様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

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研究種目：若手研究

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研究課題名（和文）Numerical simulations for the formation of dynamic decollement and subduction plate interface

研究課題名（英文）Numerical simulations for the formation of dynamic decollement and subduction plate interface

研究代表者

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研究者番号：９０８１１４９８

交付決定額（研究期間全体）：（直接経費）　　3,000,000円

研究成果の概要（和文）：本研究では、付加体力学とプレート境界断層の形成について、いくつかの点を解明した。粒状媒体の応用パターンが推力に影響を与えることを明らかにし、デコルメント断層の形成を明らかにする解析解と数値シミュレーションを発表した。また変成岩の深度に応じた圧力変換の新しい方法を提案した。２つの論文を筆頭著者として、3つの論文を共著者として出版した。

研究成果の学術的意義や社会的意義
In this project, we investigated how the faults, on which earthquakes and tsunami happen, are created and how that affects the growing land. We also proposed a new method that contributes to a hot debate in Earth Sciences over the interpretation of the rock pressure record.

研究成果の概要（英文）：During this project、 I elucidated some aspects of the mechanics of accretionary prisms and the formation of plate boundary fault. In Furuichi et al. (2018), we reavealed that stress patterns in granular media affect the dynamics of thrusting. In Bauville et al. (2020), we presented analytical solutions and numerical simulations that shed light on the formation of decollement faults.
The second part of the project, which treats of the dynamics of convergent tectonic zone was initially planned as a modeling study. However, I deviated from this initial goal as new interesting data became available. Thus, in Bauville and Yamato (2020), we proposed a new method of pressure-to-depth conversion for metamorphic rocks.
I published two articles as a first-author and three articles as a collaborator. I also presented the results in national and international conferences (JpGU and EGU general meeting). Thank to the Kakenhi budget I also visited my colleagues at the University of Rennes (France).

研究分野：Geology

キーワード：accretionary prism　critical taper theory　numerical simulations　geodynamics　metamorphism

１．研究開始当初の背景（Background at the beginning of the research）

Mechanical processes at the interface between tectonic control the evolution of the Earth through mountain building and the subduction of lithospheric material down to the mantle. It also affects human activities because of mineral resource formation, or earthquake hazard. In this project, I explored two aspects of the mechanics of convergent tectonic margins.

First, I investigated the development of tectonic structures at convergent margins, and in particular the formation of decollement faults. The decollement is a low angle thrust of relatively low strength that constitutes the base of the accretionary prism. A large corpus of analytic, analog and numerical models has investigated the control of the strength and geometry of a pre-existing decollement on the tectonics of the accretionary prism. However, in the Nankai Trough and Japan Trench, observations suggests that the decollement formed either as a consequence of the accretionary prism deformation and/or as a prolongation of the deeper subduction plate interface. The mechanism of formation of such a dynamic decollement remains incompletely understood. During the 2011 Tohoku earthquake large coseismic displacement >50m triggered the formation of a devastating tsunami. Unraveling the processes of formation and evolution of a dynamic decollement may allow us to gain a better insight into tsunamigenic faulting and the possibility of coseismic slip on the decollement.

The second part was initially planned to focus on simulations of the larger subduction region. However, this plan was changed to take advantage of newly available data about rocks in convergent margins. In that project, we tackled the problem of reconstructing the history burial of a rock from the pressure that is inferred from its mineralogical assemblage. Pressure-to-depth conversion is a crucial step towards geodynamic reconstruction but remains strongly debated.

２．研究の目的（Purpose of the research）

The broad objective of this research was to understand the formation of the tectonic structures at convergent margins. We investigated structures at several scales from whole mountain belt (100 km-scale) to plate boundary fault, accretionary prisms and tectonic nappes (10 km-scale). Specific objectives were: (1) to determine the physical factors controlling the formation of plate boundary faults in homogeneous sediment; (2) to determine the influence of rheology and geometry on the formation of tectonic folds, faults and larger structures such as nappes and accretionary prisms; (3) to propose new formulas for pressure-to-depth conversion that take into rock mechanics.

３．研究の方法（Research methods）

I used a combination of techniques in this work. First, I used theoretical continuum mechanics to derive equations and determine the parameters that are likely to affect the specific tectonic structures I studied. For the application to accretionary prism my work expanded on the “critical taper theory” (Dahlen, 1984). This theory describes the steady state geometry taken by a piece of frictional/plastic material that is sheared from the bottom. It has been used extensively in the field of structural geology to investigate the static of accretionary prism and fold-and-thrust belts.

The second and major aspect of my work was to write simulation code and use that code to investigate tectonic phenomenon. The software I developed solves the Stokes equation for a non-linear elasto-visco-plastic material. The numerical algorithm, based on the finite-difference method, is described in detail in Bauville et al. (2020).

Finally, I used a combination of data analysis and theoretical continuum mechanics to derive and validate the new pressure-to-depth conversion methods (Bauville and Yamato, 2021).

４．研究成果（Results of Research）

Bauville et al. (2020) explored the mechanics of underthrusting and the development of plate boundary faults near the Earth surface. Underthrusting at an active compressional margin is the process by which incoming rocks are thrusted below other tectonic units. In an orogenic context, the underthrusting of tectonic units leads to nappe stacking and thus plays an important role in the burial and exhumation of rocks in mountain belts. In subduction zones, underthrusted sediments may be incorporated at the base of the accretionary wedge; or they may be dragged with the subducting oceanic plate into the upper mantle where they are partly recycled through arc-magmatism. In this work, we presented an analytical description of the problem using continuum mechanics. Since the analytical provided only a static view of this dynamic process we also performed numerical simulations (Fig. 1). The simulations validated the findings of the analytical solution and showed that sometimes the analytical solution can predict the steady state conditions, while in other case a steady state never arises.

The history of pressure that a rock has undergone is one of the main tools with which scientists can reconstruct the history of mountain belts. The so-called metamorphic pressure, is determined from a rock mineralogical assemble and, under some assumptions, can be converted to depth to reconstruct the burial history. Bauville and Yamato (2021) questioned the standard assumptions used pressure-to-depth conversion. We proposed a new set of formulas for pressure-to-depth conversion based on continuum mechanics and showed that the model explains pressure data from the literature when using material properties adequate for rocks (Fig. 2). The prediction of our new model explains the data and suggests a feasible, yet drastically different geodynamic history for mountain belts around the world. In our new interpretation, deep subduction (160 km) and rapid exhumation of rocks is replaced with a relatively shallow burying (<90 km) and slow exhumation.

Thanks to the Kakenhi, I was able to invite R. Spitz from university of Lausanne for a two-week visit which resulted in the paper by Spitz et al. (2020). In this article, we explored the three-dimensional variation of tectonic nappe geometry that results from faulting and folding, and their interaction with strong rock strength contrast. The 3D numerical simulations were applied to the Helvetic Alps of Switzerland. I contributed to this article by advising the design of the study and simulations and by writing a code to visualize the results.

Humair et al. (2020) explored the interaction of folding and thrusting in the Canadian cordillera using numerical simulations. This was a long running project that we were able to finalize thanks to the support of Kakenhi. In this project, I helped design the study objectives, simulation setup and I assisted in running the simulation and extracted the results.

Overall, through this Kakenhi project, I explored several aspects of the dynamics of convergent margins by combining numerical simulations, analytical solutions and data. My studies revealed novel aspects of the dynamics of accretionary prisms and tectonic nappe formation; and we proposed a drastically new view of the kinematics and dynamics of mountain belt and high-pressure metamorphic rock history.

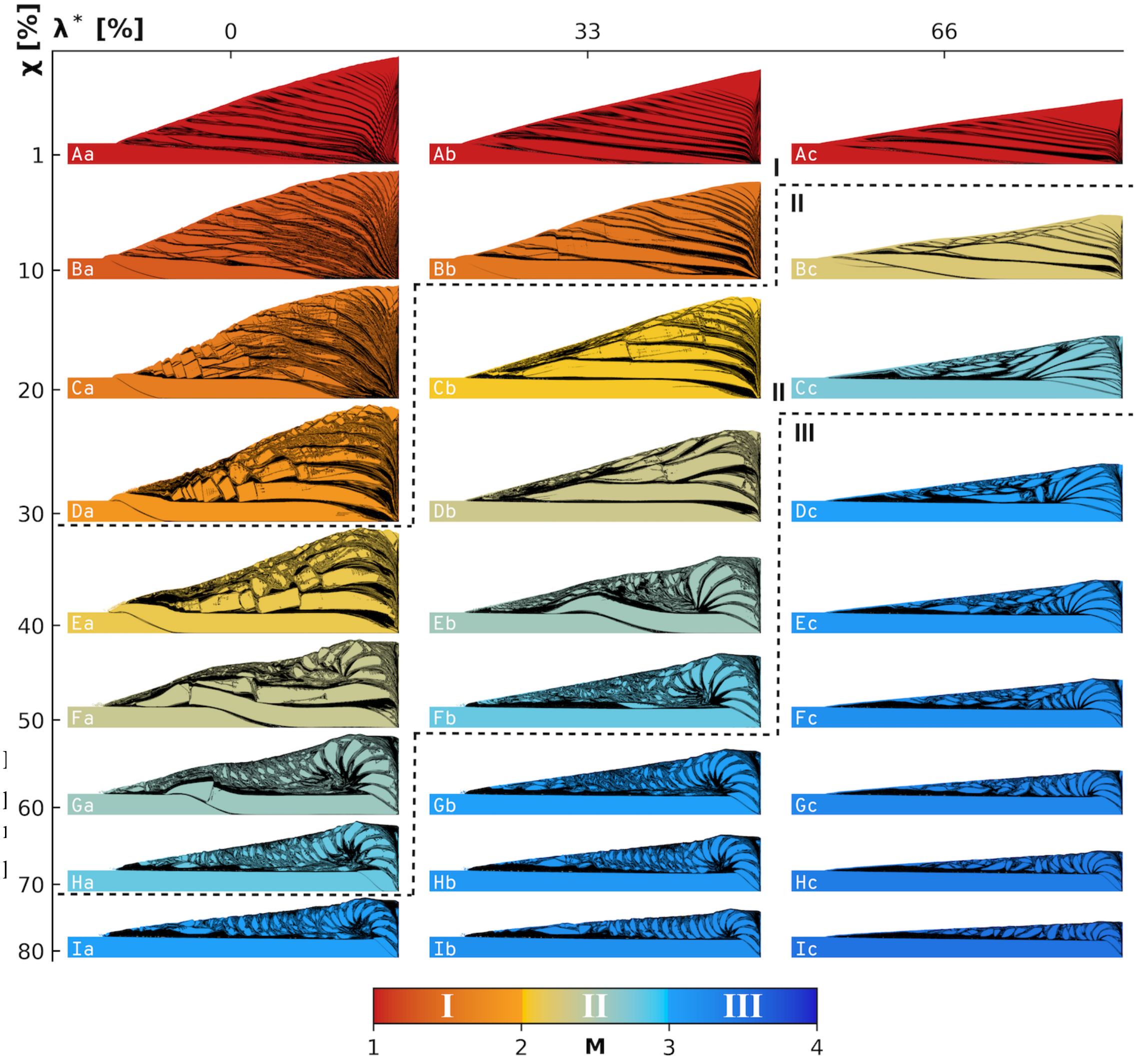

Fig. 1. Summary of numerical simulation results of Bauville et al. (2020). λ^* is the normalized fluid pressure, χ is a fault weakening factor. We showed, from the analytical solution that these two non-dimensional parameters control the statics of the system. The simulations revealed how these parameters control the dynamics and finite geometry of the system.

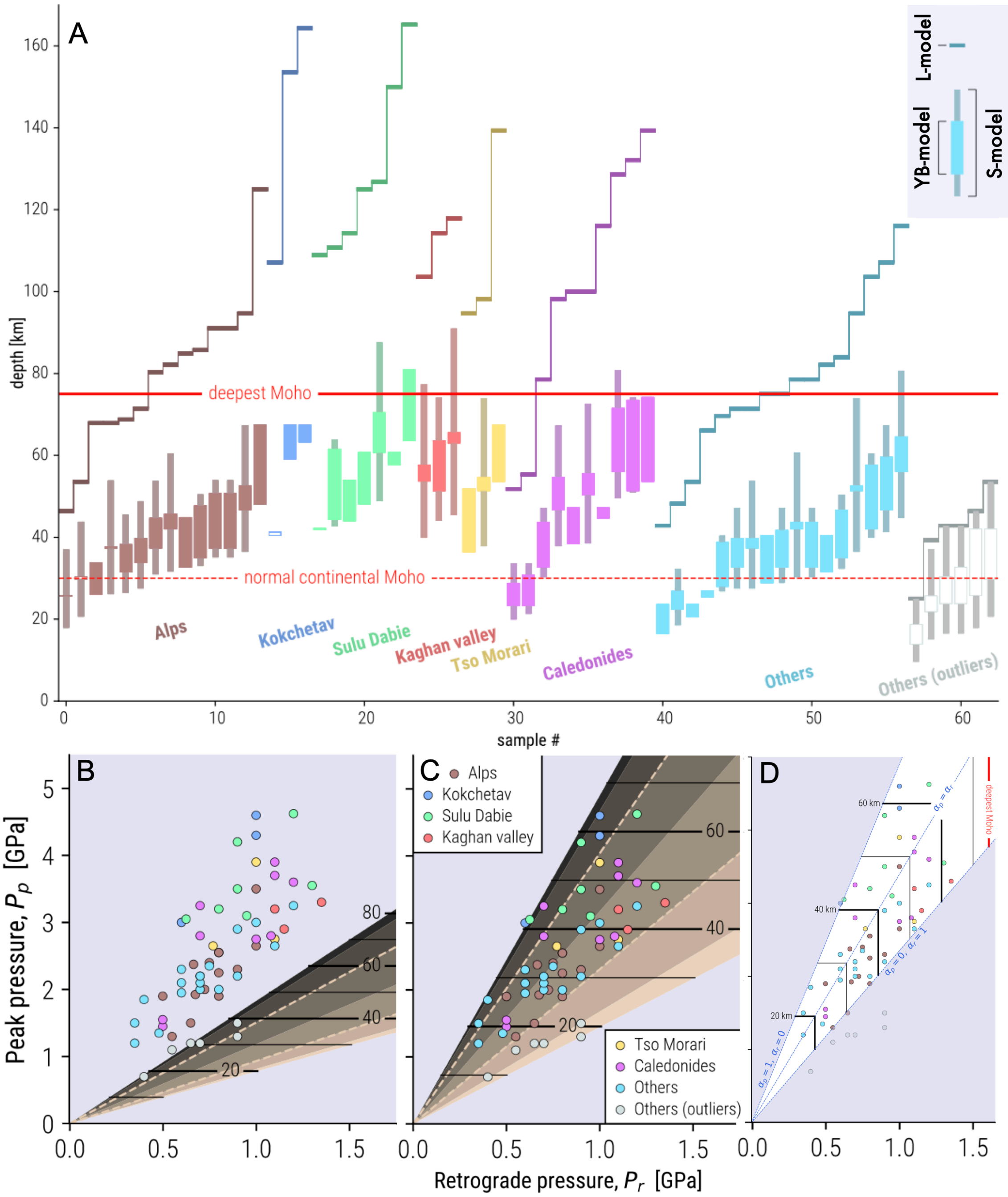

Fig. 2. Summary of the results of Bauville and Yamato (2021). (A) Depth estimated from pressure for all the samples in the dataset, using several different assumptions. (B-D) Comparison of models (fan shaped areas) and data, using different parameters and assumptions. Remarkably, some models explain the entire dataset with reasonable assumptions.

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　4件／うち国際共著　2件／うちオープンアクセス　1件）

１．著者名 Bauville, A. ,Furuichi, M., Gerbault M.	４．巻 125
２．論文標題 Control of Fault Weakening on the Structural Styles of Underthrusting‐Dominated Non‐Cohesive Accretionary Wedges	５．発行年 2020年
３．雑誌名 Journal of Geophysical Research: Solid Earth	６．最初と最後の頁 1-27
掲載論文のDOI（デジタルオブジェクト識別子） 10.1029/2019JB019220	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Spitz, R., Bauville, A., Epard J.-L., Kaus, B. J. P., Popov A. A., Schmalholz, S. M.	４．巻 0
２．論文標題 Control of 3D tectonic inheritance on fold-and-thrust belts: insights from 3D numerical models and application to the Helvetic nappe system	５．発行年 2019年
３．雑誌名 Solid Earth	６．最初と最後の頁 1-39
掲載論文のDOI（デジタルオブジェクト識別子） 10.5194/se-2019-173	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Bauville A.、Yamato P.	４．巻 22
２．論文標題 Pressure‐to‐Depth Conversion Models for Metamorphic Rocks: Derivation and Applications	５．発行年 2021年
３．雑誌名 Geochemistry, Geophysics, Geosystems	６．最初と最後の頁 最初と最後の頁
掲載論文のDOI（デジタルオブジェクト識別子） 10.1029/2020GC009280	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 -

１．著者名 Humair F.、Bauville A.、Epard J.-L.、Schmalholz S. M.	４．巻 789
２．論文標題 Interaction of folding and thrusting during fold-and-thrust-belt evolution: Insights from numerical simulations and application to the Swiss Jura and the Canadian Foothills	５．発行年 2020年
３．雑誌名 Tectonophysics	６．最初と最後の頁 最初と最後の頁
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.tecto.2020.228474	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 -

〔学会発表〕　計4件（うち招待講演　0件／うち国際学会　2件）

1．発表者名 Bauville, A. ,Furuichi, M., Gerbault M.
2．発表標題 The structural styles of underthrusting-dominated non-cohesive tectonic wedges
3．学会等名 European Geosciences Union General Assembly 2019（国際学会）
4．発表年 2019年

1．発表者名 Bauville, A. ,Furuichi, M., Gerbault M.
2．発表標題 Control of fault weakening on the structural styles of underthrusting-dominated non-cohesive tectonic wedges
3．学会等名 Japan Geoscience Union Metting 2019
4．発表年 2019年

1．発表者名 Bauville, A., Yamato, P.
2．発表標題 Pressure-to-depth conversion models for (ultra-)high-pressure metamorphic rocks: review and application
3．学会等名 EGU General Assembly 2020（国際学会）
4．発表年 2020年

1．発表者名 Bauville, A., Yamato, P.
2．発表標題 Pressure-to-depth conversion models for metamorphic rocks: review and application
3．学会等名 JpGU-AGU Joint Meeting 2020
4．発表年 2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関