A novel solid-fluid method for modeling subduction

Author(s):
Morra, Gabriele

Publication Date:
2004

Permanent Link:
https://doi.org/10.3929/ethz-a-005055500

Rights / License:
In Copyright - Non-Commercial Use Permitted
A NOVEL SOLID-FLUID METHOD FOR MODELING SUBDUCTION

A dissertation submitted to the

Swiss Federal Institute of Technology
Zürich, Switzerland

Dissertation for the degree of

Doctor of Natural Sciences

presented by

Gabriele Morra

Laurea in Fisica, University La Sapienza, Rome (Italy)
Born in Rome on October 30, 1972
Citizen of Italy

Accepted on the recommendation of

Prof. Dr. Domenico Giardini, examiner
Prof. Dr. Klaus Regenauer-Lieb, co-examiner
Prof. Dr. Hans-Peter Bunge, co-examiner

2004
Abstract

This PhD work is part of a larger project called Orogeny I, thought to be the first step towards obtaining a self-consistent dynamic model of the formation of the Alps. The chain originated by continental convergence, part of a dynamic process in which the subduction in the Mediterranean played a major role. The aim of this specific PhD project is to provide a numerical tool for forward dynamic modeling, to be used to simulate the Mediterranean tectonic scenarios. The direct application to the Mediterranean scenario will be the topic of a following PhD project, while in this thesis we will show his validity applying it to analyze the dynamical evolution of Oceanic Arcs. This problem is fundamental in Geodynamics: it was an hot topic of discussion in the beginning of plate tectonics Frank (1968); Karig (1971); Tovish and Schubert (1978); Uyeda and Kanamori (1979), and it is still today an open issue.

Before to address applicative problems, our research deals with two fundamental problems that are still open in modeling subduction. The first concerns the rheology of the upper mantle. How important is its role? Do we need to incorporate elasticity? Is elasticity important only within the slab or also outside? Are non linearities in the creep rheology of olivine important? If yes, what is their role? For example, can a run-away effect produce a shear zone in the ductile regime? The first part of our work aims to reach an insight those problems. We focus on what happens within the lithosphere during subduction. We find that both, elasticity and non-linear rheologies, play a fundamental role in controlling the dynamics. Furthermore, along with
A novel coupled solid-fluid method for modeling subduction

mineral physics laboratory research, we consider the high dependency of mantle rheology by the presence of volatiles. Since the exact parameterization of the influence on water on rheology is still a matter of debate and because the quantity in the mantle is not fully constrained we used water content as a "free parameter" for tuning lithosphere strength within a range compatible with laboratory data, while the thermal structure of slabs is well constrained.

The second problem concerns the role of mantle-lithosphere feedback during slab motion. How does it in turn affect the slabs morphology and motion? We first formulate this problem within a three-dimensional fluid-dynamic approach. We find that neglect the effect of elasticity hamper the quality of the resulting model. The lack of strength of the slab induces a "cold downwelling" instead of a "slab subduction" and the results are in general not compatible with observation. This confirms our prior results on the role of elasticity and pushes us to propose an innovative approach. We develop a coupling method that incorporates two different modeling techniques: one "solid-mechanical" for modeling the slab and the other one in which the mantle is modeled as fluid-mechanical. This approach requires the solution of several technical issues. The main ones are that we apply a lagrangian approach to both the solid and fluid parts, which completed avoid any numerical diffusion in the model, and that the mantle is originally modeled through a Boundary approach which adds exceptional computational efficiency at the model, paying the price of a limited rheological choice.

Here are resumed the topics of each chapter.

Chapter 1. A quick review on the numerical approaches that we use. The early results on the simple model of subduction with a fluid-dynamic approach are presented, showing the role of slab core strength for simple two and three-dimensional setups.

Chapter 2. Based on a published paper, it formulates the simplest setup for separating the effects of slab rheology from slab-mantle feedback. Slab-mantle feedback is suppressed and it is investigated how the subduction system responds to a selection of slab rheologies: the purely elastic, the linear visco-elastic, and the visco-elasto-plastic. A first attempt to model the thermo-mechanical dynamics of the lithosphere evolution is also presented.

Chapter 3. The solid mechanical approach for the lithosphere presented before is coupled with a fluid-dynamic one to have a more realistic model of subduction. The philosophy here is to maintain a full dynamical approach without kinematical boundary conditions but also to take care of the computational cost of the simulation. This approach allows us to go up to 3-D models without multiprocessing, fully calculating the coupled thermal-solid-mechanical
evolution of the slab. A first application to South-American trench is presented.

Chapter 4. The novel approach presented in prior chapter is applied to investigate a fundamental open question of plate tectonics. The causes of formation of trench shape for oceanic arcs are investigated systematically. Earth sphericity, toroidal mantle flow and plate age are separately considered in relation to their capability to influence trench shape evolution. Age effects appear to be dominant for isolated slabs. Toroidal effects play a larger role when the slab is weak (i.e. wet slabs) or in presence of close boundaries.

**Notation**

During all the thesis it is employs a compact tensor notation instead of the use of indices.

Tensors: 0d: a 1d: a 2d: a 3d: a

Inner product: \[ x \cdot y = z \quad \vec{x} \cdot \vec{y} = \vec{z} \quad \vec{x} \cdot \vec{y} = \vec{z} \quad \vec{x} : \vec{y} = z \]

Derivative:

\[
\begin{align*}
\frac{\partial x}{\partial y} &= \vec{z} \\
\frac{\partial x}{\partial y} &= \vec{y} \\
\frac{\partial x}{\partial y} &= \vec{z} \\
\left( \frac{\partial}{\partial y} \right) \cdot \vec{x} &= z
\end{align*}
\] (1)
A novel coupled solid-fluid method for modeling subduction
Riassunto

La modellizzazione della dinamica delle tettonica delle placche è oggi alla portata di mano. Questo grazie all’avanzamento delle capacità computazionali disponibili e delle tecniche sperimentali le quali forniscono sufficienti costraints sul comportamento reologico ad alte pressioni e temperature. Questo progetto di dottorato si inserisce all’interno di un più ampio progetto chiamato "Orogeny I" il quale si prefigge lo scopo di arrivare alla modellizzazione dinamica dell’orogenesi delle Alpi. Primissima fase di questo progetto, il dottorato è stato focalizzato verso una comprensione delle diverse tecniche per modellizzare la dinamica tettonica. Nei primi due anni di dottorato sono state verificate le potenzialità di metodi lagrangiani ed euleriani, i quali riproducono i paradigmi dominanti in tettonica: la visione solido-mecanica e quella fluido-dinamica. Durante il progetto è stato evidenziato che i due approcci isolatamente non sono in grado di riprodurre una coerente dinamica tridimensionale del processo di subduzione, il motore della tettonica delle placche.

È stato quindi sviluppato e presentato un nuovo approccio basato sull’accoppiamento di due tecnologie: il metodo degli Elementi Finiti e quello degli Elementi di Bordo. Il primo utilizzato per calcolare la risposta più complessa delle reologia meccaniche, il secondo utilizzato normalmente per ottenere velocemente risultati in grandi domini. Questo duplice approccio porta con se il naturale pregio dell’efficienza computazionale. Mentre precedentemente una simulazione tridimensionale richiedeva circa 2 mesi per essere ottenuta su una macchina monoprocessore,
con questo nuovo approccio un risultato analogo è ottenibile in un giorno.


Numerose ulteriori possibili applicazioni del metodo sono presentate nelle conclusioni.