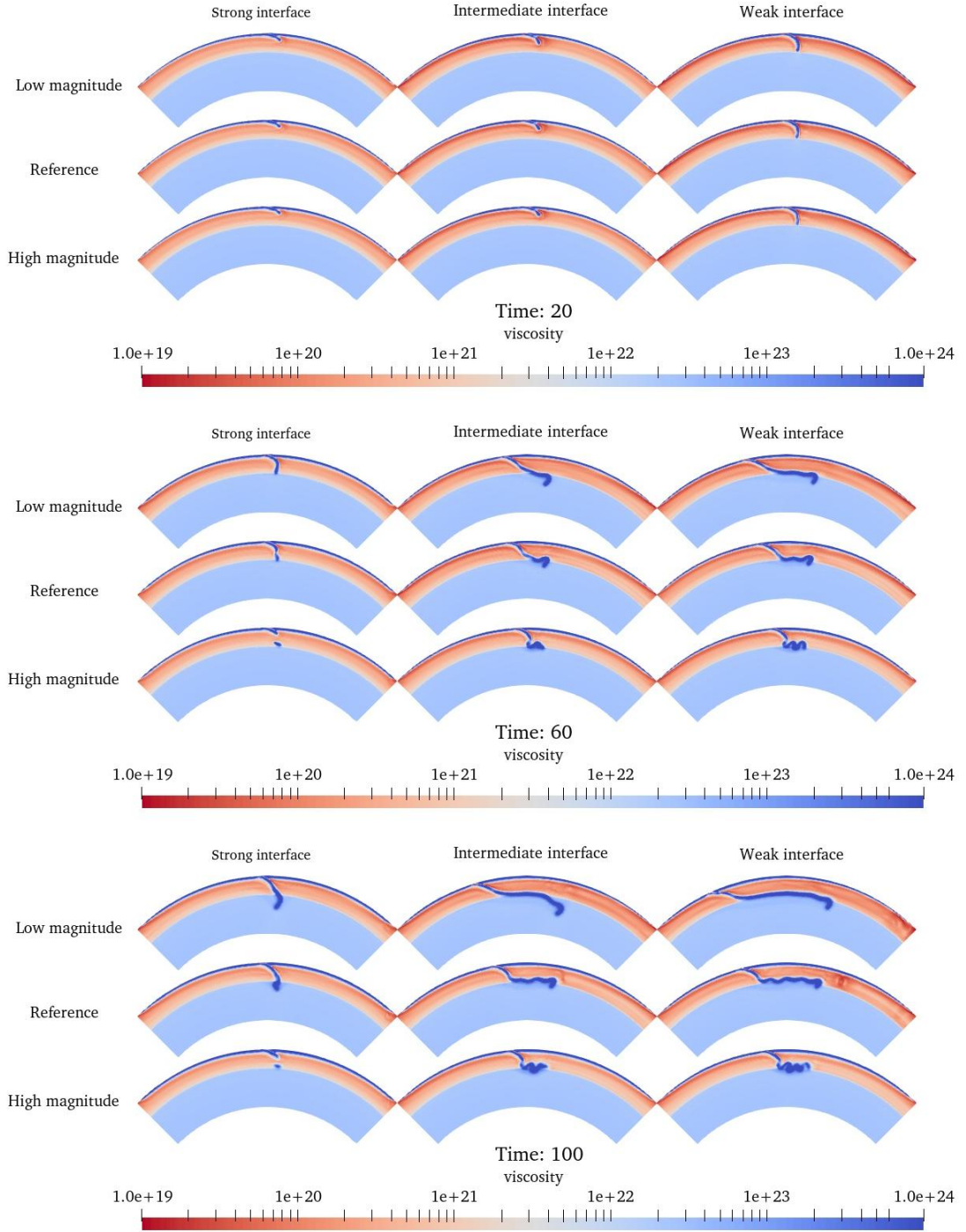


Figure 4.1 Viscosity field in the full model domain for the nine Tamara model variants at 20, 60, and 100 Myr. The three time steps are shown from top to bottom. For each time step, columns show models with strong, reference, and weak shallow interface strength, while rows show low, reference, and high magnitudes of the 410 km and 660 km Clapeyron slopes. The same logarithmic viscosity scale, ranging from 10^{19} to 10^{24} Pa s, is used in all panels. The full spherical model domain is shown in all panels. The domain is a 90° -wide spherical chunk spanning longitudes 45° – 135° and radii 4371–6371 km, corresponding to a depth range of 0–2000 km and to approximately 10000 km along the surface.

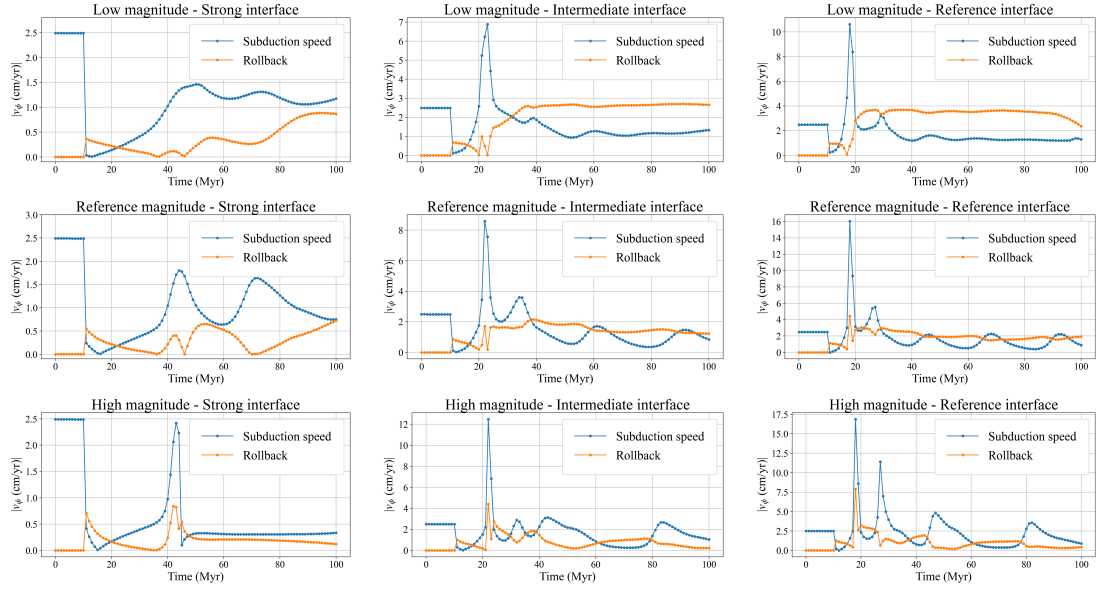


Figure 4.2 Absolute tangential velocity component $|v_\phi|$ of the subducting and overriding plates as measured in selected monitor particles in the nine Tamara model variants. Velocities are given in cm yr^{-1} and plotted as a function of model time in Myr. Rows correspond to low, intermediate (reference), and high Clapeyron-slope magnitudes, while columns correspond to strong, intermediate, and weak (reference) shallow-interface cases. Blue curves show the subducting-plate particle (index 0) and orange curves show the rollback-tracking particle (index 1). The constant velocity in the first 10 Myr corresponds to initial phase with prescribed plate velocities.

The most extreme behaviour occurs in the high-magnitude, strong-interface model, where the slab detaches from the surface plate. This can be understood as a consequence of the combined effect of strong phase-transition forcing and strong mechanical coupling at the shallow interface. The phase transition at 410 km enhances the downward pull on the already subducted part of the slab, while the strong interface limits smooth continued subduction. The resulting stress concentration near the connection between the surface plate and the descending slab eventually leads to slab break-off. This model, therefore, represents an end-member case in which the slab cannot accommodate the imposed forces by rollback and buckling alone.

Overall, the Tamara models show that the combined effect of interface strength and phase-transitions strength controls rollback, slab folding, and episodic slab motion. A stronger interface reduces trench retreat by increasing the mechanical coupling between the plates. Larger Clapeyron-slope magnitudes also reduce the total rollback, but at the same time enhance slab buckling and make the evolution more episodic. The strongest combination of these effects leads to slab detachment.

4.2 Dobroslav

The Dobroslav models were designed as Cartesian counterparts of the spherical Tamara models. This comparison is useful because Cartesian geometries are still commonly used as idealized reference setups in numerical subduction modelling, whereas a spherical geometry provides a more realistic representation of the curved Earth. The aim was therefore not to obtain perfectly identical evolutions, but to test whether the main dynamical behaviour remains comparable when the same conceptual model is expressed in the two coordinate systems.

The comparison in Figure 4.3 shows that the model evolutions start to deviate already at early times. This is also visible in the plate velocities in Figure 4.4. In particular, the subducting plates in Tamara models are slower than the corresponding Dobroslav models during the initial time periods of the free evolution. This early difference affects the later timing of slab deformation, the amplitude of velocity peaks, and the final slab morphology.

Despite these quantitative differences, the character of subduction remains similar in both geometries. In all three Clapeyron-slope cases, the slab continues to descend into the mantle, interacts with the transition-zone phase transitions, and develops similar folding or buckling at later times. The velocity curves also show episodic behaviour in both geometries, suggesting that the observed velocity peaks are linked to slab reorganization during buckling rather than being specific to only one coordinate representation.

The comparison therefore indicates that the Cartesian and spherical models do not evolve identically, especially during the early stage of the calculation when slab dynamics is very sensitive, for example, to the resolution of the decoupling layer. However, the main trends in slab behaviour are very similar. The spherical geometry modifies the timing and strength of individual events, but it does not change the overall interpretation of the generic models: phase-transitions strength promotes slab folding and episodic motion, while the model geometry mainly controls the quantitative details of the evolution.

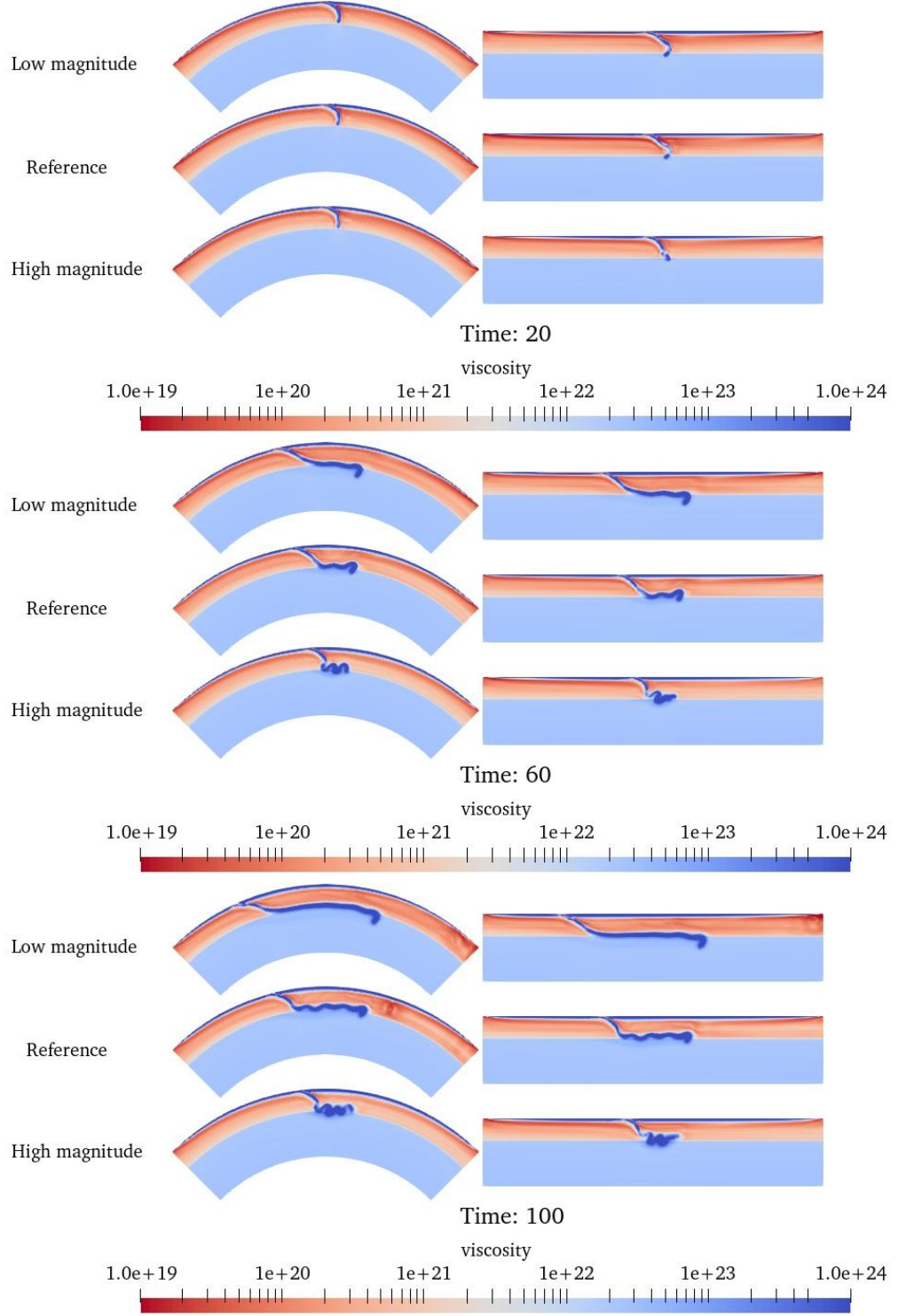


Figure 4.3 Comparison of the viscosity field in the spherical Tamara models and the corresponding Cartesian Dobroslav models for the reference (weak) interface strength at 20, 60, and 100 Myr. The three time steps are shown from top to bottom. For each time step, the left column shows the Tamara model in spherical geometry and the right column shows the corresponding Dobroslav model in Cartesian geometry. Rows correspond to low, reference, and high magnitudes of the 410 km and 660 km Clapeyron slopes. The same logarithmic viscosity scale, ranging from 10^{19} to 10^{24} Pa s, is used in all panels. The full model domains are shown. The spherical domain is a 90° -wide chunk with a depth range of 0–2000 km, while the Cartesian domain is a 10000×2000 km box.

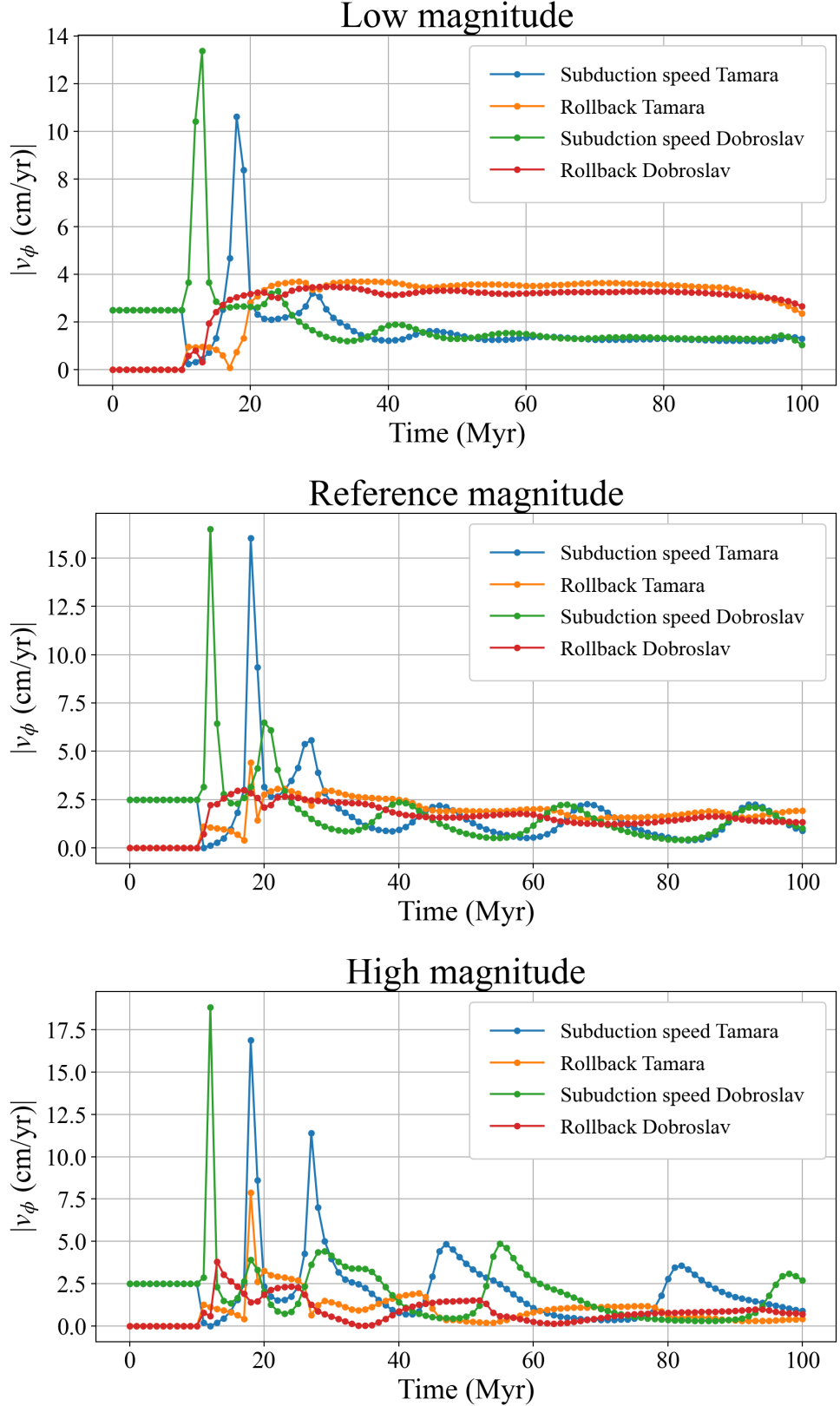


Figure 4.4 Comparison of the absolute tangential plate velocity component $|v_\phi|$ in the Tamara and Dobroslav models for the three tested Clapeyron-slope magnitudes. The panels show low, reference, and high magnitude cases from top to bottom. The subduction velocity is tracked by particle 0, while rollback is tracked by particle 1. Velocities are given in cm yr^{-1} and plotted as a function of model time in Myr.

4.3 Norbert

The Norbert model family was designed to test the sinking of a slab fragment after breaking off the subducting slab. It consists of two corresponding models, Norbert_SPH and Norbert_CART, which use the same model parameters but different coordinate geometries. The aim is to test whether the sinking of the detached slab fragment is comparable in spherical and Cartesian geometry.

The two models do not reach the same evolutionary stage at exactly the same model time. In the spherical model, the slab is initially considerably slower than the Cartesian one. As a result, it takes approximately 50 Myr longer for the slab segment to detach and to pass below the 660 km discontinuity. To compare the subsequent free sinking stage rather than the timing of the detachment itself, two equivalent time intervals were selected: 149–199 Myr for Norbert_CART and 200–250 Myr for Norbert_SPH. The viscosity snapshots in the Norbert models throughout these intervals are shown in Figure 4.5. The comparison of the sinking velocity is then shown in Figure 4.7, where the vertical velocity of the detached slab is plotted as a function of time measured from the moment when the slab fragment is fully located in the lower mantle.

For this comparison, the radial velocity was averaged over particles 2, 3, 4, 5, 10, and 11. Their positions are described in Table 3.3. These particles were selected because they sample the sinking slab fragment rather than only a single material point. The plotted quantity is therefore the mean absolute radial velocity, $\langle |v_r| \rangle$, of the selected slab particles. This averaging reduces the influence of local deformation of the detached slab and provides a more robust estimate of the sinking rate of the slab segment as a whole.

The resulting curves are shown in Figure 4.7. After the time alignment, the spherical and Cartesian models show very similar sinking velocities. Both curves decrease smoothly from approximately 1.4 cm yr^{-1} at the beginning of the selected interval to about 0.4 cm yr^{-1} after 50 Myr when the slab is approaching the lower boundary of the model domain and has to slow down. The spherical model is slightly faster during most of this time interval, but the difference is small, typically only of the order of a few tenths of a millimeter per year.

This comparison suggests that the delayed evolution of Norbert_SPH compared to Norbert_CART is again mainly associated with the differences in the initial slab descent causing the earlier detachment. Once the slab fragment is detached and sinking below the transition zone, its mean radial velocity is comparable in both coordinate representations. Since the two models use the same mantle rheology and the same phase-transition setup, the remaining small differences are more likely caused by the different initial geometry and coordinate representation than by an effect of sphericity.

Overall, the Norbert models indicate that the post-detachment sinking of the slab fragment is robust with respect to the choice of Cartesian or spherical geometry. The geometry affects the timing of detachment and the onset of deep sinking, but once comparable stages of the evolution are reached, the subsequent sinking rates are nearly the same.

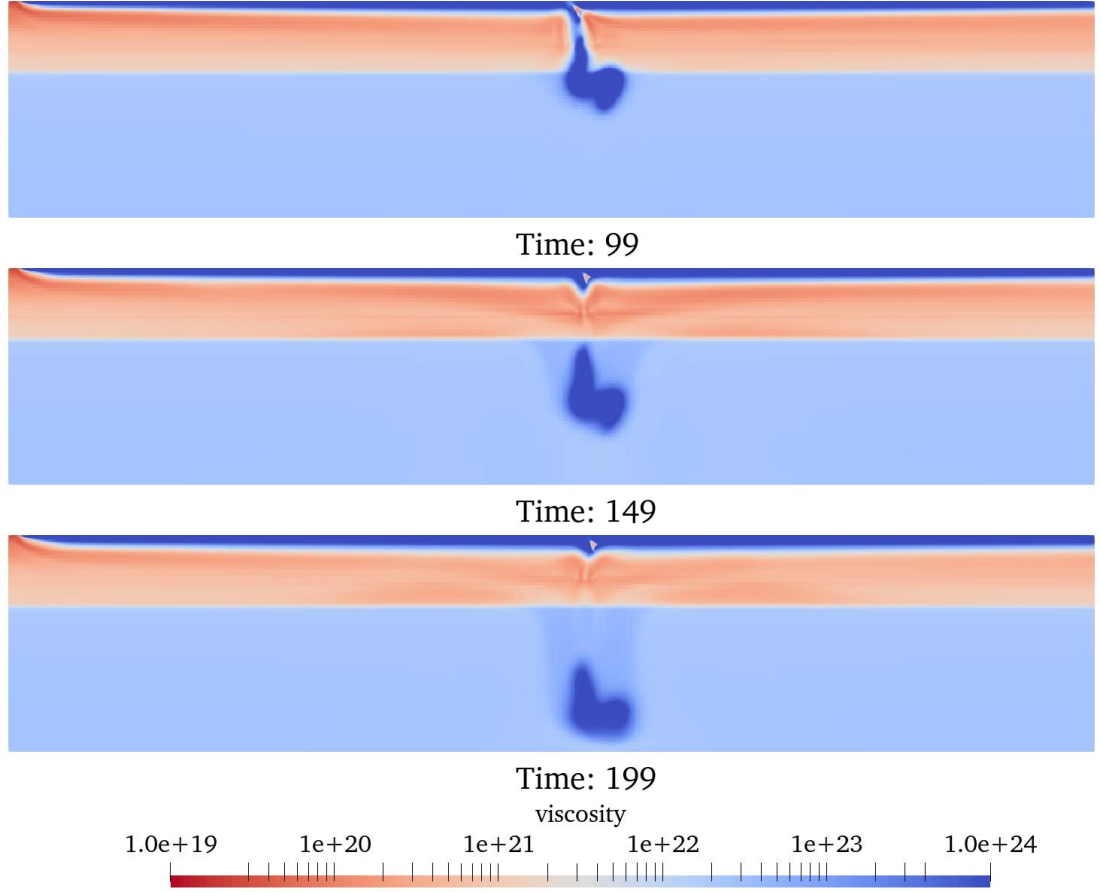


Figure 4.5 Viscosity field in the Norbert_CART model at 99, 149, and 199 Myr, illustrating the evolution of the detached slab fragment during its descent into the mantle. The same logarithmic viscosity scale, ranging from 10^{19} to 10^{24} Pa s, is used in all panels. The full Cartesian model domain is shown in all panels. The domain is 10000 km wide and 2000 km deep.

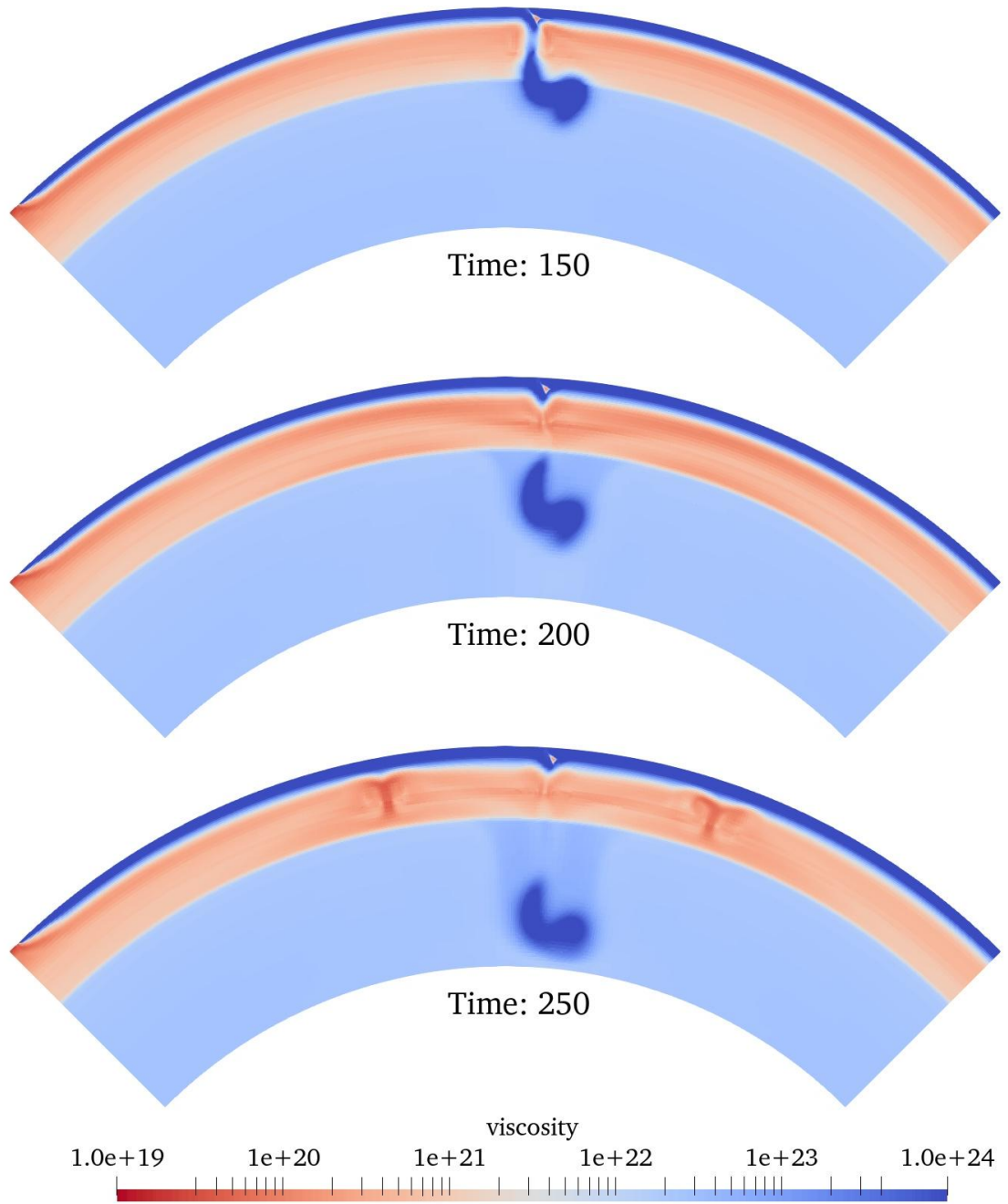


Figure 4.6 Viscosity field in the Norbert_SPH model at 150, 200, and 250 Myr. The figure illustrates the delayed detachment of the slab fragment and its subsequent descent through the mantle. The same logarithmic viscosity scale, ranging from 10^{19} to 10^{24} Pa.s, is used in all panels. The full model domains are shown in all panels. The spherical models are shown in a 90° -wide spherical chunk spanning longitudes 45° – 135° and radii 4371–6371 km, corresponding to a depth range of 0–2000 km and to approximately 10000 km along the surface.

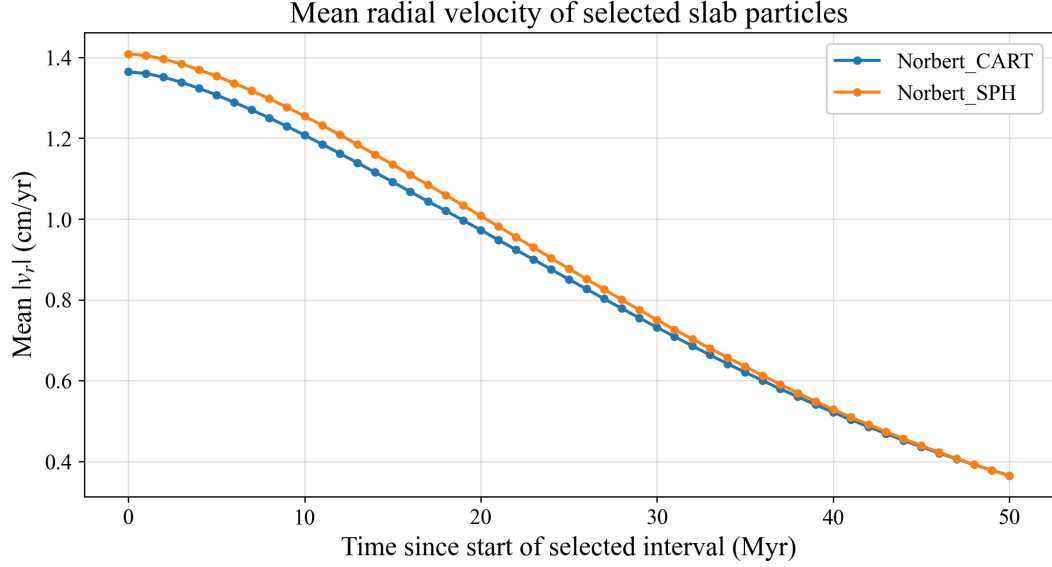


Figure 4.7 Mean absolute radial velocity of selected slab particles in the Norbert_CART and Norbert_SPH models. The average is computed from particles 2, 3, 4, 5, 10, and 11. To compare equivalent post-detachment sinking stages, the 149–199 Myr interval is used for Norbert_CART and the 200–250 Myr interval for Norbert_SPH; both time axes are shifted to start at zero. Velocities are given in cm yr^{-1} .

4.4 Vitek

The Vitek model family represents the most complex setup used in this thesis. In contrast to the generic Tamara and Dobroslav models, it includes continental lithospheric segments in the subducting plate, and a localized **weak_zone** in the overriding plate. The purpose of this model family is not to perform a parameter study, but to test whether a more realistic Hellenic-type plate configuration can be implemented in ASPECT in both spherical and Cartesian geometry, and whether the resulting subduction behaviour remains comparable.

The viscosity fields in Figures 4.9 and 4.10 show that the two Vitek models do not evolve identically. Visible differences appear already during the early stages of subduction, especially in the plate-contact region near the trench, the shallow **weak_layer**, and the overriding-plate **weak_zone**. This behaviour is consistent in comparison with the generic and Norbert model pairs, where the largest geometrical sensitivity was also observed during the initialization and early free-evolution stages. The early interaction between the incoming plate, the overriding plate, and the prescribed weak zone appears to be particularly sensitive to the exact geometrical representation of the trench region.

Despite these differences, the overall character of subduction remains similar in the spherical and Cartesian versions. In both models, the slab descends into the mantle, remains mechanically connected to the shallow plate interface during the early stages, and develops a comparable large-scale morphology by the end of the model evolution. The full-domain snapshots show that the final slab shapes are very similar, while the close-up views indicate that the main differences are concentrated near the trench and the weak zone rather than in the overall style of slab descent.

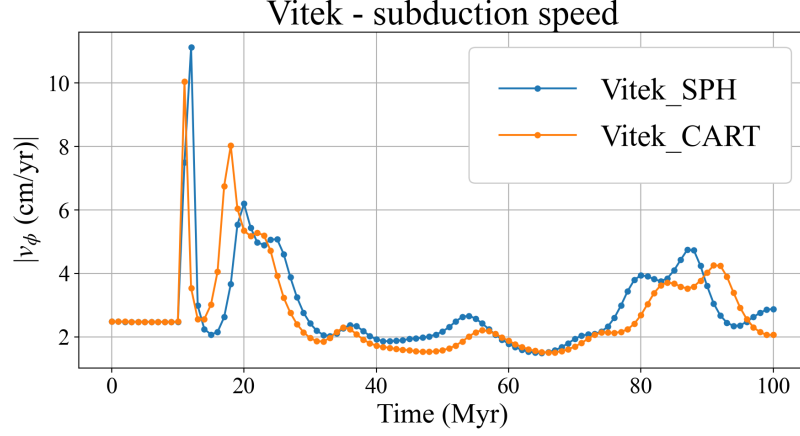


Figure 4.8 Comparison of the subduction speed in the Vitek_SPH and Vitek_CART models. The plotted quantity is the absolute tangential velocity component $|v_\phi|$ of particle 0, which is used as a marker of the subducting plate. Velocities are given in cm yr^{-1} and plotted as a function of model time in Myr.

The plate velocity comparison in Figure 4.8 supports the same interpretation. The absolute tangential velocity of particle 0, used here as a marker of the subducting plate, shows visible quantitative differences between Vitek_SPH and Vitek_CART. However, the shapes of the main velocity peaks are very similar in both geometries. The peaks occur with slightly different timing and amplitude, but they indicate comparable episodes of slab motion and reorganization. This suggests that the two models undergo the same type of dynamical evolution, even though the exact time-dependent trajectories are not identical.

The main result of the Vitek model family is therefore methodological and comparative. The Hellenic-type setup with continental segments and an overriding-plate weak zone was successfully implemented in ASPECT using both the spherical **chunk** geometry and a corresponding Cartesian box geometry. The two coordinate representations lead to visibly different details of the early evolution, most likely due to the sensitivity of the trench and plate-contact region. Nevertheless, the general style of subduction is similar. Within the limits of this single model pair, the transition from Cartesian to spherical geometry changes the quantitative evolution, but does not change the main physical character of the model.

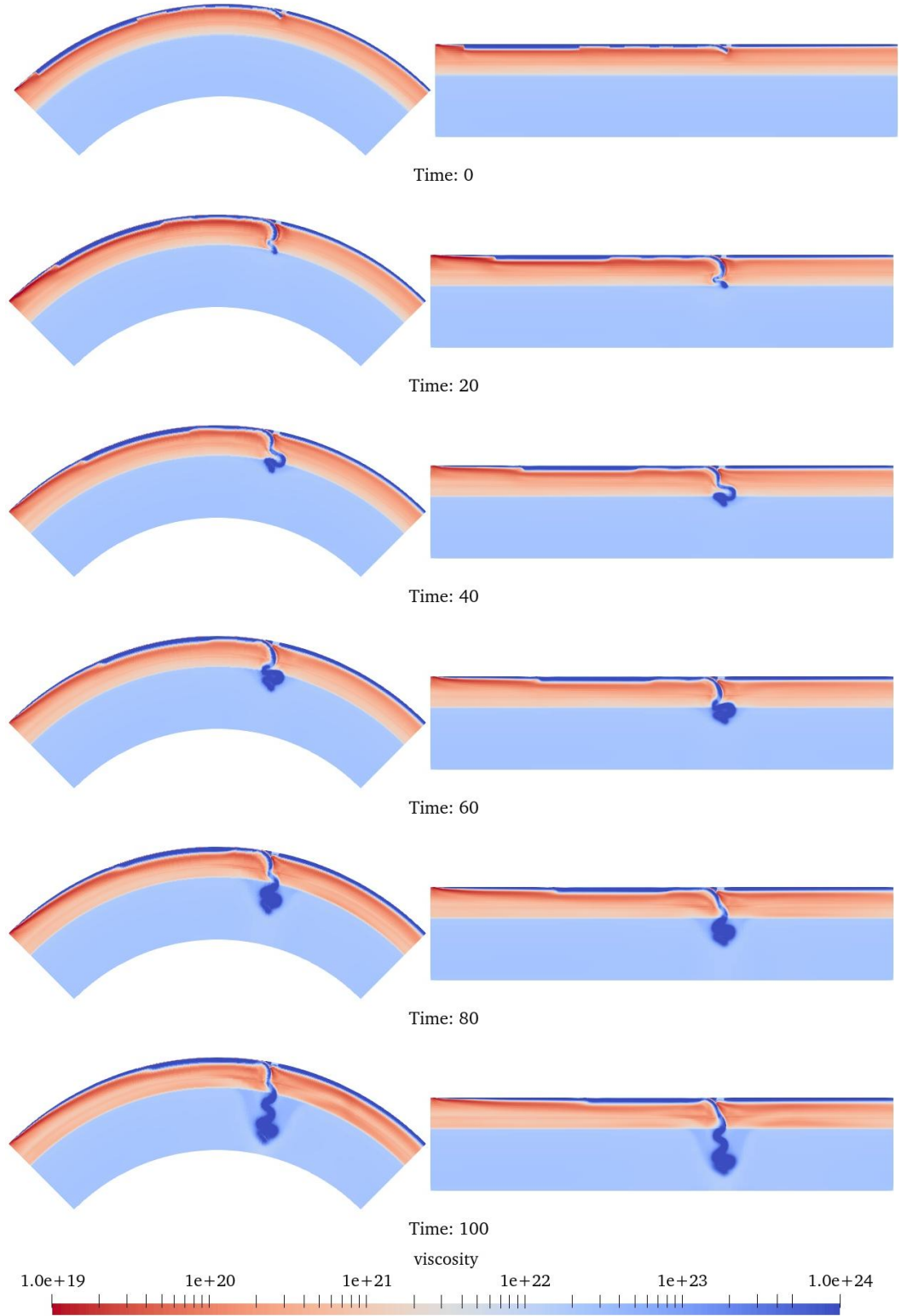


Figure 4.9 Comparison of the viscosity field in the full Vitek_SPH and Vitek_CART model domains at 0, 20, 40, 60, 80, and 100 Myr. The left column shows the spherical model and the right column shows the Cartesian model. The same logarithmic viscosity scale, ranging from 10^{19} to 10^{24} Pa.s, is used in all panels. The full model domains are shown in all panels. The spherical models are shown in a 90° -wide spherical chunk spanning longitudes 45° – 135° and radii 4371–6371 km, corresponding to a depth range of 0–2000 km and to approximately 10000 km along the surface. The Cartesian models are shown in a 10000×2000 km box.

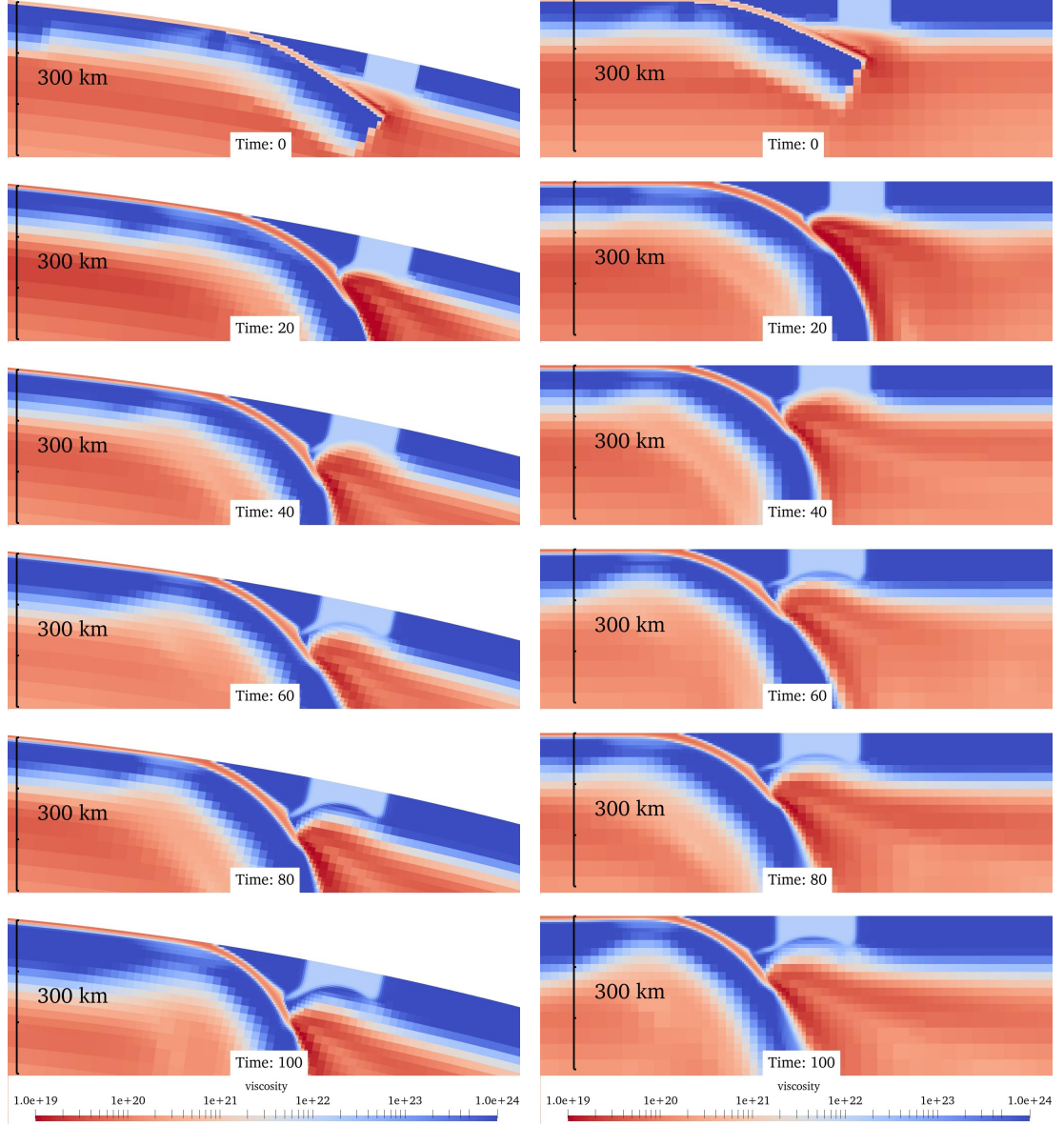


Figure 4.10 Close-up comparison of the viscosity field in the Vitek_SPH and Vitek_CART models. The left column shows the spherical model and the right column shows the Cartesian model at 0, 20, 40, 60, 80, and 100 Myr. The figure illustrates the evolution of the plate-contact region, including the shallow slab interface and the localized **weak_zone** in the overriding plate. The black scale bar has a total length of 300 km. The same logarithmic viscosity scale, ranging from 10^{19} to 10^{24} Pa s, is used in all panels.

5 Discussion

5.1 Simplified treatment of mantle phase transitions

One of the main simplifications of the present models is the treatment of mantle phase transitions. The models include two major phase transitions at depths of 410 km and 660 km, which are implemented as olivine-type transitions with prescribed density jumps and Clapeyron slopes. This approach is useful for isolating the dynamical effect of transition-zone buoyancy forces, but it is not a complete mineralogical description of the mantle.

In reality, olivine represents only about 60 % of the upper mantle mineral assemblage. The remaining material consists of other mineral phases, such as pyroxenes and garnets, which undergo their own phase transitions. A more realistic description would therefore require composition-dependent phase transitions and possibly several distinct compositional layers within the slab. In the present setup, these effects are neglected, so the resulting slab deformation should be interpreted as the response of a simplified mantle composition rather than as a fully mineralogically realistic model.

The importance of this approximation has been demonstrated in previous subduction models [36]. Arredondo and Billen (2016) showed that models including only the olivine phase transitions at 410 km and 660 km can overestimate slab folding and stagnation near the base of the transition zone. When compositional layering and a more complete set of pyrolite phase transitions are included, the slab evolution changes substantially. In particular, the deformation can become less dominated by stagnation at 660 km and more similar to broad, periodic folding.

This is directly relevant to the Tamara models, where increasing the magnitude of the Clapeyron slopes leads to stronger buckling and more episodic slab motion. These features are dynamically consistent within the simplified model setup, but their amplitude may depend on the incomplete representation of mantle mineralogy. Future models should therefore test whether the same rollback, buckling, and detachment behaviour persists when a more realistic composition-dependent phase-transition system is included.

5.2 Resolution and representation of the weak layer

A second important limitation is the use of one chosen mesh-refinement strategy. Using the same resolution setup in all model families is useful for comparison, because differences between runs are then not caused by intentionally changing the grid. However, this also means that the models do not represent a full numerical convergence study.

This is especially important for the shallow **weak_layer**. The layer is geometrically thin, but it strongly influences mechanical coupling between the incoming and overriding plates. Its effective numerical thickness depends on how well the

compositional field is resolved by the mesh and how much numerical diffusion occurs during advection. If the layer is under-resolved, it may become effectively thicker, smoother, or less sharply localized than intended. This can change the effective coupling between the plates and therefore affect rollback, slab bending, and the timing of detachment.

A similar sensitivity was already observed in previous ASPECT modelling work, where changing only the resolution affected the model evolution, especially in the region of plate contact [37]. The results of the present thesis should therefore be understood as internally consistent for the chosen resolution, but not yet fully resolution-independent.

Future work should include systematic resolution tests. A useful approach would be to repeat selected reference models with several refinement levels, while keeping all physical and geometrical parameters unchanged. This would help identify which quantities are robust and which depend on the numerical representation of the weak interface. Such tests would be particularly important for rollback velocity, slab-tip position, timing of detachment, and short velocity peaks associated with buckling.

5.3 Limited parameter-space exploration

The Tamara model family provides a controlled first-order parameter study, but only two parameters are varied systematically: the magnitude of the Clapeyron slopes and the prefactor controlling the shallow weak interface. This makes the interpretation of the results relatively clear, but it covers only a small part of the possible parameter space.

Other parameters may also have a strong influence on the evolution of the slab. These include the thickness and depth extent of the `weak_layer`, the minimum and maximum viscosity cutoffs, the stress limiter, the initial slab geometry, and the thermal age of the subducting plate. In the Vitek models, additional uncertainty is also introduced by the position and thermal structure of the continental segments, and the strength and geometry of the overriding-plate weak zone.

A broader parameter study would make it possible to separate effects that are currently partly coupled. For example, the Tamara models show that stronger interfaces reduce rollback, while larger Clapeyron-slope magnitudes both reduce the total rollback and enhance slab buckling. With a larger model ensemble, it would be possible to test whether these trends persist for different slab ages, different weak-layer thicknesses, or different viscosity limits. We can, however, conclude that the results of the limited parameter search performed here in spherical geometry are in good agreement with findings on the effects of the studied parameters previously reported based on Cartesian models [7, 29, 2, 38].

The main obstacle is computational cost. Long-term thermo-mechanical subduction models with nonlinear rheology, phase transitions, adaptive mesh refinement, and particle tracking are expensive to run. The present model set therefore represents a compromise between physical complexity, numerical resolution, and the number of tested parameter combinations.

5.4 Cartesian and spherical model geometry

The comparison between Cartesian and spherical models suggests that the effect of geometry is most important during the earliest stages of subduction. Visible differences between the corresponding model pairs appear already during the initialization run and shortly after the beginning of the free restart stage. This indicates that the models are particularly sensitive to the detailed geometry of the trench region, where the incoming and overriding plates meet, and to the immediate surroundings of the shallow weak interface.

This sensitivity is not unexpected [39]. The trench region contains strong gradients in temperature, viscosity, composition, and velocity, and it is also the place where the imposed initial slab geometry has to evolve into a mechanically consistent subduction configuration. In the present models, this region is relatively well resolved by the adaptive mesh refinement strategy, so small geometrical differences between the Cartesian and spherical setups are not smoothed out numerically. Instead, they can influence the early force balance, the initial bending of the plate, and the degree of coupling across the weak interface.

More generally, the initiation stage proved to be one of the most sensitive parts of the simulations. During the development of the model setup, the final evolution was visibly affected by the exact prescribed geometry of the initial slab. If the inserted slab was too long, the model had a stronger tendency towards early tearing or detachment. If it was too short, too shallowly dipping, or if the imposed convergence velocity during the initialization stage was too large, subduction could fail to initialize properly, and the incoming plate could remain mechanically attached to the overriding plate instead of developing a stable subduction interface.

For this reason, the comparison between Cartesian and spherical models should not be interpreted as a search for identical time-dependent solutions. The exact timing of individual velocity peaks, buckling episodes, or detachment events is sensitive to the initial configuration. A more meaningful comparison is the overall style of subduction. In the comparison between Dobroslav and Tamara (Figs. 4.3 and 4.4), the velocity peaks often have similar shapes in both geometries, even though they are shifted in time and do not have identical amplitudes. This suggests that the same type of dynamical events occurs in both coordinate representations, but not necessarily at the same model time.

A similar conclusion follows from the Norbert models. The spherical version shows a delayed evolution compared to the Cartesian version, which is most likely connected to the early subduction and detachment stage. However, once comparable post-detachment intervals are aligned, the mean radial sinking velocity of the detached slab fragment differs only slightly between the two geometries. The main difference is therefore not the subsequent sinking rate of the detached slab, but the timing at which the model reaches this stage.

From this point of view, the model pairs are consistent. In both geometries, the slab descends into the mantle, interacts with the transition zone, develops buckling, and exhibits episodic motion. The geometry modifies the quantitative details of the evolution, especially its timing, but it does not change the main physical interpretation of the generic models.

At the same time, the results show that model geometry should not be treated as a purely technical choice. Cartesian models remain useful idealized reference

setups, especially for controlled parameter studies. However, for large model domains, such as the 10000 km wide domains used in this thesis, the curvature of the Earth is no longer negligible. In the ASPECT–GWB workflow used here, constructing a spherical chunk model is not substantially more difficult than constructing the corresponding Cartesian model. Therefore, when the model domain is large enough for curvature to matter, the use of spherical geometry is a natural improvement: it removes an important geometrical limitation without requiring a fundamentally different modelling approach.

Finally, we note that while in our 2D models with limited depth extent of 2000 km the results do not differ substantially between the Cartesian and spherical models, fully 3D spherical models extending down to the core-mantle boundary suggest stronger differences in trench rollback and sinking velocities compared to 3D Cartesian [28] due to the more prominent reduction of space at greater depths.

Conclusion

This thesis investigated simplified two-dimensional models of lithospheric subduction in Cartesian and spherical geometry. The models were constructed in the Geodynamic World Builder and solved with ASPECT. The main aim was to test whether comparable subduction setups can be implemented in both geometries and to evaluate how model geometry, mantle phase transitions, and the strength of the shallow plate interface affect the evolution of a subducting slab.

The first result is methodological. The ASPECT-GWB workflow proved to be suitable for constructing controlled subduction models with prescribed oceanic plates, a shallow weak interface, an initially inserted slab, and mantle phase transitions. The generic spherical model family, Tamara, developed stable subduction after the initialization stage and could therefore be used as a reference setup for a parameter study. This confirms that spherical chunk models can be implemented without substantially changing the modelling strategy used for Cartesian boxes.

The Tamara model family showed that the slab dynamics is sensitive to both parameters tested in this thesis. A stronger shallow interface, represented by a lower lubrication-layer prefactor, reduced trench rollback by increasing the mechanical coupling between the subducting and overriding plates. Increasing the magnitude of the Clapeyron slopes at the 410 km and 660 km phase transitions also reduced the total rollback, but at the same time enhanced slab buckling and made the slab motion more episodic. In the end-member case combining strong phase-transition effects with a strong interface, the slab detached from the surface plate. This demonstrates that rollback, buckling, episodicity, and slab detachment are controlled by the combined effect of interface rheology and transition-zone buoyancy forces.

The comparison between the spherical Tamara models and the Cartesian Dobroslav models showed that the two geometries do not produce identical time-dependent solutions. Differences appear already during the initialization stage and shortly after the beginning of the free evolution, especially near the trench and the shallow plate interface. Nevertheless, the overall character of subduction remains comparable in both geometries. In both Tamara and Dobroslav, the slab descends into the mantle, interacts with the transition zone, develops buckling, and exhibits episodic velocity changes. The geometry therefore mainly affects the timing and amplitude of individual events, rather than changing the basic style of slab evolution.

The Norbert model family provided a second test of the geometry dependence. In these models, the shallow weak interface was shortened in order to follow the descent of a detached slab fragment. The spherical model evolved more slowly during the early detachment stage, and the selected slab material reached the post-detachment sinking stage later than in the Cartesian model. However, after aligning comparable sinking intervals, the mean radial velocities of selected slab particles were nearly the same in both geometries. This indicates that the geometry influences the timing of detachment, but the subsequent sinking rate of the detached slab fragment is robust with respect to the choice of Cartesian or

spherical coordinates.

The Vitek model family extends the same modelling strategy to a more realistic Hellenic-type plate configuration with continental lithospheric segments and a localized weak zone in the overriding plate. The model was implemented in both Cartesian and spherical geometry. As in the generic and shorter-interface models, the two geometries do not produce identical time-dependent evolutions, especially during the early stages near the trench and the plate-contact region. However, the overall character of subduction remains comparable: the slab descends in a similar way, the final viscosity fields are very similar, and the main peaks in the subducting-plate velocity have comparable shapes in both geometries. This suggests that the conclusions obtained from the simpler model families also hold for the more complex Hellenic-type setup: the geometry affects mainly the quantitative details and timing of the evolution, but not the general style of subduction.

The results of this thesis suggest that Cartesian models remain useful idealized setups for studying general trends in subduction dynamics. However, for large model domains, where the curvature of the Earth becomes significant, spherical geometry provides a natural improvement. In the models studied here, spherical geometry did not change the qualitative interpretation of the results, but it did affect the early evolution and the timing of individual dynamical events. Therefore, spherical models are preferable when the aim is to construct large-domain subduction models that are closer to Earth geometry, while Cartesian models can still be used as efficient reference cases.

Several limitations remain. The mantle phase transitions are represented by a simplified olivine-based system with only the 410 km and 660 km transitions, the resolution of the weak layer was not tested systematically, and only a limited part of the parameter space was explored. Future work should therefore include a more complete mineralogical treatment of phase transitions, systematic resolution tests, and broader parameter studies involving weak-layer geometry, viscosity limits, slab age, and overriding-plate weakening. These extensions would help determine which features of the present models are robust and which depend on the simplifying assumptions used here.

Overall, the results presented in this thesis are promising and show that the ASPECT–GWB workflow provides a useful basis for further development of subduction models in Cartesian and spherical geometries. The models remain simplified, but they reproduced several characteristic features of slab evolution, including rollback, buckling, episodic motion, and slab detachment. Future work should extend this approach through broader parameter studies, systematic testing of both physical and numerical parameters, and a more careful exploration of the initial slab and trench geometries. If computational resources allow, the same modelling strategy could also be extended to three dimensions, where along-strike variations and more realistic regional plate configurations could be included.

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A Appendix

The complete numerical input files used in this thesis are provided as electronic supplementary material. They include all ASPECT parameter files, the corresponding Geodynamic World Builder files, and the particle input files. The printed appendix contains selected representative listings and summaries of the main differences between model setups.

A.1 ASPECT parameter files

A.1.1 ASPECT parameter file for Tamara and Norbert_SPH

The following listing shows the ASPECT parameter file used for the spherical Tamara/Norbert_SPH setup. The file is shown in its initialization form. To use it for a restart run, the changes indicated in the comments in the listing have to be applied.

Listing A.1 ASPECT parameter file for the spherical Tamara/Norbert_SPH setup.

```
1 set Dimension = 2
2 set Use years in output instead of seconds = true
3 set End time = 10.2e6
4 # Initialization run ends at 10.2 Myr.
5 # For the restart run, change the end time to the final model time:
6 # set End time = 100e6
7 set Output directory = output
8 set World builder file = sphere.wb
9 set CFL number = 0.5
10 set Maximum time step = 40000
11 set Nonlinear solver scheme = iterated Advection and Stokes
12 set Max nonlinear iterations = 20
13 set Nonlinear solver tolerance = 1e-5
14 # Uncomment the following line for the restart run:
15 #set Resume computation = true
16
17 subsection Checkpointing
18   set Steps between checkpoint = 10
19 end
20
21 subsection Solver parameters
22   set Composition solver tolerance = 1e-12
23   set Temperature solver tolerance = 1e-12
24   subsection Stokes solver parameters
25     set Number of cheap Stokes solver steps = 1000
26     set Maximum number of expensive Stokes solver steps = 50
27     set Linear solver tolerance = 1e-5
28   end
29 end
30
31 subsection Compositional fields
32   set Number of fields = 1
33   set Names of fields = weak_layer
34 end
35
36 subsection Material model
37   set Material averaging = harmonic average only viscosity
38   set Model name = compositing
39   subsection Visco Plastic
40     set Thermal expansivities = background: 2e-5 | 2e-5 | 2e-5 ,weak_layer: 2e-5 | 2e-5 | 2e-5 | 2e-5
41     set Thermal diffusivities = 1e-6, 1e-6
42     set Thermal conductivities = 3.0, 3.0
43     set Reference temperature = 1573
```

```

44 set Minimum viscosity = 1e19
45 set Maximum viscosity = 1e24
46 set Viscous flow law = composite
47 set Viscosity averaging scheme = geometric
48 set Minimum strain rate = 1e-22
49 set Reference strain rate = 1e-15
50 set Heat capacities = background: 1250, weak_layer:1250
51
52 set Prefactors for dislocation creep = background: 31.5e-18 | 31.5e-18 | 6.51e-30
53 , weak_layer: 1e-21 | 31.5e-18 | 31.5e-18 | 6.51e-30
54 set Stress exponents for dislocation creep = background: 3.5 | 3.5 | 1
55 , weak_layer: 1 | 3.5 | 3.5 | 1
56 set Activation energies for dislocation creep = background: 480e3 | 480e3 | 530e3 ,
57 weak_layer: 0 | 480e3 | 480e3 | 530e3
58 set Activation volumes for dislocation creep = background: 1.1e-5 | 1.1e-5 | 1.3e-5 ,
59 weak_layer: 0 | 11e-6 | 11e-6 | 1.3e-5
60 set Prefactors for diffusion creep = background: 1e-9 | 1e-9 | 1.3e-16
61 , weak_layer: 1e-9 | 1e-9 | 1e-9 | 1.3e-16
62 set Grain size exponents for diffusion creep = background: 1 | 1 | 1
63 , weak_layer: 1 | 1 | 1 | 1
64 set Activation energies for diffusion creep = background: 335e3 | 335e3 | 200e3 ,
65 weak_layer: 335e3 | 335e3 | 335e3 | 200e3
66 set Activation volumes for diffusion creep = background: 4e-6 | 4e-6 | 1.1e-6 ,
67 weak_layer: 4e-6 | 4e-6 | 4e-6 | 1.1e-6
68 set Densities = background: 3300 | 3573 | 3914
69 , weak_layer: 3300 | 3300 | 3573 | 3914
70
71 set Grain size = 1
72
73 set Angles of internal friction = 11.53695903, 11.53695903
74 set Cohesions = 2e30, 2e30
75 set Yield mechanism = limiter
76 set Stress limiter exponents = 10
77 set Maximum yield stress = 200e6
78
79 set Phase transition depths = background: 410000 | 660000, weak_layer:
80 150000 | 410000 | 660000
81 set Phase transition temperatures = background: 1680 | 1745 , weak_layer:
82 1600 | 1680 | 1745
83 set Phase transition Clapeyron slopes = background: 2e6 | -2.5e6, weak_layer:
84 0 | 2e6 | -2.5e6
85 set Phase transition widths = background: 15000 | 15000 , weak_layer:
86 15000 | 15000 | 15000
87
88 set Constant viscosity prefactors = 1,1
89 end
90
91 subsection Latent heat
92 set Phase transition density jumps = 273, 341, 0, 273, 341
93 set Corresponding phase for density jump = 0,0, 1,1,1
94
95 set Phase transition depths = background: 410000 | 660000, weak_layer:
96 150000 | 410000 | 660000
97 set Phase transition temperatures = background: 1680 | 1745 , weak_layer:
98 1600 | 1680 | 1745
99 set Phase transition Clapeyron slopes = background: 2e6 | -2.5e6, weak_layer:
100 0 | 2e6 | -2.5e6
101
102 set Phase transition widths = background: 15000 | 15000, weak_layer:
103 15000 | 15000 | 15000
104
105 set Reference specific heat = 1250
106 set Thermal conductivity = 3
107
108 set Thermal expansion coefficient = 2e-5
109 set Viscosity prefactors = 1,1,1,1,1,1
110 set Density differential for compositional field 1 = 0
111 set Reference density = 3300
112 set Compressibility = 0
113 end
114
115 subsection Compositing

```

```

100     set Viscosity = visco plastic
101     set Density = latent heat
102     set Thermal expansion coefficient = latent heat
103     set Specific heat = latent heat
104     set Thermal conductivity = latent heat
105     set Compressibility = latent heat
106     set Entropy derivative pressure = latent heat
107     set Entropy derivative temperature = latent heat
108     set Reaction terms = latent heat
109   end
110 end
111
112 subsection Initial composition model
113   set Model name = world builder
114 end
115
116 subsection Geometry model
117   set Model name = chunk
118   subsection Chunk
119     set Chunk inner radius = 4371e3
120     set Chunk outer radius = 6371e3
121     set Chunk minimum longitude = 45
122     set Chunk maximum longitude = 135
123     set Longitude repetitions = 5
124     set Radius repetitions = 1
125   end
126 end
127
128 subsection Boundary velocity model
129   set Tangential velocity boundary indicators = bottom, east, west #, top
130   set Prescribed velocity boundary indicators = top:function
131   # Initialization run:
132   # The top boundary is driven by the velocity function below.
133   #
134   # Restart run:
135   # Remove the prescribed velocity from the top boundary and make the top
136   # boundary tangential:
137   #
138   # set Tangential velocity boundary indicators = bottom, east, west, top
139   # set Prescribed velocity boundary indicators = top:function
140   #
141   # The Function subsection can remain in the file; it is ignored if no
142   # boundary uses top:function.
143   subsection Function
144     set Coordinate system = spherical
145     set Use spherical unit vectors = true
146     set Variable names = r, phi
147     set Function expression = 0; if(phi>1.57, -0.025,0)
148   end
149 end
150
151 subsection Heating model
152   set List of model names = adiabatic heating, constant heating, shear heating, latent heat
153   subsection Adiabatic heating
154     set Use simplified adiabatic heating = true
155   end
156   subsection Constant heating
157     set Radiogenic heating rate = 0
158   end
159 end
160
161 subsection Boundary temperature model
162   set Fixed temperature boundary indicators = top, bottom
163   set List of model names = initial temperature
164 end
165
166 set Adiabatic surface temperature = 1573
167
168 subsection Initial temperature model
169   set Model name = world builder
170 end
171
172 subsection Gravity model

```

```

173 set Model name = radial constant
174 subsection Radial constant
175     set Magnitude = 9.81
176 end
177 end
178
179 subsection Mesh refinement
180     set Initial global refinement      = 5
181     set Initial adaptive refinement    = 4
182     set Skip solvers on initial refinement = true
183     set Strategy                      = minimum refinement function , maximum refinement
        function, viscosity , composition threshold
184     subsection Minimum refinement function
185         set Coordinate system = spherical
186         set Variable names = r, phi
187         set Function expression = if(r>6341e3,if(phi>1.57,8,6),if(r>6271e3,6,if(r>5671e3,6,4)))
188     end
189     subsection Maximum refinement function
190         set Coordinate system = spherical
191         set Variable names = r, phi
192         set Function expression = if(r>6341e3,if(phi>1.57,9,7),if(r>6271e3,7,if(r>5671e3,7,7)))
193     end
194     subsection Composition threshold
195         set Compositional field thresholds = 0.1
196     end
197     set Time steps between mesh refinement = 10
198 end
199
200 subsection Particles
201     set Particle generator name      = ascii file
202     set Integration scheme           = rk2
203     set Interpolation scheme         = cell average
204     set List of particle properties   = pT path, velocity, position, initial position
205     set Allow cells without particles = true
206
207     subsection Generator
208         subsection Ascii file
209             set Data directory = ./
210             set Data file name = particle_positions.dat
211         end
212     end
213 end
214
215 subsection Postprocess
216     set List of postprocessors = velocity statistics, temperature statistics, visualization, heat
        flux statistics, depth average, particles
217
218     subsection Particles
219         set Data output format      = ascii, vtu
220         set Number of grouped files = 1
221         set Time between data output = 1e6
222     end
223     subsection Depth average
224         set Time between graphical output = 1e6
225         set Number of zones = 100
226     end
227     subsection Visualization
228         set Number of grouped files      = 1
229         set Output format                 = vtu
230         set Time between graphical output = 1e6
231         set List of output variables = material properties, strain rate, strain rate tensor, stress,
            shear stress, stress second invariant, principal stress, temperature anomaly, spherical
            velocity components, adiabat, heating
232     end
233 end

```

A.1.2 Changes for the Dobroslav and Norbert Cartesian model

The Dobroslav parameter file differs from the spherical Tamara/Norbert_SPH parameter file only in the settings related to Cartesian geometry, boundary velocity, gravity, mesh refinement, and visualization output. The material model, solver settings, heating model, particle setup, and most postprocessing settings are unchanged.

Listing A.2 Parameter-file settings that differ in the Dobroslav Cartesian model.

```
1 # World Builder file
2 set World builder file = dobroslav.wb
3
4
5 # -----
6 # Cartesian geometry
7 # -----
8
9 subsection Geometry model
10   set Model name = box
11   subsection Box
12     set X extent = 10000e3
13     set Y extent = 2000e3
14     set X repetitions = 5
15   end
16 end
17
18
19 # -----
20 # Boundary velocity model
21 # -----
22
23 subsection Boundary velocity model
24   set Tangential velocity boundary indicators = bottom, left, right
25   set Prescribed velocity boundary indicators = top:function
26
27   # Initialization run:
28   # The top boundary is driven on the subducting-plate side of the trench.
29   #
30   # Restart run:
31   # Remove the prescribed top-boundary velocity and make the top boundary
32   # tangential:
33   #
34   #   set Tangential velocity boundary indicators = bottom, left, right, top
35   #   # set Prescribed velocity boundary indicators = top:function
36   #
37   # The Function subsection can remain in the file; it is ignored if no
38   # boundary uses top:function.
39
40   subsection Function
41     set Variable names = x, y
42     set Function expression = if(x<5000e3, 0.025, 0); 0
43   end
44 end
45
46
47 # -----
48 # Gravity model
49 # -----
50
51 subsection Gravity model
52   set Model name = vertical
53   subsection Vertical
54     set Magnitude = 9.81
55   end
56 end
57
58
59 # -----
```

```

60 # Mesh refinement
61 # -----
62
63 subsection Mesh refinement
64   set Initial global refinement      = 5
65   set Initial adaptive refinement    = 4
66   set Skip solvers on initial refinement = true
67   set Strategy                      = minimum refinement function, maximum refinement function,
        viscosity, composition threshold
68
69   subsection Minimum refinement function
70     set Coordinate system = cartesian
71     set Variable names = x, y
72
73     # Box y-coordinate is measured upward from the bottom.
74     # For a 2000 km deep box:
75     # y > 1970 km corresponds to the upper 30 km,
76     # y > 1900 km corresponds to the upper 100 km,
77     # y > 1300 km corresponds to the upper 700 km.
78
79     set Function expression = if(y>1970e3, if(x<5000e3, 8, 6), if(y>1900e3, 6, if(y>1300e3, 6, 4)
80   ))
81 end
82
83 subsection Maximum refinement function
84   set Coordinate system = cartesian
85   set Variable names = x, y
86   set Function expression = if(y>1970e3, if(x<5000e3, 9, 7), if(y>1900e3, 7, if(y>1300e3, 7, 7)
87   ))
88 end
89
90 subsection Composition threshold
91   set Compositional field thresholds = 0.1
92 end
93
94 set Time steps between mesh refinement = 10
95 end
96
97 # -----
98 # Visualization output
99 # -----
100
101 subsection Postprocess
102   subsection Visualization
103     set List of output variables = material properties, strain rate, strain rate tensor, stress,
        shear stress, stress second invariant, principal stress, temperature anomaly, adiabat,
        heating
104   end
105 end

```

A.1.3 Changes for the Vitek_SPH model

The Vitek_SPH parameter file is based on the spherical Tamara parameter file. Only the settings that differ from Tamara are listed below.

Listing A.3 Parameter-file settings that differ in the Vitek_SPH model relative to Tamara.

```

1 # World Builder file
2 set World builder file = Vitek_SPH.wb
3
4
5 # -----
6 # Compositional fields
7 # -----
8
9 subsection Compositional fields
10   set Number of fields = 2
11   set Names of fields = weak_layer, weak_zone

```

```

12 end
13
14
15 # -----
16 # Material model
17 # -----
18
19 subsection Material model
20   subsection Visco Plastic
21
22   # Vitek uses the same rheological structure as Tamara, but includes
23   # an additional compositional field weak_zone and Vitek-specific thermal
24   # parameters.
25
26   set Thermal expansivities = background: 2e-5 | 2e-5 | 2e-5 , weak_layer: 2e-5 | 2e-5 | 2e-5 | 2e-5
27   , weak_zone: 2e-5 | 2e-5 | 2e-5
28   set Thermal diffusivities = 6.79157e-7, 6.79157e-7, 6.79157e-7
29   set Thermal conductivities = 2.9, 2.9, 2.9
30
31   set Minimum viscosity = background: 1e19, weak_layer: 1e19, weak_zone: 1e19
32   set Maximum viscosity = background: 1e24, weak_layer: 1e24, weak_zone: 1.5e22
33
34   set Heat capacities = background: 1250, weak_layer: 1250, weak_zone: 1250
35
36   set Prefactors for dislocation creep = background: 31.5e-18 | 31.5e-18 | 6.51e-30 ,
37   weak_layer: 1e-21 | 31.5e-18 | 31.5e-18 | 6.51e-30 , weak_zone: 31.5e-18 | 31.5e-18 | 6.51
38   e-30
39   set Stress exponents for dislocation creep = background: 3.5 | 3.5 | 1 ,
40   weak_layer: 1 | 3.5 | 3.5 | 1 , weak_zone: 3.5 | 3.5 | 1
41   set Activation energies for dislocation creep = background: 480e3 | 480e3 | 530e3 ,
42   weak_layer: 0 | 480e3 | 480e3 | 530e3 , weak_zone: 480e3 | 480e3 | 530e3
43   set Activation volumes for dislocation creep = background: 1.1e-5 | 1.1e-5 | 1.3e-5 ,
44   weak_layer: 0 | 1.1e-6 | 1.1e-6 | 1.3e-5 , weak_zone: 1.1e-5 | 1.1e-5 | 1.3e-5
45
46   set Prefactors for diffusion creep = background: 1e-9 | 1e-9 | 1.3e-16 ,
47   weak_layer: 1e-9 | 1e-9 | 1e-9 | 1.3e-16 , weak_zone: 1e-9 | 1e-9 | 1.3e-16
48   set Grain size exponents for diffusion creep = background: 1 | 1 | 1 ,
49   weak_layer: 1 | 1 | 1 | 1 , weak_zone: 1 | 1 | 1
50   set Activation energies for diffusion creep = background: 335e3 | 335e3 | 200e3 ,
51   weak_layer: 335e3 | 335e3 | 335e3 | 200e3 , weak_zone: 335e3 | 335e3 | 200e3
52   set Activation volumes for diffusion creep = background: 4e-6 | 4e-6 | 1.1e-6 ,
53   weak_layer: 4e-6 | 4e-6 | 4e-6 | 1.1e-6 , weak_zone: 4e-6 | 4e-6 | 1.1e-6
54
55   set Densities = background: 3300 | 3573 | 3914, weak_layer: 3300 | 3300 | 3573 | 3914,
56   weak_zone: 3300 | 3573 | 3914
57
58   set Angles of internal friction = 11.53695903, 11.53695903, 11.53695903
59   set Cohesions = 2e30, 2e30, 2e30
60
61   set Phase transition depths = background: 410000 | 660000, weak_layer: 150000 |
62   410000 | 660000, weak_zone: 410000 | 660000
63   set Phase transition temperatures = background: 1680 | 1745 , weak_layer: 1600 |
64   1680 | 1745, weak_zone: 1680 | 1745
65   set Phase transition Clapeyron slopes = background: 2e6 | -2.5e6, weak_layer: 0 | 2e6
66   | -2.5e6 , weak_zone: 2e6 | -2.5e6
67   set Phase transition widths = background: 15000 | 15000 , weak_layer: 15000 |
68   15000 | 15000 , weak_zone: 15000 | 15000
69
70   set Constant viscosity prefactors = 1,1,1
71 end
72
73 subsection Latent heat
74
75   # The latent-heat model uses the same phase-transition structure as in
76   # Tamara for the background and weak_layer materials, but the thermal
77   # conductivity is changed consistently with the Vitek setup.
78
79   set Thermal conductivity = 2.9
80
81   # The weak_zone field has zero density differential; it is used only
82   # to reduce the maximum viscosity in the overriding plate.
83   set Density differential for compositional field 1 = 0
84 end

```

```

70 end
71
72
73 # -----
74 # Boundary velocity model
75 # -----
76
77 subsection Boundary velocity model
78   set Tangential velocity boundary indicators = bottom, east, west #, top
79   set Prescribed velocity boundary indicators = top:function
80
81   # Initialization run:
82   # The trench in Vitek_SPH is shifted to phi = 81 degrees.
83   # In radians, this is approximately phi = 1.4137.
84   #
85   # Restart run:
86   # Remove the prescribed top-boundary velocity and make the top boundary
87   # tangential:
88   #
89   #   set Tangential velocity boundary indicators = bottom, east, west, top
90   #   # set Prescribed velocity boundary indicators = top:function
91
92   subsection Function
93     set Coordinate system = spherical
94     set Use spherical unit vectors = true
95     set Variable names = r, phi
96     set Function expression = 0; if(phi > 1.4137, -0.025,0)
97   end
98 end
99
100
101 # -----
102 # Mesh refinement
103 # -----
104
105 subsection Mesh refinement
106   subsection Minimum refinement function
107     set Coordinate system = spherical
108     set Variable names = r, phi
109
110     # The longitude threshold follows the shifted Vitek trench at phi = 81 degrees.
111
112     set Function expression = if(r>6341e3,if(phi > 1.4137,8,6),if(r>6271e3,6,if(r>5671e3,6,4)))
113   end
114
115   subsection Maximum refinement function
116     set Coordinate system = spherical
117     set Variable names = r, phi
118     set Function expression = if(r>6341e3,if(phi > 1.4137,9,7),if(r>6271e3,7,if(r>5671e3,7,7)))
119   end
120
121   subsection Composition threshold
122     set Compositional field thresholds = 0.1, 0.1
123   end
124 end

```

A.1.4 Changes for the Vitek_CART model

The Vitek_CART parameter file is based on the Vitek_SPH parameter file. Only the settings that differ from the spherical version are listed below.

Listing A.4 Parameter-file settings that differ in the Vitek_CART model relative to Vitek_SPH.

```

1 # World Builder file
2 set World builder file = Vitek_CART.wb
3
4
5 # -----
6 # Cartesian geometry

```

```

7 # -----
8
9 subsection Geometry model
10 set Model name = box
11 subsection Box
12 set X extent = 10000e3
13 set Y extent = 2000e3
14 set X repetitions = 5
15 end
16 end
17
18 # -----
19 # Boundary velocity model
20 # -----
21
22
23 subsection Boundary velocity model
24 set Tangential velocity boundary indicators = bottom, left, right
25 set Prescribed velocity boundary indicators = top:function
26
27 # Initialization run:
28 # The trench in Vitek_CART is located at x = 6000 km.
29 # The top boundary is driven only on the subducting-plate side
30 # of the trench.
31 #
32 # Restart run:
33 # Remove the prescribed top-boundary velocity and make the top
34 # boundary tangential:
35 #
36 # set Tangential velocity boundary indicators = bottom, left, right, top
37 # set Prescribed velocity boundary indicators = top:function
38 #
39 # The Function subsection can remain in the file; it is ignored if no
40 # boundary uses top:function.
41
42 subsection Function
43 set Coordinate system = cartesian
44 set Variable names = x, y
45 set Function expression = if(x<6000e3, 0.025, 0); 0
46 end
47 end
48
49 # -----
50 # Gravity model
51 # -----
52
53
54 subsection Gravity model
55 set Model name = vertical
56 subsection Vertical
57 set Magnitude = 9.81
58 end
59 end
60
61 # -----
62 # Mesh refinement
63 # -----
64
65
66 subsection Mesh refinement
67 set Initial global refinement = 5
68 set Initial adaptive refinement = 4
69 set Skip solvers on initial refinement = true
70 set Strategy = minimum refinement function, maximum refinement function,
    viscosity, composition threshold
71
72 subsection Minimum refinement function
73 set Coordinate system = cartesian
74 set Variable names = x, y
75
76 # Box y-coordinate is measured upward from the bottom.
77 # For a 2000 km deep box:
78 # y > 1970 km corresponds to the upper 30 km,

```

```

79 # y > 1900 km corresponds to the upper 100 km,
80 # y > 1300 km corresponds to the upper 700 km.
81 #
82 # The x-threshold follows the shifted Vitek trench at x = 6000 km.
83
84 set Function expression = if(y>1970e3,if(x < 6000e3,8,6),if(y>1900e3,6,if(y>1300e3,6,4)))
85 end
86
87 subsection Maximum refinement function
88   set Coordinate system = cartesian
89   set Variable names = x, y
90   set Function expression = if(y>1970e3,if(x < 6000e3,9,7),if(y>1900e3,7,if(y>1300e3,7,7)))
91 end
92
93 subsection Composition threshold
94   set Compositional field thresholds = 0.1, 0.1
95 end
96
97 set Time steps between mesh refinement = 10
98 end
99
100
101 # -----
102 # Visualization output
103 # -----
104
105 subsection Postprocess
106   subsection Visualization
107     set List of output variables = material properties, strain rate, strain rate tensor, stress,
108     shear stress, stress second invariant, principal stress, temperature anomaly, adiabat,
109     heating
110   end
111 end

```

A.2 Geodynamic World Builder files

The following section summarizes the Geodynamic World Builder input files used to prescribe the initial model geometries. For the generic model families, one representative file is shown in full and the corresponding Norbert variant is documented only by the settings that differ from it. The Vitek models are listed as complete files, because their Hellenic-type setup contains additional features, including continental lithospheric segments and a weak zone in the overriding plate, and therefore differs more substantially from the generic models.

A.2.1 World Builder file for Tamara and Norbert_SPH

The following listing shows the Geodynamic World Builder file used for the spherical Tamara model. The Norbert_SPH model is based on the same spherical setup, but uses a shortened shallow **weak_layer** on the incoming plate. Only the settings that differ in Norbert_SPH are listed after the full Tamara file.

Listing A.5 Geodynamic World Builder file for the spherical Tamara model.

```

1 {
2   "version": "1.0",
3   "coordinate system": {"model": "spherical",
4   "depth method": "begin at end segment",
5   "radius": 6371000.0},
6   "cross section": [[0,0],[180,0]],
7   "surface temperature": 273, "potential mantle temperature": 1573,
8   "thermal expansion coefficient": 2e-5,
9   "specific heat": 1250, "thermal diffusivity": 1.0e-6,
10  "features":

```

```

11 | [
12 |
13 | // mantle material and temperature
14 |
15 |     {"model": "mantle layer",
16 |      "name": "mantle",
17 |      "min depth": 0e3, "max depth": 2000e3,
18 |      "coordinates": [[45,-1],[135,-1],[135,1],[45,1]],
19 |      "composition models": [{"model": "uniform", "compositions": [1]}]},
20 |
21 |
22 | {"model": "oceanic plate", "name": "Overriding",
23 |  "min depth": -10e3, "max depth": 150e3,
24 |  "coordinates" : [[45,-5],[45,5],[90,5],[90,-5]],
25 |  "temperature models": [{"model": "plate model", "min depth": -10e3, "max depth": 170e3, "bottom
26 |  temperature": -1, "spreading velocity": 0.05,
27 |  "ridge coordinates": [[46,-5],[46,5]]
28 |  }],
29 |  "composition models": [{"model": "uniform", "max depth": 7.5e3, "compositions": [1]},
30 |  {"model": "uniform", "min depth": 7.5e3, "max depth": 150e3, "
31 |  compositions": [1]}]},
32 |
33 | {"model": "oceanic plate", "name": "right weak ridge",
34 |  "min depth": -10e3, "max depth": 50e3,
35 |  "coordinates" : [[44,-5],[44,5],[46,5],[46,-5]],
36 |  "temperature models": [{"model": "linear", "min depth": -10e3, "max depth": 50e3, "top
37 |  temperature": 1573, "bottom temperature": -1}],
38 |  "composition models": [{"model": "uniform", "max depth": 2000e3, "compositions": [1]}]},
39 |
40 | {"model": "oceanic plate", "name": "Subducting with crust",
41 |  "min depth": -10e3, "max depth": 350e3,
42 |  "coordinates" : [[90,-5],[90,5],[132,5],[132,-5]],
43 |  "temperature models": [{"model": "plate model", "min depth": -10e3, "max depth": 170e3, "bottom
44 |  temperature": -1, "spreading velocity": 0.05,
45 |  "ridge coordinates": [[135,-5],[135,5]]
46 |  }],
47 |  "composition models": [{"model": "uniform", "min depth": -10e3, "max depth": 7.5e3, "
48 |  compositions": [0]},
49 |  {"model": "uniform", "min depth": 7.5e3, "max depth": 150e3, "
50 |  compositions": [1]}]},
51 |
52 | {"model": "oceanic plate", "name": "Subducting withOUT crust",
53 |  "min depth": -10e3, "max depth": 350e3,
54 |  "coordinates" : [[132,-5],[132,5],[135,5],[135,-5]],
55 |  "temperature models": [{"model": "plate model", "min depth": -10e3, "max depth": 170e3, "bottom
56 |  temperature": -1, "spreading velocity": 0.05,
57 |  "ridge coordinates": [[135,-5],[135,5]]
58 |  }],
59 |  "composition models": [{"model": "uniform", "max depth": 7.5e3, "compositions": [1]},
60 |  {"model": "uniform", "min depth": 7.5e3, "max depth": 150e3, "
61 |  compositions": [1]}]},
62 |
63 | {"model": "oceanic plate", "name": "Left weak ridge",
64 |  "min depth": -10e3, "max depth": 50e3,
65 |  "coordinates" : [[134,-5],[134,5],[135,5],[135,-5]],
66 |  "temperature models": [{"model": "linear", "min depth": -10e3, "max depth": 50e3, "top
67 |  temperature": 1573, "bottom temperature": -1}],
68 |  "composition models": [{"model": "uniform", "max depth": 2000e3, "compositions": [1]}]},
69 |
70 | {"model": "subducting plate", "name": "Slab",
71 |  "coordinates": [[90,-5],[90,5]],
72 |  "dip point": [0,0], "max depth": 1000e3,
73 |  "segments": [{"length": 200e3, "thickness": [150e3,120e3], "angle": [0,25]},
74 |  {"length": 180e3, "thickness": [120e3,120e3], "angle": [25]}],
75 |  "composition models": [{"model": "uniform", "compositions": [0], "max distance slab top": 7.5e3,
76 |  {"model": "uniform", "compositions": [1], "min distance slab top": 7.5e3, "
77 |  "max distance slab top": 200e3 }]},
78 |  "temperature models": [{"model": "mass conserving",

```

```

74     "reference model name": "plate model",
75     "density":3416, "thermal conductivity":3.0,"adiabatic heating":true,
76     "spreading velocity":0.05,
77     "subducting velocity":0.05,
78     "ridge coordinates":[[[135,-5],[135,5]]],
79     "coupling depth":100e3,
80     "forearc cooling factor":0.0,
81     "taper distance":0e3,
82     "min distance slab top":-200e3, "max distance slab top":400e3}]
83 }
84 ]
85 }

```

Listing A.6 Settings that differ in the Norbert_SPH World Builder file relative to Tamara.

```

1  # The Norbert_SPH model uses the same spherical setup as Tamara.
2  # The main difference is the shortened shallow weak_layer on the incoming plate.
3  # In Tamara, the weak_layer extends from 90 to 132 degrees.
4  # In Norbert_SPH, it extends only from 90 to 102 degrees.
5  # The near-ridge part of the incoming plate between 102 and 135 degrees
6  # does not contain the weak_layer.
7
8  # -----
9  # Overriding plate ridge
10 # -----
11
12 # Tamara:
13 # "ridge coordinates":[[[46,-5],[46,5]]]
14
15 # Norbert_SPH:
16 "ridge coordinates":[[[42,-5],[42,5]]]
17
18
19 # -----
20 # Removed right weak ridge
21 # -----
22
23 # The "right weak ridge" feature present in Tamara is not used in Norbert_SPH.
24 # The right side of the model domain is therefore not softened by this additional
25 # hot ridge feature.
26
27
28 # -----
29 # Subducting plate with weak_layer
30 # -----
31
32 # Tamara:
33 # "coordinates" :[[[90,-5],[90,5],[132,5],[132,-5]]]
34
35 # Norbert_SPH:
36 {"model":"oceanic plate", "name":"Subducting with crust",
37  "min depth":-10e3, "max depth":350e3,
38  "coordinates" :[[[90,-5],[90,5],[102,5],[102,-5]]],
39  "temperature models":[{"model":"plate model", "min depth":-10e3, "max depth":170e3, "bottom
40    temperature":-1,"spreading velocity":0.05,
41    "ridge coordinates":[[[135,-5],[135,5]]]
42    }],
43  "composition models":[{"model":"uniform", "min depth":-10e3, "max depth":7.5e3, "compositions"
44    :[0]},
45    {"model":"uniform", "min depth":7.5e3, "max depth":150e3, "compositions"
46    :[1]}}],
47
48 # -----
49 # Subducting plate without weak_layer
50 # -----
51
52 # Tamara:
53 # "coordinates" :[[[132,-5],[132,5],[135,5],[135,-5]]]
54
55 # Norbert_SPH:

```

```

54 {"model":"oceanic plate", "name":"Subducting withOUT crust",
55   "min depth":-10e3, "max depth":350e3,
56   "coordinates" :[[102,-5],[102,5],[135,5],[135,-5]],
57   "temperature models":[{"model":"plate model", "min depth":-10e3, "max depth":170e3, "bottom
    temperature":-1, "spreading velocity":0.05,
58   "ridge coordinates":[[135,-5],[135,5]]
59   }],
60   "composition models":[{"model":"uniform", "max depth":7.5e3, "compositions":[1]},
    {"model":"uniform", "min depth":7.5e3, "max depth":150e3, "compositions"
61   :[1]}]}

```

A.2.2 World Builder file for Dobroslav and Norbert_CART

The following listing shows the Geodynamic World Builder file used for the Cartesian Dobroslav model. The Norbert_CART model is based on the same Cartesian setup, but uses a shortened shallow **weak_layer** on the incoming plate. In addition, the right weak-ridge feature present in Dobroslav is omitted. Only the settings that differ in Norbert_CART are listed after the full Dobroslav file.

Listing A.7 Geodynamic World Builder file for the Cartesian Dobroslav model.

```

1 {
2   "version":"1.0",
3   "coordinate system":{"model":"cartesian"},
4   "cross section":[[0,0],[10000e3,0]],
5   "surface temperature":273, "potential mantle temperature":1573,
6   "thermal expansion coefficient":2e-5,
7   "specific heat":1250, "thermal diffusivity":1.0e-6,
8   "features":
9   [
10
11   // mantle material and temperature
12
13   {"model":"mantle layer",
14    "name":"mantle",
15    "min depth":0e3, "max depth":2000e3,
16    "coordinates":[[0,-1],[10000e3,-1],[10000e3,1],[0,1]],
17    "composition models":[{"model":"uniform", "compositions":[1]}]},
18
19
20   {"model":"oceanic plate", "name":"Overriding",
21    "min depth":-10e3, "max depth":150e3,
22    "coordinates" :[[5000e3,-5],[5000e3,5],[10000e3,5],[10000e3,-5]],
23    "temperature models":[{"model":"plate model", "min depth":-10e3, "max depth":170e3, "bottom
    temperature":-1, "spreading velocity":0.05,
24    "ridge coordinates":[[9900e3,-5],[9900e3,5]]
25    }],
26    "composition models":[{"model":"uniform", "max depth":7.5e3, "compositions":[1]},
    {"model":"uniform", "min depth":7.5e3, "max depth":150e3, "
27    compositions":[1]}]},
28
29
30   {"model":"oceanic plate", "name":"right weak ridge",
31    "min depth":-10e3, "max depth":50e3,
32    "coordinates" :[[10100e3,-5],[10100e3,5],[9900e3,5],[9900e3,-5]],
33    "temperature models":[{"model":"linear", "min depth":-10e3, "max depth":50e3, "top
    temperature":1573, "bottom temperature":-1}],
34    "composition models":[{"model":"uniform", "max depth":2000e3, "compositions":[1]}]},
35
36
37   {"model":"oceanic plate", "name":"Subducting with crust",
38    "min depth":-10e3, "max depth":350e3,
39    "coordinates" :[[300e3,-5],[300e3,5],[5000e3,5],[5000e3,-5]],
40    "temperature models":[{"model":"plate model", "min depth":-10e3, "max depth":170e3, "bottom
    temperature":-1, "spreading velocity":0.05,
41    "ridge coordinates":[[0e3,-5],[0e3,5]]
42    }],

```

```

43     "composition models":[{"model":"uniform", "min depth":-10e3, "max depth":7.5e3, "
compositions":[0]},
44         {"model":"uniform", "min depth":7.5e3, "max depth":150e3, "
compositions":[1]}]},
45
46
47 {"model":"oceanic plate", "name":"Subducting withOUT crust",
48     "min depth":-10e3, "max depth":350e3,
49     "coordinates" :[[0e3,-5],[0e3,5],[300e3,5],[300e3,-5]],
50     "temperature models":[{"model":"plate model", "min depth":-10e3, "max depth":170e3, "bottom
temperature":-1,"spreading velocity":0.05,
51     "ridge coordinates":[[0e3,-5],[0e3,5]]
52     }],
53     "composition models":[{"model":"uniform", "max depth":7.5e3, "compositions":[1]},
54         {"model":"uniform", "min depth":7.5e3, "max depth":150e3, "
compositions":[1]}]},
55
56
57 {"model":"oceanic plate", "name":"Left weak ridge",
58     "min depth":-10e3, "max depth":50e3,
59     "coordinates" :[[ -100e3,-5],[ -100e3,5],[100e3,5],[100e3,-5]],
60     "temperature models":[{"model":"linear", "min depth":-10e3, "max depth":50e3, "top
temperature":1573, "bottom temperature":-1}],
61     "composition models":[{"model":"uniform", "max depth":2000e3, "compositions":[1]}]},
62
63
64 { "model":"subducting plate", "name":"Slab",
65     "coordinates":[[5000e3,-5],[5000e3,5]],
66     "dip point":[5500e3,0], "max depth":1000e3,
67     "segments":[{"length":200e3, "thickness":[150e3,120e3], "angle":[0,25]},
68         {"length":180e3, "thickness":[120e3,120e3], "angle":[25]}]},
69     "composition models":[{"model":"uniform", "compositions":[0], "max distance slab top":7.5e3},
70         {"model":"uniform", "compositions":[1], "min distance slab top":7.5e3,
"max distance slab top":200e3 }],
71     "temperature models":[{"model":"mass conserving",
72         "reference model name": "plate model",
73         "density":3416, "thermal conductivity":3.0,"adiabatic heating":true,
74         "spreading velocity":0.05,
75         "subducting velocity":0.05,
76         "ridge coordinates":[[0e3,-5],[0e3,5]]},
77         "coupling depth":100e3,
78         "forearc cooling factor":0.0,
79         "taper distance":0e3,
80         "min distance slab top":-200e3, "max distance slab top":400e3}]
81     }
82 ]
83 }

```

Listing A.8 Settings that differ in the Norbert_CART World Builder file relative to Dobroslav.

```

1  # The Norbert_CART model uses the same Cartesian setup as Dobroslav.
2  # The main difference is the shortened shallow weak_layer on the incoming plate.
3  # In Dobroslav, the weak_layer extends from x = 300 km to x = 5000 km.
4  # In Norbert_CART, it extends only from x = 3666.7 km to x = 5000 km.
5  # The near-ridge part of the incoming plate between x = 0 km and x = 3666.7 km
6  # does not contain the weak_layer.
7
8  # -----
9  # Overriding plate ridge
10 # -----
11
12 # Dobroslav:
13 # "ridge coordinates":[[9900e3,-5],[9900e3,5]]
14
15 # Norbert_CART:
16 "ridge coordinates":[[10333.333e3,-5],[10333.333e3,5]]
17
18
19 # -----
20 # Removed right weak ridge
21 # -----

```

```

22
23 # The "right weak ridge" feature present in Dobroslav is not used in Norbert_CART.
24 # The right side of the model domain is therefore not softened by this additional
25 # hot ridge feature.
26
27
28 # -----
29 # Subducting plate with weak_layer
30 # -----
31
32 # Dobroslav:
33 # "coordinates" : [[300e3,-5],[300e3,5],[5000e3,5],[5000e3,-5]]
34
35 # Norbert_CART:
36 {"model":"oceanic plate", "name":"Subducting with crust",
37  "min depth":-10e3, "max depth":350e3,
38  "coordinates" : [[3666.7e3,-5],[3666.7e3,5],[5000e3,5],[5000e3,-5]],
39  "temperature models":[{"model":"plate model", "min depth":-10e3, "max depth":170e3, "bottom
40    temperature":-1,"spreading velocity":0.05,
41    "ridge coordinates":[[0e3,-5],[0e3,5]]
42    }],
43  "composition models":[{"model":"uniform", "min depth":-10e3, "max depth":7.5e3, "compositions"
44    : [0]},
45    {"model":"uniform", "min depth":7.5e3, "max depth":150e3, "compositions"
46    : [1]}}],
47
48 # -----
49 # Subducting plate without weak_layer
50 # -----
51
52 # Dobroslav:
53 # "coordinates" : [[0e3,-5],[0e3,5],[300e3,5],[300e3,-5]]
54
55 # Norbert_CART:
56 {"model":"oceanic plate", "name":"Subducting withOUT crust",
57  "min depth":-10e3, "max depth":350e3,
58  "coordinates" : [[0e3,-5],[0e3,5],[3666.7e3,5],[3666.7e3,-5]],
59  "temperature models":[{"model":"plate model", "min depth":-10e3, "max depth":170e3, "bottom
60    temperature":-1,"spreading velocity":0.05,
61    "ridge coordinates":[[0e3,-5],[0e3,5]]
62    }],
63  "composition models":[{"model":"uniform", "max depth":7.5e3, "compositions": [1]},
64    {"model":"uniform", "min depth":7.5e3, "max depth":150e3, "compositions"
65    : [1]}}]

```

A.2.3 World Builder files for Vitek_SPH and Vitek_CART

The Vitek model family represents the Hellenic-type setup with continental lithospheric segments and a localized weak zone in the overriding plate. Since this setup differs substantially from the generic Tamara and Dobroslav models, both the spherical and Cartesian World Builder files are listed in full.

Listing A.9 Geodynamic World Builder file for the Vitek_SPH model.

```

1 {
2   "version":"1.0",
3   "coordinate system":{"model":"spherical", "depth method":"begin at end segment", "radius"
4     :6371000},
5   "cross section":[[0,0],[180,0]],
6   "surface temperature":273,
7   "potential mantle temperature":1573,
8   "thermal expansion coefficient":2e-05,
9   "specific heat":1250,
10  "thermal diffusivity":6.79156908665105e-07,
11  "features":[
12    {"model":"mantle layer", "name":"mantle", "min depth":0, "max depth":2000000,

```

```

12     "coordinates": [[45,-1],[135,-1],[135,1],[45,1]]},
13
14 {"model": "oceanic plate", "name": "Overriding", "min depth": -10000, "max depth": 150000,
15  "coordinates": [[44,-5],[44,5],[81,5],[81,-5]],
16  "temperature models": [{"model": "plate model", "min depth": -10000, "max depth": 170000, "
    bottom temperature": -1, "spreading velocity": 0.1,
17    "ridge coordinates": [[[0,-5],[0,5]]]}]},
18
19 {"model": "continental plate", "name": "Weak zone in overriding plate - eta_max 1.5e22 Pa s, 80
    km deep", "min depth": -10000, "max depth": 80000,
20  "coordinates": [[77.4,-5],[77.4,5],[78.3,5],[78.3,-5]],
21  "composition models": [{"model": "uniform", "min depth": -10000, "max depth": 80000, "
    compositions": [1]}]},
22
23 {"model": "oceanic plate", "name": "Subducting oceanic background with crust", "min depth"
    :-10000, "max depth": 350000,
24  "coordinates": [[81,-5],[81,5],[132,5],[132,-5]],
25  "temperature models": [{"model": "plate model", "min depth": -10000, "max depth": 170000, "
    bottom temperature": -1, "spreading velocity": 0.06,
26    "ridge coordinates": [[[135,-5],[135,5]]]}]},
27  "composition models": [{"model": "uniform", "min depth": -10000, "max depth": 7500, "
    compositions": [0]}]},
28
29 {"model": "oceanic plate", "name": "Subducting near-ridge background without crust", "min depth
    ":-10000, "max depth": 350000,
30  "coordinates": [[132,-5],[132,5],[135,5],[135,-5]],
31  "temperature models": [{"model": "plate model", "min depth": -10000, "max depth": 170000, "
    bottom temperature": -1, "spreading velocity": 0.06,
32    "ridge coordinates": [[[135,-5],[135,5]]]}]},
33
34 {"model": "continental plate", "name": "DG dry continental stripe", "min depth": -10000, "max
    depth": 120000,
35  "coordinates": [[84,-5],[84,5],[88.68,5],[88.68,-5]],
36  "temperature models": [{"model": "linear", "min depth": -10000, "max depth": 120000, "top
    temperature": 273, "bottom temperature": -1}],
37  "composition models": [{"model": "uniform", "min depth": -10000, "max depth": 7500, "
    compositions": [0]}]},
38
39 {"model": "continental plate", "name": "PN dry continental stripe", "min depth": -10000, "max
    depth": 120000,
40  "coordinates": [[91.38,-5],[91.38,5],[93.36,5],[93.36,-5]],
41  "temperature models": [{"model": "linear", "min depth": -10000, "max depth": 120000, "top
    temperature": 273, "bottom temperature": -1}],
42  "composition models": [{"model": "uniform", "min depth": -10000, "max depth": 7500, "
    compositions": [0]}]},
43
44 {"model": "continental plate", "name": "GT dry continental stripe", "min depth": -10000, "max
    depth": 120000,
45  "coordinates": [[98.22,-5],[98.22,5],[101.1,5],[101.1,-5]],
46  "temperature models": [{"model": "linear", "min depth": -10000, "max depth": 120000, "top
    temperature": 273, "bottom temperature": -1}],
47  "composition models": [{"model": "uniform", "min depth": -10000, "max depth": 7500, "
    compositions": [0]}]},
48
49 {"model": "continental plate", "name": "Africa dry continental stripe", "min depth": -10000, "
    max depth": 150000,
50  "coordinates": [[106.95,-5],[106.95,5],[129.45,5],[129.45,-5]],
51  "temperature models": [{"model": "linear", "min depth": -10000, "max depth": 150000, "top
    temperature": 273, "bottom temperature": -1}],
52  "composition models": [{"model": "uniform", "min depth": -10000, "max depth": 7500, "
    compositions": [0]}]},
53
54 {"model": "oceanic plate", "name": "Left weak ridge", "min depth": -10000, "max depth": 50000,
55  "coordinates": [[134,-5],[134,5],[135,5],[135,-5]],
56  "temperature models": [{"model": "linear", "min depth": -10000, "max depth": 50000, "top
    temperature": 1573, "bottom temperature": -1}]},
57
58 {"model": "subducting plate", "name": "Slab", "coordinates": [[81,-5],[81,5]],
59  "dip point": [0,0], "max depth": 1000000,
60  "segments": [{"length": 200000, "thickness": [150000,120000], "angle": [0,25]},
61    {"length": 180000, "thickness": [120000,120000], "angle": [25]}]},
62  "composition models": [{"model": "uniform", "compositions": [0], "max distance slab top"
    : 7500}],

```

```

63     "temperature models":[{"model":"mass conserving", "reference model name":"plate model", "
density":3416, "thermal conductivity":2.9, "adiabatic heating":true,
64     "spreading velocity":0.06, "subducting velocity":0.06,
65     "ridge coordinates":[[[135,-5],[135,5]]],
66     "coupling depth":100000, "forearc cooling factor":0, "taper distance":0,
67     "min distance slab top":-200000, "max distance slab top":400000}}]
68 }
69 }

```

Listing A.10 Geodynamic World Builder file for the Vitek_CART model.

```

1 {
2   "version":"1.0",
3   "coordinate system":{"model":"cartesian"},
4   "cross section":[[0,0],[10000e3,0]],
5   "surface temperature":273,
6   "potential mantle temperature":1573,
7   "thermal expansion coefficient":2e-05,
8   "specific heat":1250,
9   "thermal diffusivity":6.79156908665105e-07,
10  "features":[
11    {"model":"mantle layer", "name":"mantle", "min depth":0, "max depth":2000000,
12     "coordinates":[[0,-1],[10000e3,-1],[10000e3,1],[0,1]]},
13
14    {"model":"oceanic plate", "name":"Overriding", "min depth":-10000, "max depth":150000,
15     "coordinates":[[6000e3,-5],[6000e3,5],[10111.1111e3,5],[10111.1111e3,-5]],
16     "temperature models":[{"model":"plate model", "min depth":-10000, "max depth":170000, "
bottom temperature":-1, "spreading velocity":0.1,
17     "ridge coordinates":[[[15000e3,-5],[15000e3,5]]]}]},
18
19    {"model":"continental plate", "name":"Weak zone in overriding plate - eta_max 1.5e22 Pa s, 80
km deep", "min depth":-10000, "max depth":80000,
20     "coordinates":[[6300e3,-5],[6300e3,5],[6400e3,5],[6400e3,-5]],
21     "composition models":[{"model":"uniform", "min depth":-10000, "max depth":80000, "
compositions":[1]}]},
22
23    {"model":"oceanic plate", "name":"Subducting oceanic background with crust", "min depth"
:-10000, "max depth":350000,
24     "coordinates":[[333.3333e3,-5],[333.3333e3,5],[6000e3,5],[6000e3,-5]],
25     "temperature models":[{"model":"plate model", "min depth":-10000, "max depth":170000, "
bottom temperature":-1, "spreading velocity":0.06,
26     "ridge coordinates":[[[0e3,-5],[0e3,5]]]}]},
27     "composition models":[{"model":"uniform", "min depth":-10000, "max depth":7500, "
compositions":[0]}]},
28
29    {"model":"oceanic plate", "name":"Subducting near-ridge background without crust", "min depth"
:-10000, "max depth":350000,
30     "coordinates":[[0e3,-5],[0e3,5],[333.3333e3,5],[333.3333e3,-5]],
31     "temperature models":[{"model":"plate model", "min depth":-10000, "max depth":170000, "
bottom temperature":-1, "spreading velocity":0.06,
32     "ridge coordinates":[[[0e3,-5],[0e3,5]]]}]},
33
34    {"model":"continental plate", "name":"DG dry continental stripe", "min depth":-10000, "max
depth":120000,
35     "coordinates":[[5146.6667e3,-5],[5146.6667e3,5],[5666.6667e3,5],[5666.6667e3,-5]],
36     "temperature models":[{"model":"linear", "min depth":-10000, "max depth":120000, "top
temperature":273, "bottom temperature":-1}],
37     "composition models":[{"model":"uniform", "min depth":-10000, "max depth":7500, "
compositions":[0]}]},
38
39    {"model":"continental plate", "name":"PN dry continental stripe", "min depth":-10000, "max
depth":120000,
40     "coordinates":[[4626.6667e3,-5],[4626.6667e3,5],[4846.6667e3,5],[4846.6667e3,-5]],
41     "temperature models":[{"model":"linear", "min depth":-10000, "max depth":120000, "top
temperature":273, "bottom temperature":-1}],
42     "composition models":[{"model":"uniform", "min depth":-10000, "max depth":7500, "
compositions":[0]}]},
43
44    {"model":"continental plate", "name":"GT dry continental stripe", "min depth":-10000, "max
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46     "temperature models":[{"model":"linear", "min depth":-10000, "max depth":120000, "top
temperature":273, "bottom temperature":-1}],

```

```

47     "composition models":[{"model":"uniform", "min depth":-10000, "max depth":7500, "
48     compositions":[0]}]},
49 {"model":"continental plate", "name":"Africa dry continental stripe", "min depth":-10000, "
50     max depth":150000,
51     "coordinates":[[616.6667e3,-5],[616.6667e3,5],[3116.6667e3,5],[3116.6667e3,-5]],
52     "temperature models":[{"model":"linear", "min depth":-10000, "max depth":150000, "top
53     temperature":273, "bottom temperature":-1}],
54     "composition models":[{"model":"uniform", "min depth":-10000, "max depth":7500, "
55     compositions":[0]}]},
56 {"model":"oceanic plate", "name":"Left weak ridge", "min depth":-10000, "max depth":50000,
57     "coordinates":[[0e3,-5],[0e3,5],[111.1111e3,5],[111.1111e3,-5]],
58     "temperature models":[{"model":"linear", "min depth":-10000, "max depth":50000, "top
59     temperature":1573, "bottom temperature":-1}]},
60 {"model":"subducting plate", "name":"Slab", "coordinates":[[6000e3,-5],[6000e3,5]],
61     "dip point":[6500e3,0], "max depth":1000000,
62     "segments":[{"length":200000, "thickness":[150000,120000], "angle":[0,25]},
63     {"length":180000, "thickness":[120000,120000], "angle":[25]}]},
64     "composition models":[{"model":"uniform", "compositions":[0], "max distance slab top"
65     :7500}],
66     "temperature models":[{"model":"mass conserving", "reference model name":"plate model", "
67     density":3416, "thermal conductivity":2.9, "adiabatic heating":true,
68     "spreading velocity":0.06, "subducting velocity":0.06,
69     "ridge coordinates":[[0e3,-5],[0e3,5]]],
70     "coupling depth":100000, "forearc cooling factor":0, "taper distance":0,
71     "min distance slab top":-200000, "max distance slab top":400000]}]

```