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Andean Orogeny and Plate Generation

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Summary. We present the basic conception of a new fluid-dynamic and geodynamic project on the Andean orogeny. We start with a kinematic analysis of the entire orogeny and test different numerical options to explain these systematized observations by a physical model. Therefore we consider partly kinematic, partly dynamic regional models as well as purely dynamic models. Because of stochastic effects which are unavoidable in purely fluid-mechanical mechanisms of this kind and which influence the specific form of the Andes and because of the, to a large extend, unknown initial conditions, the partly kinematic, partly dynamic models have their right to exist. A purely dynamic model would be, of course, much more satisfactory. Therefore we want to approach nearer to the purely dynamic models prescribing a less number of parameters and dropping some artificial constraints. We have a concept to embed a regional model into a global spherical-shell model to determine the boundary conditions of the regional model as a function of time. So we avoid the artificially simplified boundary conditions of some published models of the Andean mechanism. On the other hand, the regional model has to retroact upon the global surrounding model. So, we have an iteration concept. For the two mentioned reasons there are, analogously to the two kinds of regional models, also two kinds of spherical-shell convection models, namely circulation models and forward models. As a first step, we present a spherical-shell model of mantle convection with thermal evolution and generation of continents and, as a complement, the depleted mantle reservoir. Our presented numerical result is that plate tectonics occurs only if at least the lithosphere deviates from purely viscous rheology and if there is a low-viscosity layer beneath of it. We suppose especially a viscoplastic yield stress for the lithosphere and a mainly temperature-independent asthenosphere which is determined, e. g., by the intersection points of water abundance and water solubility curves. The number of plates, at a certain fixed time of evolution, depends on Rayleigh number and, to a minor degree, on yield stress. We discuss our new efforts to improve the basic code Terra. The numerical regional Andean model has to be embedded into a global circulation model. Therefore we need an improved Terra for the latter one.

1 Introduction

A physical process is thought to be clearly understood if the numerical model succeeded to reproduce the essential features of this process where the model is based on the solution of the balance equations, if this solution is stable in a certain range of parameters and if the parts of a more complex model are understood separately.
a) The definition of the boundaries of a natural system is often very difficult. The same applies for the specification of the *boundary conditions*. The Earth as a whole has natural boundaries. The matter transfer from and to space is rather small for the geological time except for the accretion period at the beginning. The energy exchange is essentially known and can be described by the boundary conditions. If, however, a system, as e.g. the Andes, has no natural boundaries we have to take into account that the artificially supposed boundaries have boundary conditions that are neither temporally constant nor known at all.
b) For regional models neither the beginning age nor the *initial conditions* are known.
c) The Earth's crust and mantle are polycrystalline solids but the internal heating generates solid-state convection, the mathematical description of which is fluid dynamics. So, *stochastic processes* are unavoidable so that a specific final configuration cannot be forecasted in a fully deterministic manner.
d) If we set us the task of designing a numerical model of the evolution of a specific mountain range, e.g. the Andes, then we also have to *systematize* a multitude of *observations*. Of course, we should expect that only some essential observational features can appear in the model. We want to give some examples for such kind of questions. What is the essential condition for the appearance of orogenesis with its stock-work tectonics? How to explain *episodic* orogenesis by *continuous* subduction? What induces the eastward migration of crustal shortening?
e) We search for a numerical model of the *generation of plate tectonics* taking into account the effects of the endogenic water cycle and want to present first results. The connection with the Andean model is produced by the idea to determine the boundary and initial conditions of an *embedded regional model* by a global spherical-shell model.

2 Observations and conceptions of modeling of the Andean orogeny and surrounding circulation models of the Earth's mantle

This Section is divided into five parts:
a) geological description of dynamic problems of the Andean orogeny
b) models which are partially kinematic and partially dynamic. In this kind of models, essential features are prescribed in order to gain a large adaptation to geological and geophysical observations (tectonic movements, magmatism, seismic fault-plane solutions etc).
c) geochemical models of growth and differentiation of continents which do not contain any dynamic modeling
d) self-consistent dynamic models of the subduction process to understand the physical mechanism behind subduction
e) fully dynamic circulation models.

We intent to use such a global dynamic model to define the time-dependent boundary conditions of an embedded regional dynamic model of Andean subduction and orogeny.

Up to now, the model types b) to e) are only loosely connected. A principal aim of this paper is to search for a better integration of these model types and to better understand b) and possibly d).

a) *Conception.* The problems of this subsection are specified in items.

- It would be important to understand why a plateau-type orogen formed between a purely oceanic lithospheric plate (Nazca plate) and a continent (South America) [53]. As a rule, such elevated plateaus are formed by underthrusting a continental plate beneath another one. E. g., the plateaus of Tibet and Iran have been created in such a way. During the Cenozoic, however, the Altiplano and the Puna Plateau developed as 4 km high plateaus during uninterrupted subduction of the Nazca plate.
- It would be necessary to explain why, simplified expressed, except in the western Altiplano, the deformation starts in the West and migrates to and finishes in the East [53]. Simultaneously also the volcanism moves eastward [71]. There is no time lapse between onset of magmatism and onset of shortening in the central Andes [42]. Fig. 2.3 of [71] shows a pronounced eastward migration of arc volcanism but only for the segment between 20° S and 28° S. In the segment between 14° S and 20° S, the volcanism starts only at $\tau = 25..30$ Ma and is broadly distributed, so there is no distinct migration. The age is denoted by τ. Fig. 2.7 of [71] demonstrates the strong increase of arc volcanism and of ignimbrites as a function of time starting at $\tau = 30$ Ma for the segment between 14° S and 28° S. This phenomenon could be connected with the 30 Ma Africa-Eurasia collision [62]. In the early period of the Andean orogeny, phases of high convergence rates as the Incaic and Quechua phases coincide with phases of tectonic shortening in the overriding plate. For the time span $\tau = 25$ Ma .. 0 Ma, however, plate convergence and Andean strain rates are decoupled [42]. This seems to be a further hint toward a connection with the 30 Ma Africa-Eurasia collision. In Section 3, we propose an investigation on fluid-dynamic mechanisms which could possibly explain phenomena of that kind.
- In the Andes, there are two two-sided orogens, the Western and Eastern Cordilleras, the wings of which are differently strong developed. The Altiplano with a low degree of deformation is situated between them. It is remarkable that the Altiplano has a high heat flow. This is in contradiction to the hypothesis that the continental lithosphere is extraordinarily thick in this region since the thermal lattice conductivity would allow only a less efficient heat transfer. Other attempts of explanation are to be found in paragraph b).
- In spite of more than 200 Ma continuous subduction of the Nazca plate [51], the high topography did not begin to grow earlier than an age of about 35 Ma [42]. During the early stages of orogeny, the strain-rate variations in the orogen reflect changes in plate convergence rate. But for ages smaller than 20 Ma, the two rates are obviously decoupled [42]. In this connection we should think about which process has thinned the South American lithosphere. Geological data show that the central Andean plateau was at most at half of its present-day height when the eastern marginal thrust belt began to grow [42]. It would be desirable if we could explain these observations by a physical model.

- Also in the Andes, mountain building has an episodic nature and is spatially limited in spite of essentially continuous subduction taking place simultaneously everywhere at the 7500 km long front of the Andes [42]. This is not really explained up to now. We would like to evaluate the different attempts of explanation possibly in search of an appropriate secondary mechanism.
- The decreasing convergence rate is *not* mimicked by the Andean strain rates that even increased, especially in the Eastern Cordillera and the Subandean belt [39, 42, 53]. Although the Nazca-South American convergence reached its climax at an age of 25-20 Ma and decreased after this time, the shortening rates rise considerably, especially in the Subandean belt, so that they have their highest values between 10 and 0 Ma of age. It is necessary to explain this delay.
- Also the following problem has not been understood from a physical point of view. The Nazca plate has rather small dip angles for latitudes between 2° S and 15° S as well as between 27° S and 33° S. But the active volcanism is mainly restricted to the segment in between with a more steeply dipping subduction zone [1,37,42,61]. This and the arc shape is probably connected with the observation that the shortening is stronger in the center than on the wings [31, 36, 40]: The shortening rate of the central Andes is 1 - 1.75 cm/a, that of the southern Andes is 0 - 0.5 cm/a [47].
- A further open question is whether the lower crust of the central Andes has a felsic composition [42,79]. This has probably a connection with the question of an initial weakening of the central base and with the anomalously high mantle heat flow of the plateau region (Altiplano) [42]. In the case of an affirmative answer we should check the models of Babeyko et al. [2, 3] and Sobolev et al. [63] in order to avoid their artificial boundary conditions. This idea would probably lead to a two-stage evolution of the central Andean plateau.
  The hitherto enumerated questions seem to be relevant but only a few of them could be resolved in the project since more basic questions of the 3D subduction mechanics are unresolved yet (see d)).
- Some authors consider the global asymmetry of subduction zones as a problem: Only the western Pacific margins and the northern and southern Antilles have present-day extensional basins. Attempted explanations [12, 60] seem to be unconvincing from a physical point of view. Furthermore, a switch from backarc extension to backarc contraction in mid-Cretaceous was observed [42].

b) *Partially dynamic models.* Medvedev et al. [47, 48] propose a thin-sheet numerical model for the deformation of the central and southern Andes. They assume that the continental and oceanic crust is a much stronger viscous fluid than the rocks in an assumed slanting subduction channel. They invented this channel as a thin sliding layer above the subducting plate. The model ignores deformation in the continent and in the oceanic crust and assumes that the stresses associated with deformation have the deforming effect in the subduction channel and in the crust between ocean and Brazilian shield only. Although the model is three-dimensional, it contains rather strongly simplified assumptions. Poiseuille flow is assumed with respect to the channel-normal velocity. A lateral movement of the two plates causes a Couette flow in the subduction channel. The movements of the plates are prescribed: The present movement of the Nazca plate with 5-6 cm/a in eastward direction and the westward velocity of the Brazilian shield with 3 cm/a are prescribed by the boundary conditions. The sideward boundaries act as indenting plates. The inclination of the subducting slab, dipping 15-30° to the east, is prescribed, too. Realistic shortening rates were found when the orogenetic lithosphere was assumed to be 20-100 times weaker than the foreland lithosphere. The incorporation of a weak and easily flowable middle crust of the upper plate generates the necessary reduction of the topographic relief and provides a mechanism to explain the flatness of the Andean plateau. Vietor [72] presented a 2D rectangular-box model with a noncohesive Navier-Coulomb rheology driven by kinematic boundary conditions applied as fixed velocities. He showed that the lateral expansion of a weak zone at the base of the plateau can switch the tectonics of the plateau from vertical thickening to lateral expansion. This kind of switch has been observed also in the Basin and Range province of North America.

Babeyko et al. [2] calculate a 2D thermo-mechanical model with prescribed velocities at the right and left sideward boundaries of the box model. Therefore the box is growing higher and narrower as a function of time. So, the model contains neither the subducting slab nor the Brazilian shield but the main topics of the model are the high heat flow at the Altiplano-Puna plateau and the peak of ignimbrite activity in the late Miocene and Pliocene. Radiogenic heat production of the crust with growing thickness, shear heating and heat brought by intrusions prove to be too small to explain the high heat flux of the plateau. Therefore Babeyko et al. [2] calculate the effects of a hot lower crust with internal convection. In doing so, they use a quartz-dominated rheology and apply a high heat flow from below. In this model, the hypothesis of a delamination of the continental lithospheric mantle and of the lower crust due to eclogitization [3] plays a role in the background conception. We remark that the latter conception fits well to the fact that it is impossible to explain the *episodicity* of the Andean orogenesis or orogenesis in general by a *continuous* subduction, only. It remains to be seen whether it is really necessary to assume a laterally connected layer of thermal convection in the remaining lower crust since the heat flow of the Altiplano-Puna plateau is not only high but also laterally strongly variable. So, also the option of a multitude of intrusions should be checked again. Babeyko et al. [3] propose a similar 2D model containing the plateau *plus* the Brazilian shield but not the subducting slab. Ongoing eclogitization of the lower mafic crust beneath the plateau is proposed to be responsible for the orogenetic episodes.

However, Sobolev et al. [63, 64] investigate the total mechanism of Andean orogeny. They use a viscoelastic rheology supplemented by Mohr-Coulomb plasticity for the layered lithospheres. The drift of the overriding plate and the pulling of the slab is prescribed by the velocities at the boundaries of the 2D model area and it is not calculated by solution of the balance equations though. What drives Andean orogeny? Sobolev et al. [63, 64] answer this question by numerical experiments using their 2D model and varying only one influence parameter each. They conclude that the major factor is the westward drift of the South American plate. Furthermore they use alternatively a stronger thin crust (35-40 km) or a thick crust (40-45 km) in the backarc as well as different friction coefficients. Both additional parameters produce considerable effects. The model, however, did not confirm that climate-controlled changes of the sedimentary trench-fill has a significant influence on the shortening rate. We think highly of these results [3, 63, 64] and want to refer to them in Section 3.

Burov and Toussaint [17] apply the same mixed FE/FD code Parovoz (Poliakov et al. [54]), which is based on the FLAC technique (Cundall [20]), and use it for the India-Eurasia collision and especially for the Himalayan mountain belt. They conclude that the total amount of subduction may *largely* vary as a function of the denudation rate. Sedimentation helps down-thrusting of the lower plate. However, very strong or very slow sedimentation augment the probability of plate coupling. They conclude that there is an optimum sedimentation to support subduction. This is in contrast with the conclusion of Sobolev et al. [63], regarding the Andes, that sedimentation plays only a *minor* role for subduction. These opposing conclusions are the more remarkable since the two groups of authors used virtually the same code. It is not probable that the different geographical regions are the cause for this disagreement. The cause of this contradiction still has to be clarified.

The last mentioned models are two-dimensional. However, the structure of the Andes varies as a function of latitude. The thrust belts at the east flank of the Andes show, e. g., large differences [41]. Furthermore, Gerbault et al. [23] refer to the relatively low elevation and the thick crust in the Altiplano, in comparison to the higher elevation, but thinner crust in the Puna plateau. They speculate whether orogen-parallel lower crustal flow could play a role. Problems of this kind can, of course, be investigated only in a three-dimensional model.

A 3D model of the Andean dynamics of the last 10 Ma has been presented by Heidbach et al. [29]. Iaffaldano et al. [35] couple the global circulation model of Bunge et al. [16] with the global lithospheric model of Bird [11] which, however, uses a thin-sheet approximation. Heidbach et al. [29] use the results of the circulation model to calculate the creeping velocities of the asthenosphere at the bottom of the plates. The boundary conditions are rather realistic since the circulation models prescribe the velocities of the plates as a function of time. A dislocation creep rheology of olivine is used inside the lithosphere. Heidbach et al. [29] determine the geographical distribution of the maximum horizontal compressional stress, S_H, for the ages of 10 Ma, 3.2 Ma, and 0 Ma where the topographies are a priori prescribed in the model. They obtain a good coincidence of the computed S_H with the observed one for $\tau = 0$ Ma and conclude that the growth of the central Andes controls the overall slow down of the Nazca/South American plate convergence. So, we close the paragraph on the partly dynamical models which directly refer to the Andes.

c) Now, there are at least five *geochemical/geological models* for the origin of the continental crust [21]. One of them postulates an additional fractionation of the arc crust. A delamination of cumulate layers beneath the seismological Moho back into the mantle could play a role.

d) *Dynamic subduction models which do not refer explicitely to the orogeny of the Andes.* Many efforts have been made to find self-consistent solutions to the generation problem of oceanic lithospheric plates. The oceanic lithosphere was generated by a strong temperature dependence of the shear viscosity in most of such numerical experiments (Christensen [19]), Hansen and Yuen [28], etc.). It proved to be impossible to produce plate-like solutions *and* subduction by a purely viscous rheology. Therefore the viscous creep has been supplemented by different constitutive laws and mechanisms [8, 9, 52, 58, 66, 67, 70]. Gerya et al. [26] treat the slab breakoff triggered by thermal diffusion using a 2D finite-difference and marker-in-cell technique. The temperature- and pressure-dependent thermal conductivity proves to have a significant effect on thermal weakening of the slab. Gerya et al. [24] present a 2D high-resolution petrological-thermomechanical model of the slab using a fine-scale oceanic crust with 1 km sediment, 2 km hydrothermally altered basalts and lower 5 km of gabbro whereas the mantle is supposed to be either anhydrous or contains about 2 wt. % water. In this 2D model, the water is entrained by the slab and generates not only a hydration front above the subducting slab but also small unmixed and mixed plumes which rise from the upper surface of the slab. This model contains certain features of our started 3D Andean backarc model (cf. Section 3). Gerya et al. [25] search for the reason why subduction is one-sided. They achieve one-sided convection assuming that the subducting plate is considerably thicker than the overriding plate. They start from the assumption that not only the subducting plate has oceanic crust and oceanic subcrustal lithosphere but also the overriding plate which is considerably thinner, yet. But we observe a perpendicular downgoing slab in the case of an ocean-ocean collision. Subduction angles smaller than 90° are observed, however, for ocean-continent collisions where the slabs subduct obliquely under the continent, the lithosphere of which is considerably thicker than and chemically different from the lithosphere of the subducting plate. Therefore we believe that for modeling the oblique subduction, the existence of a continent on the overriding plate and its very thick subcontinental lithospheric mantle should be crucial for the model. Further numerical models were published by [6,18,22,30,69]. They could be relevant for the conception of our regional model of Andean orogenesis. Schellart et al. [57] show that slab width controls the curvature of subduction zone and the tendency to retreat backwards as a function of time. So it is understandable that the shortening is very large in the case of the central Andes. Billen [10] reports on slab dynamics, especially on models showing that spatial and temporal variations in slab strength determine whether slabs subduct into the lower mantle or remain in the transition zone.

e) *Circulation models.* Not only because we do not know the initial conditions but also because of some stochastic features of mantle convection [73, 74], it is necessary to introduce mantle circulation models in order to reconstruct the Mesozoic and Cenozoic history. Based on seismic tomographic models and reconstructions of plate motions successful circulation models have been derived for the last 100 Ma [13, 15] which could be used as a spherical-shell model which should define the time-dependent boundary conditions of our special Andean model. Other circulation models have been discussed [7,81] and should be compared with [13,15].

3 Our new model of Andean orogenesis

a) General features of the model. We do not want to treat the problem of Andean orogenesis by purely regional models only, as the papers described in Section 2, b), except Heidbach et al. [29] do since, in this case, the temporally varying boundary conditions are unknown. Therefore it is often assumed, for reasons of simplicity, that there are no or only very simple effects from outside of the regional computational domain. As mentioned in Section 2, however, some changes in the arc volcanism and in the tectonic-shortening behavior are evidently in connection with the 30 Ma-Africa-Eurasia collision. Therefore we intend to embed a regional 3D model into a 3D spherical-shell model. So, we want to solve the balance equations of momentum, energy and mass in the spherical-shell model using somewhat larger time steps on a coarser whole-mantle grid, coarser than in the regional model. The values of creeping velocity, temperature and pressure, determined in that way and lying at the boundaries of the *regional* computational domain, serve then as temporarily fixed boundary conditions for some smaller time steps for which the balance equations are solved in the regional computational domain. Then, the final values of this regional computation will be transferred to the coarser grid of the whole mantle where the balance equations will be solved for the next time step. So, we want to jump iteratively between global and regional domain.

b) The spherical-shell model. We continue with considerations on the spherical-shell model, only afterwards we report on the regional model. As a base of the spherical-shell model, we intend to use the code Terra which was developed by Baumgardner [4], has been parallelized by Bunge et al. [14] and has been rearranged by Yang et al. [77] to allow for steep viscosity gradients. Walzer et al. [75] developed a convection model of the 4500 Ma of thermal evolution of the Earth's mantle with stable but temporally variable oceanic lithospheric plates, using Terra. Walzer et al. [73] present a spherical-shell model for 4500 Ma of mantle evolution with convection, plate tectonics *and* chemical differentiation. Origin and growth of the continents and of the depleted mantle are modeled by the interplay of differentiation and convection. They could numerically show that today, also in the model, different mantle reservoirs exist in spite of 4500 Ma of stirring convection. The latter two papers are based on forward computations starting with certain initial conditions and fulfilling certain very simple boundary conditions. Number, size, form, distribution and velocities of plates and continents are not constrained or even prescribed. Such a procedure is appropriate for more fundamental investigations since, in this case, it is senseful to compare the computed distributions of the mentioned quantities as well as Rayleigh number, Ra, Urey number, Ur, laterally averaged heat flow, qob, etc, as a function of time with observations.

It is a different matter in case of the 3D circulation models where number, size, form, distribution and velocities of the plates are prescribed (for the younger geological past). In this case we have to take care that the balance equations are really fulfilled. But this kind of spherical-shell model is necessary if we want to study *definite* plates, continents and orogens like Nazca plate, South American plate, South American continent and the Andes. We have to decide on the kind of a global 3D spherical-shell *circulation* model. Furthermore we have to adopt a global model of lithospheric motions, e. g., that of Bird [11] or another one. In no way, we intend to repeat or modify the procedure of Heidbach et al. [29] since the thin-sheet approximation used there is not able to solve our intended questions. But we think highly of this valuable and stimulating paper.

c) Numerical improvements. It is necessary to invent further improvements in Terra to solve the questions of the geodynamic modeling. Partly we already began to work in such a direction. Müller [50] and Köstler [43] work on improvements of Terra which, however, could not be used yet in our latest simulations. Müller analyzed the discretization of the Stokes problem and found a local grid refinement with hanging nodes which is inf-sup stable. Beate Sändig augmented the block size of the Jacobi smoother in the solver and K"ostler adapted the grid transfer because of the small irregularities of the icosahedric grid. However, the influence of these alterations on the convergence behavior proved to be small. Further studies on the Krylov subspace method and multigrid method have been carried out and are continued to apply the latest results of numerical research to the Stokes solver in Terra. Especially a multigrid solver of the coupled Stokes problem, proposed by Larin and Reusken [44], promises to be successful for an augmentation of the convergence rates and an improved pressure correction. We intend to implement such a solver and a MINRES procedure and we agreed on cooperation with John Baumgardner (San Diego, USA) regarding these problems. As a latest result, Baumgardner got the new free-slip boundary treatment debugged and working correctly. It is to be expected that he can move forward now on a set of benchmarks and get a Terra benchmark paper.

d) The regional model. Before we sketch the *regional* model, we want to outline the idea behind of it. This idea has to be considered like a tentative diagnosis. It is well possible that we will be compelled to modify it. Apart from the details described in Section 2, a), the model should contain or allow to derive the following items for the geological present. The present-day average heat flow of the backarc, consequently the area between Western and Eastern Cordillera, should be 85 ± 16 mW/m^2, the heat flow of the Brazilian shield should be 42 ± 7 mW/m^2. The deformation ages across the southern central Andes migrated from the west to the east [53]. At a latitude of 21° S, the following ages, τ, have been observed: western flank/Precordillera τ = 47..38 Ma, central Altiplano τ = 32..12 Ma, Eastern Cordillera/Interandean τ = 42..7 Ma. We suppose that the thickness of the Brazilian shield was and is 200 km. The present backarc lithosphere is 50-60 km thick. The present high backarc asthenosphere below of it shows a very low shear viscosity. We presume that the strength structure of the craton can be described by the right-hand side of Fig. 1.

Using these assumptions, we can sketch the following mechanism. The subduction of the slab is rendered possible by the presence of large quantities of water. The absorption of large amounts of water by the oceanic crust essentially lowers the melting point [27,38,55]. So, the deflection of the oceanic lithospheric plate will be made possible in the first place. The upper and lower boundary surfaces of the asthenosphere as a low-viscosity layer are determined by the intersecting points of the curves of water solubility and water abundance [49]. Therefore the thickness of the asthenosphere is a function of location and time. If the slab is dipped into the mantle, it carries *continuously* water into the upper mantle. Many tectonic problems cannot be explained by plate collision or friction. E. g., the subduction of the Nazca

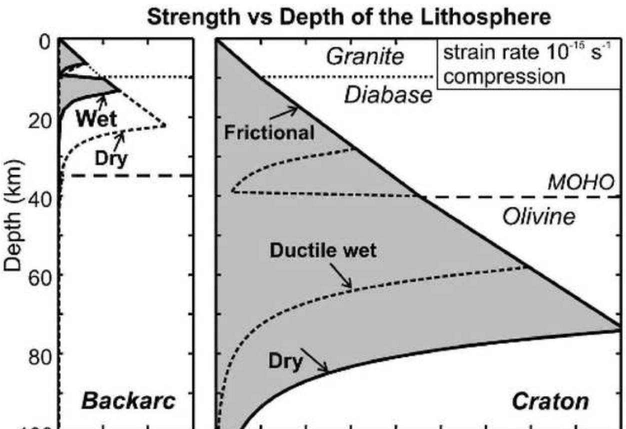


Fig. 1. Strength versus depth for hot backarc belts and cold cratons according to Hyndman et al. [34].

plate essentially takes place *continuously*, but the orogenetic events of the Andes are *episodically* distributed on the time axis. We propose to solve this problem as follows. According to Model V of Davidson and Arculus [21], the cumulate complement of the evolved continental crust beneath the seismological Moho and the continental lithospheric mantle below of it will be so flowable by absorption of water that they *episodically* detach from the middle and upper crust. Then they sink down into the mantle because of a Rayleigh-Taylor instability. In this process, the eclogitization of the lower crust plays a part. From the Nb/Ta-Nb plot for primitive mantle, depleted mantle and continental crust [56] it follows that there is such an eclogitic reservoir in the mantle. To express it in another way, although it would be possible to reestablish the primitive mantle by a total stirring of the depleted-mantle and continental-crust reservoirs regarding many chemical elements, for the Nb/Ta-Nb plot this is not possible without the assumption of an additional eclogite reservoir. The proposed mechanism would also explain the felsic composition of the present Altiplano and Puna crust [80].

So we think that the high backarc asthenosphere with particularly low viscosity evolves gradually by the continuous water transfer from the slab. Small-scale thermal convection takes place continuously in the backarc asthenosphere explaining the high heat flow at the surface of the only 50-60 km thick lithosphere of the Altiplano-Puna region. This heat flow is considerably higher than that of the Brazilian shield as well as that of the neighboring parts of the Nazca plate. By the enduring growth of the quantity of water in the backarc produced by the slab movement, the backarc asthenosphere spreads piecewise eastward by episodic detachment of pieces of the mantle lithosphere and of the eclogitisized lower crust. This explains the *episodicity* of the orogenetic events and their *eastward migration*. The mobile belt of the backarc asthenosphere is exclusively generated and maintained by the water transfer of the slab. The word exclusively refers, of course, only to our model. If the slab mechanism vanishes then this continental margin will loose its fertility. Therefore *continuous* slab subduction is necessary to produce the *episodes* of orogenesis. The orogenesis was particularly active at the two margins of the backarc asthenospheric zone. These boundaries are characterized by the largest lateral viscosity contrasts between backarc and craton or between backarc and Nazca slab. Therefore the Eastern and Western Cordilleras are situated at the leading and trailing edges of the fertile belt. This means for the code of our regional model that it has to be designed to tackle also high *lateral* viscosity gradients. Walzer and Hendel [73] emphasized that there have to exist *considerable* viscosity gradients in radial direction at the well-known mineral phase boundaries since activation energies and volumes jump there. The activation enthalpy determines the exponent of the e-function of the viscosity. The same applies for the intersecting points of the curves of water solubility and water abundance which define top and bottom boundaries of the asthenosphere.

From the previous considerations, it follows that *our* regional computational domain has to be considerably smaller than that of Heidbach et al. [29]. So, the quantities of the larger parts of the South American and the Nazca plates have to be taken from the results of the global circulation model, in contrast [29]. Furthermore in contrast to the coarser grid of the surrounding circulation model, the grid-point distances of the regional domain have to be much smaller. A further grid refinement is necessary at the surface of the subducting slab, at the boundary between craton and backarc asthenosphere and at the Earth's surface. The time window, however, may not be restricted to the last 10 Ma as in the [29]-model but at, e. g., 119 Ma [45].

The depth of the regional computational domain is about 900 km in order to include all influences of the phase boundaries on the slab plus a small additional domain. Regarding the phase boundaries of the upper mantle, only the effects of the phase boundary distortion by advection of thermal anomalies should be taken into account. In comparison to this, the effects of the phase boundary distortion due to release or absorption of latent heat and the effects of expansion or contraction due to release or absorption of latent heat are small. Although the transition from basalt/gabbro to eclogite includes only minor volumes it has a density increase of 15 %. Therefore this transition is relevant for modeling the delamination or a less viscous detachment of the lower crust. That is why the basalt-eclogite transition should be taken into account.

We intend to describe the transport of water by a tracer approach. In [73], we had modified the tracer module of Dave Stegman and used it to describe the transport of heat-producing elements. In the *first* numerical cases of the model, we should simply use a bulk-silicate-earth (BSE) distribution of the heat-producing elements, U, Th and K, temporally declining but spatially simply homogeneous heating from within [32, 46]. As usual [73, 75], we intend to add a core-cooling model [33, 65]. The CMB temperature, T_c, is *laterally* constant in this procedure. But T_c of the surrounding spherical-shell model is adapted to the temporally variable heat flow through the CMB after each time step. In *later* numerical experiments, tracers are to be used to take into account the different abundances of heat-producing elements in the different reservoirs. This is probably already necessary to show that the high heat flow of the Altiplano-Puna region is not *mainly* caused by the higher abundances of U, Th, K in the felsic crust which has a *present* thickness of 50-60 km but by small-scale convection in the high backarc asthenosphere.

We do not want to criticize the partly dynamic, partly kinematic models described in Section 2, b). But we intend to produce an Andean model with *less* restrictive assumptions. In spite of the higher number of degrees of freedom, the new model should allow to derive the essential features of the Andean orogenesis. In doing so, the catalog of unresolved or only partly resolved problems of Section 2 a) ought to be our guide. The models of Sobolev et al. [63, 64] and Babeyko et al. [2, 3] are good and very stimulating. However, we intend to alter not only the computational method but also the treated schedule of problems. We suppose that the westward migration of the Brazilian shield is *not* the main reason for the entirety of the Andean orogenetic processes but the water subducted by the Nazca plate. We believe that this water generates the orogenetically active backarc belt. Nevertheless, the very active thrust faults of the Subandean Ranges show that the westward movement of the Brazilian shield has a large influence especially in the last 10 Ma. We continue with some numerical considerations on the construction of the computational code to realize the outlined model.

e) Numerical methods: Coupling a regional with a global mantle convection model. The computational model Terra uses a discretization of the sphere which consists of 10 diamonds evolving from the projection of the regular icosahedron onto the sphere [5]. Because domain decomposition is done in every diamond separately by explicit message passing, it is worthwhile to use one diamond as a regional domain and to couple this regional to the global model of Terra. The lateral extension of one diamond edge on the Earth's surface is 7000 km and the depth of this domain can be chosen arbitrarily. The size of such a segment is very appropriate to model the Andean subduction zone as Schellart et al. [57] found that subduction zone width strongly influences trench migration and crustal extension, respectively shortening. Because parallelization in Terra is done in lateral directions, it can be applied very efficiently to a regional domain which is a wide aspect ratio spherical shell segment. For instance on an SGI Altix 4700 machine with Intel Itanium2 Montecito Dual Core processors we could achieve an efficient cache usage with subdomains of 33x33x129 grid points which would give an overall regional grid spacing of 7 km at the surface and 6 km at the bottom boundary if we use 1024 processors on one diamond with a depth of 900 km. This is 4 times less the spacing we could achieve in the whole spherical shell. Communication overhead would be much less than 10 % for this configuration. A similar approach has been done with the convection code CitcomS in [68], where a 2 times finer regional grid is used to model the ascent of a plume through the surrounding mantle.

Nevertheless, at the boundaries of the subducting slab an even smaller grid spacing is desirable and very strong gradients in material parameters, in particular viscosity, have to be taken into account. Therefore we have further advanced the Terra code with respect to stability, local grid refinement, and solver techniques. Precisely we have successfully investigated an inf-sup-stable grid modification that enables us to use grids with hanging nodes. Thus we are able to adapt the grid resolution rapidly towards a heavily refined region with only a few successively refined layers. We have changed the smoother of the multigrid solver, the preconditioner, the algorithm for the solution of an included Stokes problem and the method for the time integration. We have started refactoring the solver to achieve greater flexibility with regard to algorithm changes. We created a test framework that automates the build process, starts automatically a series of test cases on different machines in

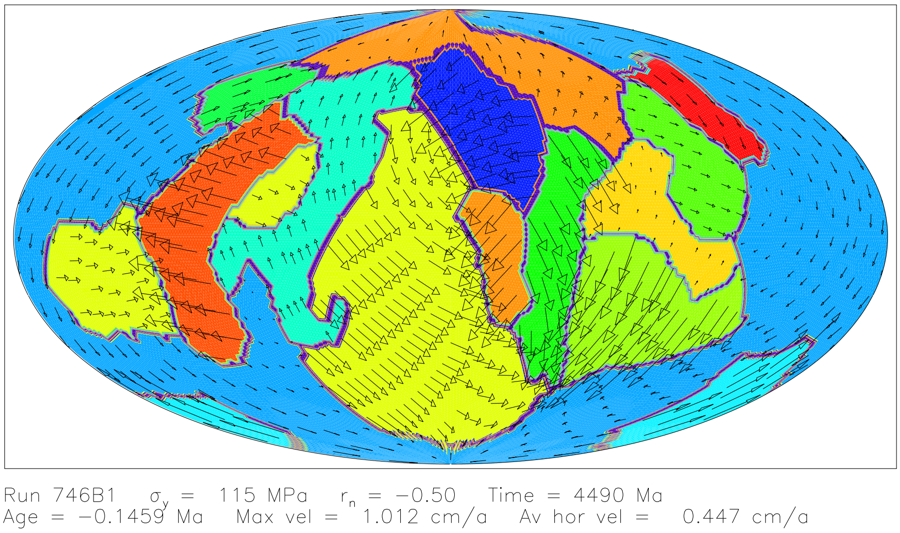


Fig. 2. An equal-area projection of the lithospheric plates (colors) and creep velocities (arrows) of our 3D spherical-shell convection-evolution model *with* chemical differentiation and continents (not shown here) for the present time. The viscoplastic yield stress is $\sigma_y = 115$ MPa.

different resolutions and checks the results. This way the response time to changes and errors in the code will be noticeably reduced. That means, we will have facilities assisting even radical changes of the code.

Moving towards the coupling of the two mentioned models we first want to implement a regional model containing all small scale parameters of interest, but without dynamic coupling to the whole mantle convection. The first step to achieve this is to modify the existing convection code by simply constraining the computational domain to one diamond. This results in additional vertical boundaries and the necessity to be able to prescribe appropriate conditions on them, since up to now the code is concerned with the whole shell which has only two spherical boundaries. We can easily provide a fully featured parallel multigrid solver for the convection in the domain of interest, including parallel implemented markers for chemical differentiation by a slight modification of the existing code.

In addition to the simple adaption described we plan to implement refined solving strategies to meet the requirements of strongly varying viscosity due to differences in temperature, pressure and water content between subducted material and its surroundings. We will use the techniques we investigated for whole mantle convection like the local grid refinement, a special preconditioning technique as well as our existing test framework. In particular, the above-mentioned preconditioned MINRES algorithm will be implemented. The benefits achieved this way would also pay off for the global model.

Having obtained a small scale method that uses essentially the same solver we have very good preconditions to integrate the small high resolution area seamlessly in the global convection. The spatial grid will be refined with the described technique of hanging nodes towards the boundaries of the small scale model with only a few successive refinement steps. One has however also to couple the time stepping scheme of both methods in a very flexible manner. We will have to address both, stability

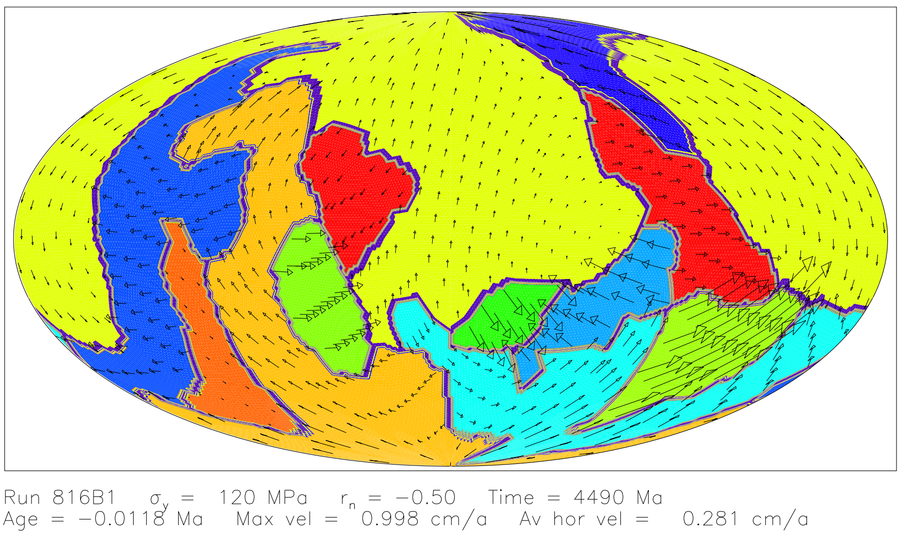


Fig. 3. Text see Fig. 2, but $\sigma_y = 120$ MPa.

and optimality with respect to the load balancing. The plan to achieve these goals is very simple, because we do not need full adaptivity in space and time, but prescribe the spatiotemporal resolution according to optimal load balancing.

f) Numerical methods: Using a 2D model for rheology influence on subduction. Furthermore, we mention that there exists a 2D version of Terra which can already model viscosity contrasts of up to 10^{10} between adjacent points [78]. This code is currently used by the group of Slava Solomatov at Washington University in St. Louis to study mantle convection with realistic rheologies and related issues such as kinetics of phase transformations and grain growth. As we also use this code to study different solving strategies in two dimensions first, there is a benefit to be expected also in modeling the influences of composition and grain size on subduction. Moreover, the matrix-dependent transfer technique in the 2D code still promises an improvement of the convergence of the multigrid in the 3D code. Therewith it will be possible also to model lateral viscosity variations of several orders of magnitude between adjacent points in the global and in the regional 3D model.

4 First results: Plate generation

These results do not yet refer to a circulation model but to forward computations where we solve the balance equations to a spherical shell starting from assumed initial conditions at an age of 4500 Ma. The included tracer code is constructed in such a way as to conserve the four sums of the numbers of atoms of the pairs ^{238}U-^{206}Pb, ^{235}U-^{207}Pb, ^{232}Th-^{208}Pb, and ^{40}K-^{40}Ar. The decay of these four radionuclides and the primordial heat are the principal energy sources driving the Earth's solid-state mantle convection and lateral plate movements by heating from within. There is only a small contribution by heating from the core-mantle boundary (CMB) but it

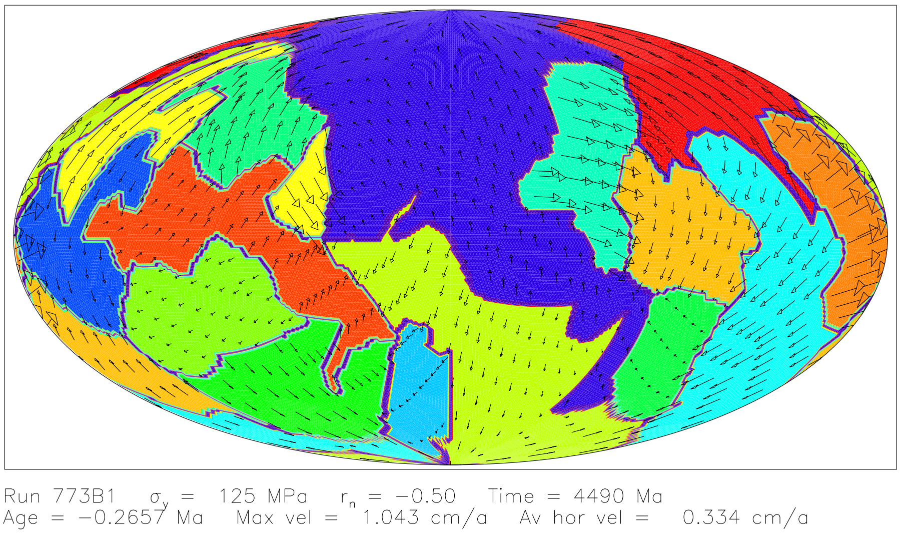


Fig. 4. Text see Fig. 2, but $\sigma_y = 125$ MPa.

is not negligible. In this model, there is a certain partial random influence [74] on the formation of oceanic lithospheric plates and of continents. The two essential conditions of *our* model for the generation of plates are the assumption of a viscoplastic yield stress, σ_y, for the lithosphere and the existence of a low-viscosity asthenosphere below it [73, 75]. It is evident that it is impossible to produce plate tectonics without a deviation from the purely viscous rheology and without asthenosphere. The viscosity, η, of mantle and crust is calculated by

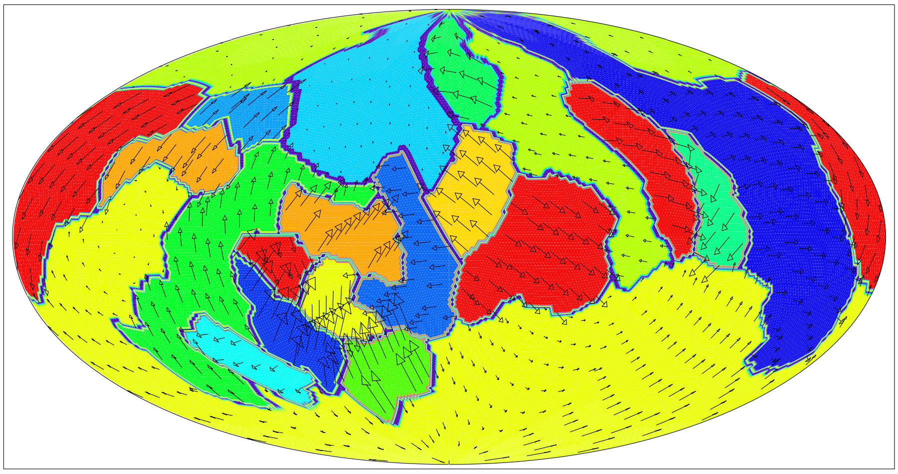
$$\eta(r,\theta,\phi,t) = 10^{r_n} \cdot \frac{\exp(c\,\overline{T_m/T_{av}})}{\exp(c\,\overline{T_m/T_{st}})} \cdot \eta_3(r) \cdot \exp\left[c_t \cdot T_m \left(\frac{1}{T} - \frac{1}{T_{av}}\right)\right] \qquad (1)$$

where r is radius, θ colatitude, ϕ longitude, t time, r_n viscosity-level parameter, T_m melting temperature, T_{av} laterally averaged temperature, T_{st} initial temperature profile, T temperature as a function of r, θ, ϕ, t; c and c_t are constants. The quantity $\eta_3(r)$ denotes the viscosity profile at initial temperature and for $r_n = 0$. The parameter r_n serves for a stepwise shift of the viscosity profile to vary the time-averaged Rayleigh number from run to run. For an idealized plate tectonics with sharp boundaries, the divergence divh **v** would form mountain crests of a pseudo-topography drawn on the spherical surface where

$$\mathrm{divh}\,\mathbf{v} = \nabla_h \cdot \mathbf{v} = \frac{1}{r_0}\left[\cot\theta \cdot v_\theta + \frac{\partial v_\theta}{\partial \theta} + \frac{1}{\sin\theta} \cdot \frac{\partial v_\phi}{\partial \phi}\right] \qquad (2)$$

and r_0 is the Earth's radius. The velocity components v_r, v_θ and v_ϕ are assigned to r, θ and ϕ. Only the divergent and convergent plate boundaries appear as hogbacks of divh **v**. For transform faults, the pseudo-topography of the curl

$$\mathrm{roth}\,\mathbf{v} = (\nabla \times \mathbf{v})_h = \frac{1}{r_0}\left[\cot\theta \cdot v_\phi + \frac{\partial v_\phi}{\partial \theta} + \frac{1}{\sin\theta} \cdot \frac{\partial v_\theta}{\partial \phi}\right] \qquad (3)$$



Run 796B1 σ_y = 130 MPa r_n = −0.50 Time = 4490 Ma
Age = −0.0246 Ma Max vel = 0.873 cm/a Av hor vel = 0.274 cm/a

Fig. 5. Text see Fig. 2, but $\sigma_y = 130$ MPa.

shows mountain crests. The surface expression of the square root of the second invariant of the strain-rate tensor, invh **v**, will produce mountain crests for *all* plate boundaries,

$$\mathrm{invh}\,\mathbf{v} = \dot{\epsilon}_{surf} = \frac{1}{r_0}\left[\left(\frac{\partial v_\theta}{\partial \theta}\right)^2 + \left(\frac{1}{\sin\theta}\cdot\frac{\partial v_\phi}{\partial \phi} + v_\theta \cdot \cot\theta\right)^2 + \frac{1}{2}\left(\frac{1}{\sin\theta}\cdot\frac{\partial v_\theta}{\partial \phi} + \frac{\partial v_\phi}{\partial \theta} - v_\phi \cdot \cot\theta\right)^2\right]^{1/2} \quad (4)$$

Therefore we used the crest lines of invh **v** to determine the exact plate boundaries. A successive grid refinement toward the surface could improve the procedure, yet. The Figures 2 to 5 present the plate distribution and the plate velocities for the geological present time where r_n and the viscosity-profile factor, $\eta_3(r)$, were kept constant and only the yield stress, σ_y, was varied in equal steps from case to case. Deriving the viscosity profile, we assumed that the oceanic lithosphere is produced not only by the temperature dependence of viscosity but also by devolatilization and secondary chemical segregation generating the layering of oceanic lithosphere. For higher σ_y, the number of plates is larger than for low σ_y. We observed a similar, but stronger effect for the variation of the temporal average, Ra, of the Rayleigh number. Keeping the other parameters constant, we obtain more plates for low Ra and less plates for high Ra. The arrows in Figures 2 to 5 denote the lateral creep velocities at the surface. These plate velocities have not only different directions but also different absolute values. Some plates contain continents, other plates are free of continents. The continents are not shown here. Fig. 6 shows the laterally averaged heat flow, *qob*, as a function of age. This quantity arrives at realistic values for the present time close to the laterally averaged, measured surface heat flow of the Earth. It is remarkable that the decrease of *qob* as a function of time is rather moderate in comparison to that of parameterized models [59]. In [76], we emphasized that this result is in agreement with the results of komatiite research. This slow decrease of *qob* is a further indication that not only the temperature dependence of viscosity is the reason for the generation of oceanic lithosphere but also devolatilization and other chemical effects.

5 Conclusions

We began to research into models of Andean orogenesis and present some basic considerations. We obtained explicit results in the further development of the code Terra and regarding the generation of plate tectonics on a spherical-shell mantle. Here, only plate generation is presented in some detail. Referring to the items a) to d) of the Introduction, we summarize the following considerations, regarding item e) also specific results. Because of the limitations of available computing capacity and the necessary fine grid of the Andean dynamic model, we have to cut out only a small part of the spherical shell as a regional model with unknown time-dependent boundary conditions. For the same reasons and because of the restriction of knowledge of observed global plate motions to the younger Phanerozoic, also the evolution time of the regional model has to be restricted. Therefore, the initial conditions of the regional model are unknown, too. We intend to embed the regional model into a global circulation model to determine the initial conditions and the time-dependent boundary conditions of the Andean model. We have to prefer a circulation model in order to eliminate the majority of stochastic processes. If we would not do so, the model could not arrive at the *specific* form of plates and continents. We developed a hierarchy of observational facts which ought to be explained by the embedded Andean evolution model. In Section 4, we present a specific model of generation of

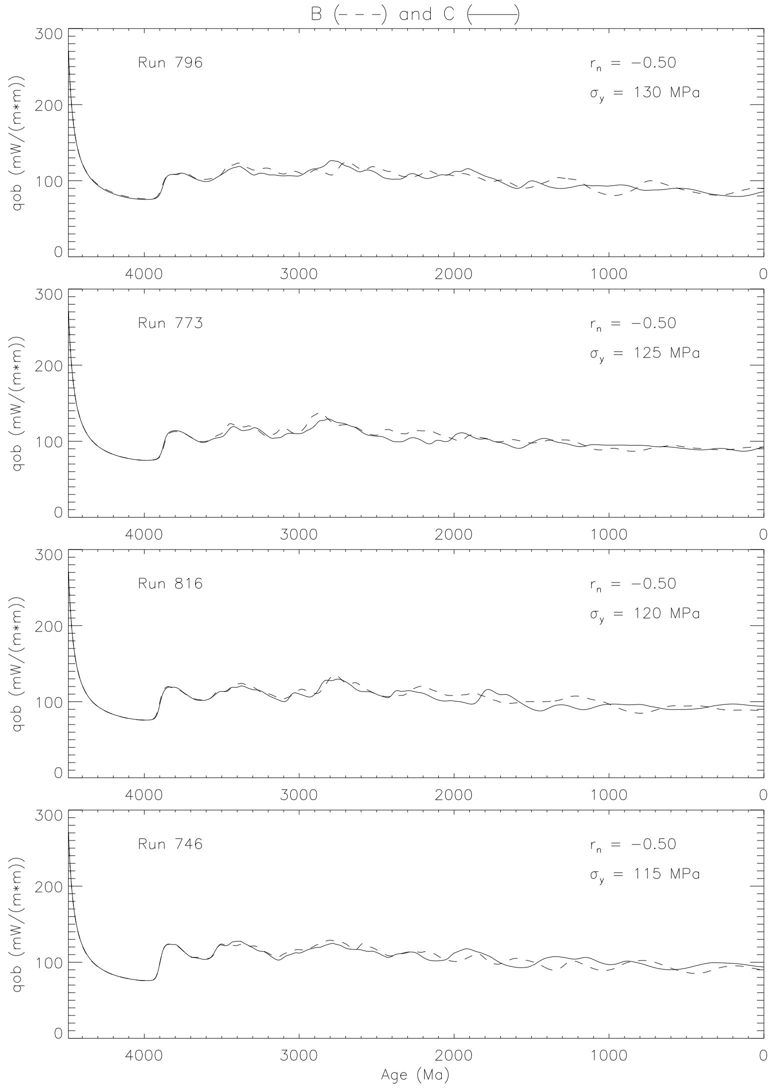


Fig. 6. The evolution of the laterally averaged surface heat flow, *qob*, for neighbor runs. The viscosity-level parameter, r_n, is kept constant at -0.50. Dashed lines belong to basic runs with about 10.5 million tracers, solid lines to comparative runs with about 84 million tracers.

plate tectonics showing only a few cases with a systematic variation of the yield stress. The number of plates depends mainly on the temporally averaged Rayleigh number, Ra, but to a minor degree also on the yield stress, σ_y. A variation of the parameters shows the existence of a central area in the $Ra - \sigma_y$ plot where stable plate-like solutions on the sphere have been found.

Acknowledgements

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