Computational Approaches to Understanding Surface Heat Flow, the Metamorphic Rock Record, and Subduction Geodynamics

by

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A dissertation

submitted in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy in Geosciences

Boise State University

November 2021

BOISE STATE UNIVERSITY GRADUATE COLLEGE

DEFENSE COMMITTEE AND FINAL READING APPROVALS

of the dissertation submitted by

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Dissertation Title: Computational Approaches to Understanding Surface Heat Flow, the Metamorphic Rock Record, and Subduction Geodynamics

Date of Final Oral Examination: August 27, 2021

The following individuals read and discussed the dissertation submitted by student Buchanan C. Kerswell, and they evaluated the student's presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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DEDICATION

To my mentors, colleagues, friends, and loved ones who take special interests in my life.

This work is yours as much as it is mine.

ACKNOWLEDGMENT

This work was only possible through the efforts of many individuals. My advisor, Dr. Matthew Kohn, deserves special recognition for his contributions, mentorship, and relentless support during the course of my studies. Dr. Taras Gerya and the Geophysical Fluid Dynamics group at the Institut für Geophysik, ETH Zürich, generously offered their high-performance computing resources from the Euler cluster, invaluable instruction, discussion, and support on the numerical modelling methods, and many free meals in Zürich. Additional high-performance computing support from the Borah cluster was provided by the Research Computing Department at Boise State University. Thanks to Dr. D. Hasterok for providing references and guidance on citing the large dataset in chapter three. Special thanks to Dr. Philippe Agard, Dr. Laetitia Le Pourhiet, and graduate students at Sorbonne Université for their incredible expertise and showing me the best of summertime Paris. Thanks to many anonymous reviewers, graduate students, and colleagues for helpful comments on technical aspects of each chapter. My deep appreciation of metamorphic rocks and Alpine geology was formed thanks to outstanding field excursions expertly guided by EFIRE and ZiP graduate students, faculty, and affiliates. Funding for this work was provided by the National Science Foundation grant OIA1545903 awarded to Dr. Matthew Kohn, Dr. Sarah

Penniston-Dorland, and Dr. Maureen Feineman. Datasets and code for reproducing this research are available at https://github.com/buchanankerswell.

ABSTRACT

Pressure-temperature-time (PTt) estimates from high-pressure (HP) metamorphic rocks and global surface heat flow (SHF) rates evidently encode information about pressure-temperature-strain (PTS) fields deep in subduction zones (SZs). Previous work demonstrates the possibility of decoding such geodynamic information by comparing physics-based numerical models with empirical observations of SHF and the metamorphic rock record. However, antithetical interpretations of (non)uniformity with respect to PTS fields are emerging from this line of inquiry. For example, while mechanical coupling depths inverted from SHF are narrowly distributed among SZs, maximum pressure-temperature (PT) conditions inverted from exhumed metamorphic rocks are relatively wide-ranging, and yet also uniformly distributed across pressures up to 2.4 GPa. This dissertation scrutinizes (dis)similarities among SZs inferred from large numerical and empirical datasets by applying a variety of computational techniques. First, coupling depths for 13 modern SZs are predicted after observing coupling in 64 numerical geodynamic simulations. Second, spatial patterns of SHF are assessed in two-dimensions by interpolating thousands of SHF observations near several SZ segments. Third, PTt distributions of over one million markers traced from the previous set of 64 SZ simulations are compared with hundreds of empirical

PTt estimates from the rock record to assess the effects of thermo-kinematic boundary conditions (TKBCs) on deep mechanical processing of rock in SZs. These studies conclude the following. Mechanical coupling between plates is primarily controlled by the upper plate lithospheric thickness, with marginal responses to other TKBCs. SHF interpolations show high variance within and among SZ segments, suggesting local, rather than widespread, continuity of PTS fields deep within SZs. Computed marker recovery rates correlate with TKBCs, and are therefore expected to vary among SZs. Finally, computed PTt distributions of markers show patterns consistent with transient, localized recovery from a cooling, serpentinizing plate interface. Together, this work encourages more antireductionist and diversified views of subduction geodynamics until SHF and PTt datasets can more precisely distinguish (dis)similarities in PTS fields within and among SZs. Strategically scaling PTt and SHF datasets in the future will improve computational precision and confidence, and thus will advance subduction zone research.

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LIST OF ABBREVIATIONS

HP high-pressure

PT pressure-temperature

PTS pressure-temperature-strain

PTt pressure-temperature-time

SHF surface heat flow

SZ subduction zone

TKBCs thermo-kinematic boundary conditions

UPT upper plate thickness

LIST OF SYMBOLS

GPa	Gigapascal
K	Kelvin
Ma	*Mega annum* or million-years
Z_{UP}	Upper plate thickness
Z_{cpl}	Mechanical coupling depth
Φ	Thermal parameter
η	viscosity
$\vec{v}_{conv}$	convergence velocity
$^{\circ}C$	Celcius
km	kilometer
t_{OP}	oceanic plate age

CHAPTER 1:

INTRODUCTION

Keypoints:

- Proxy datasets are key for inference about geodynamics deep in SZs
- Computation leverages large data to infer, build, and test geodynamic models

CHAPTER 2:

EFFECTS OF THERMO-KINETIC BOUNDARY CONDITIONS ON MECHANICAL PLATE COUPLING IN SUBDUCTION ZONES

Keypoints:

- Mechanical coupling responds strongly to upper plate thickness (UPT)
- Inverting UPT from surface heat flow (SHF) allows coupling depth estimation
- Consistent upper plate thickness would support common coupling depths

2.1 Abstract

Deep mechanical coupling between converging plates is a key feature of subduction zone (SZ) geodynamics. Onset of coupling likely corresponds with metamorphic dehydration reactions, and therefore, dependent on pressure-temperature-strain (PTS) fields within SZs.

Here we consider the effects of changing thermo-kinematic boundary conditions (TKBCs) on coupling using two-dimensional numerical models of oceanic-continental convergent margins. Coupling is implemented numerically by including experimentally-determined (de)hydration reactions of antigorite and olivine. Thermal feedbacks regulate (de)hydration self-consistently within the mantle wedge and stabilize coupling after ca. 5 Ma. We observe strong responses to coupling depth when changing upper plate thickness (UPT), and weak responses when changing thermal parameter (Φ). Regression of our results allows coupling depth estimation for modern SZ segments by inverting UPT from surface heat flow (SHF). We consider the implications for common coupling depths among SZs, which would require consistent UPT, and thus, globally consistent SHF in the backarc region.

2.2 Introduction

PTS fields deep in SZs strongly depend on the depth where the subducting plate and overlying mantle transition from mechanically decoupled (moving differentially with respect to each other) to mechanically coupled (moving with the same local velocity, Furukawa, 1993; Peacock *et al.*, 1994; Wada *et al.*, 2008). Coupling drives mantle wedge circulation, and the decoupling-coupling transition defines a rapid increase in temperature along the top of the subducting plate (Peacock, 1996). Many observations from numerical experiments and SHF infer coupling depths occurring globally at 70-80 km in modern SZs, essentially independent of other TKBCs including oceanic-plate age (t_{OP}), convergence velocity ($\vec{v}_{conv}$), and subduction geometry (Furukawa, 1993; Wada *et al.*, 2008; Wada & Wang, 2009). It is significant and curious why modern subduction zones appear to achieve similar depths of coupling despite their different physical characteristics.

Notwithstanding, many numerical geodynamic models use coupling depths of 70-80 *km* as TKBCs (e.g., Abers *et al.*, 2017; Currie *et al.*, 2004; Syracuse *et al.*, 2010; van Keken *et al.*, 2011, 2018; Wada *et al.*, 2012; Gao & Wang, 2014; Wilson *et al.*, 2014), although not exclusively (e.g. 40-56 *km*, England & Katz, 2010; Peacock, 1996). Similar coupling depths among SZs is an attractive hypothesis for at least two reasons: 1) it helps explain the relatively narrow range of sub-arc slab depths (England *et al.*, 2004; Syracuse & Abers, 2006) as mechanical coupling is expected to be closely associated with the onset of flux melting, and 2) since mechanical coupling is required to detach and recover rocks from the subducting plate (Agard *et al.*, 2016), a common depth of coupling may also help explain why the maximum pressures recorded by subducted oceanic material worldwide is ca. 2.3-2.5 *GPa* (roughly 80 *km*, Agard *et al.*, 2009).

Beyond playing a crucial role in SZ geodynamics, the location and extent of mechanical coupling along the plate interface is implicated in other geodynamic phenomena (seismicity, metamorphism, volatile fluxes into the mantle wedge, volcanism, and plate motions, e.g., Čížková & Bina, 2013; Gonzalez *et al.*, 2016; Peacock, 1990, 1991, 1993, 1996; Peacock & Hyndman, 1999; Hacker *et al.*, 2003; van Keken *et al.*, 2011; Grove *et al.*, 2012; Gao & Wang, 2017). Consequently, the mechanics of coupling have been extensively studied and discussed. Coupling fundamentally depends on the strength (viscosity) of materials above, within, and below the plate interface. In general, high water fluxes due to compaction and dehydration of clays and other hydrous minerals in the shallow forearc mantle wedge, coupled with increases in PT, form layers of low viscosity sheet silicates—especially talc and serpentine—that inhibit transmission of shear stress from the slab to the mantle wedge (Peacock & Hyndman, 1999). The lack of traction along the interface combined with cooling from the subducting plate surface ensures the shallow mantle wedge remains cold and rigid. Experimentally determined flow laws (e.g., Agard *et al.*, 2016), petrologic observations (e.g., Agard *et al.*, 2016), and geophysical observations (e.g., Gao & Wang, 2014; Peacock & Hyndman, 1999) all support the plausibility of this conceptual model of subduction interface behaviour.

This chapter focuses on two fundamental questions: 1) how does mechanical coupling depth respond to TKBCs, and 2) how stable is mechanical coupling depth through time? We use two-dimensional numerical geodynamic models of subduction to investigate potential correlations between coupling depth, UPT (inverted from backarc heat flow), and the thermal parameter (Φ). Wada & Wang (2009) previously investigated steady-state slab-mantle coupling depths by modelling 17 active subduction zones. Among other parameters, their models specified convergence rate, subduction geometry, thermal structure of incoming and overriding plate, and degree of coupling along the subduction interface. Their experiments prescribed interface rheology for numerical control and discriminated the best-fit depth based on observed fore-arc heat flow. In our models, we specify the same TKBCs to simulate the range of modern SZ systems. However, subduction dip angle and, most importantly, the point of mechanical coupling are regulated self-consistently by evolving PTS fields in the deforming continuum. That is, coupling depth in each of our models is not a fully determined feature, but rather a semi-spontaneous model outcome. As in other previous studies (e.g., Ruh *et al.*, 2015), we include the rheological effect of the dehydration reaction $antigorite \Leftrightarrow olivine + orthopyroxene + H_2O$, which drives mechanical coupling by an abrupt viscosity increase with antigorite loss. The position of this reaction along the subduction interface determines the coupling depth.

We quantify the effects of Φ and UPT on the depth of this reaction using multi-variate linear regression. We then visualize thermal feedbacks within the system in terms of the distributions of temperature, viscosity, and mantle flow velocity. Lastly, we discuss how feedbacks stabilize the coupling depth through millions of years of subduction.

CHAPTER 3:

A COMPARISON OF HEAT FLOW INTERPOLATIONS NEAR SUBDUCTION ZONES

Keypoints:

- Inconsistent spatial patterns characterize heat flow near subduction zones
- Heat flow investigations favour 2D interpolations over 1D transects
- Scaling datasets and new interpolation schema will advance SZ research

3.1 Abstract

Heat fluxing through the Earth's surface provides indirect observations of pressure-temperature-strain (PTS) fields deep in SZs. Global heat flow databases, therefore, are invaluable for generating and testing belief about SZ geodynamics. Here we argue that investigating surface heat flow (SHF) in two-dimensions by interpolation, rather than

in one-dimension by projection, forms better interpretations about spatial continuity of deep processes. We directly compare interpolations based on the First (spatial continuity) and Third (similarity) Laws of Geography applied to the most updated global heat flow database. We observe inconsistent spatial patterns and of SHF in magnitude and variance near subduction zones, regardless of interpolation method. The implications include discontinuous PTS fields at depth, countering hypotheses of commonly thin upper plate lithospheres and mechanical coupling depths among subduction zones. Strategic scaling of SHF datasets will improve interpolation precision and confidence—leading to better tools for distinguishing differences within and among SZs. We propose new data acquisition and composite interpolation schema as avenues for future SZ research.

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