EA The Influence of Mechanical Stratigraphy on the Evolution of the Papua New Guinea Fold and Thrust Belt*

Youseph Ibrahim[1], Patrice Rey[1], and Luke Mahoney[2]

Search and Discovery Article #51659 (2020)**
Posted May 11, 2020

*Adapted from extended abstract based on oral presentation given at 2020 1st AAPG/EAGE PNG Geoscience Conference & Exhibition, PNG's Oil and Gas Industry Maturing Through Exploration, Development and Production, Port Moresby, Papua New Guinea, February 25-27, 2020
 DOI:10.1306/51659Ibrahim2020

[1]University of Sydney, Australia (yibr0590@uni.sydney.edu.au)
[2]Oil Search Ltd, Australia

Abstract

Fold and thrust belts form as the crust accommodates shortening due to compressional tectonic forces. Their structural architecture varies widely and is influenced by a multitude of factors including the driving boundary conditions, the amount of shortening and the level of basement involvement (i.e. thin-skinned vs thick-skinned tectonics). Understanding the formation and evolution of fold and thrust belts is crucial for assessing structural traps, fluid flow, and refining geologic interpretations. Here, we investigate how the mechanical properties of rocks affect the structural style of fold and thrust belts. Mechanical stratigraphy refers to the mechanical layering present in a stratigraphic column, involving the succession of competent and less competent lithologies. For a given set of boundary conditions and amount of shortening, the mechanical stratigraphy is expected to influence the partitioning of shortening between folds and thrusts, their respective distribution pattern, their respective wavelengths, and their interaction.

Introduction

To explore the influence of mechanical stratigraphy on the structural evolution of fold and thrust belts, we run two-dimensional, coupled thermal and mechanical numerical experiments using the Underworld numerical framework. The reference model setup is shown in Figure 1. On the right wall, we apply a horizontal boundary velocity which pushes a rigid wedge-shaped indenter towards the left. The left wall in all models acts as a rigid backstop. The base of the model moves freely in the X direction but not in the Y direction. In subsequent models, we tested the influence of an isostasy-like boundary condition to the base of the model allowing for the development of a flexural response. In order to explore the influence of mechanical stratigraphy on structural styles many models were run using a variety of alternating weak and strong layers.

Observations

We observe that the vertical strength profile, which involves the sum of various strength wavelengths (Figure 1), leads to multiple horizontal wavelengths of deformation (Figure 2). A large strain wavelength likely forms due to the large-wavelength competence contrasts within the overall stratigraphic package. This wavelength controls the spacing of thrusts and associated folds in the competent layer (blue in Figure 1 and Figure 2). A smaller strain wavelength is observed in the incompetent unit and may be a result of mechanical heterogeneity within the incompetent layers (brown in Figure 1 and Figure 2). This low-frequency wavelength gives way to a more complex and heterogeneous set of structures (Figure 2). A key observation is that strain partitioning in fold and thrust belts is likely to occur both within single units and over the entire multilayer stack. Strain partitioning in single sedimentary units is dependent on the mechanical heterogeneities within those units, as when homogenous layering is used, deformation solely operates at the large wavelength scale. Similarly, in the overall multilayer stack, we observe that the competence contrasts control the strain partitioning between folding and faulting, including their interactions and their geometries.

When the stratigraphic ordering is shifted, we observe that the position of the competent layer (blue stack) exerts a large influence on the structural style within a fold and thrust belt. In addition, our experiments suggest that the ratio of competent to incompetent rocks also influence the wavelength of folding, the location of faults, and their vergence. Hence, two configurations of a stratigraphic column with the same ratio of competent to incompetent rocks may experience different deformation styles, depending on the positions of the competent and incompetent units within the stratigraphy. However, if the position of the competent unit within two different stratigraphic columns is the same, deformation style will vary with the ratios of competent to incompetent rocks.

Results

In all the previous experiments, the base the model acted as a rigid boundary. This leads to the formation of a very thick pile of material, reaching many kilometres of height. In a second series of experiments, we implemented more realistic basal conditions in a model inspired by the stratigraphic column of the Gobe Region of the Papuan Fold Belt, which is comprised of competent limestones, intermediate sandstones, and incompetent muds and shales. We aim to calibrate the mechanical stratigraphy of the lithological stack involved in the Papuan Fold Belt. This will allow us to run numerical models aimed at investigating structural styles in areas that are poorly imaged by seismic data, while using robustly imaged structures to ground-truth our models. The numerical box is 42 km long and 17.4 km wide with a grid resolution of 80 m. To document the impact of the basal boundary condition, we ran a model with a basal boundary conditions able to approximate a realistic flexural response. Figure 3 describes the model setup. We compare the effects of two different isostasy boundary conditions. In the “average isostasy” model, the pressure at the base of the entire model is averaged and a vertical velocity condition is applied at the base of the model to maintain this pressure constant. In the ‘Airy isostasy’ model, the vertical velocity condition is calculated to maintain constant the initial pressure underneath each grid column.

Results

These models (Figure 4) document the control mechanical stratigraphy has on multi-wavelength deformation of the Papuan Fold Belt. The type of isostasy boundary condition employed is observed to exert a large influence on the evolution and geometry of the fold and thrust belt. The most striking difference between the two models is the formation of a large wavelength syncline, with major intra- synclinal deformation in the Airy-isostasy model, which is absent in the 'average' isostasy model. This syncline develops between a through-going conjugate thrust pair, which appears in both models. In the airy-isostasy model, intrasynclinal damage consists of a duplex-like structure of stacked anticlines, separated by conjugate thrust faults (Figure 4A). Deformation is gentler in the average-isostasy models, as an anticline pop-up structure forms between the two conjugate thrusts. In our models, the mechanical stratigraphy is a first order control on fault geometry, as competence contrasts cause faults to refract and detach in the highly incompetent units. Moreover, thickness variations of the incompetent layers depend heavily on faulting in the overlying and underlying competent layers.

This pilot study demonstrates that numerical experiments can deliver realistic sets of structures commonly observed in fold and thrust belts. Using the Papuan Fold Belt as an example, we aim to model the structural styles that result from the local mechanical stratigraphy. This approach is potentially useful for resource exploration as it provides a technique for predicting subsurface trap geometries within fold and thrust belts. Ultimately, classifying the mechanical stratigraphy of fold and thrust belts with heterogeneous sedimentary layering is key to understanding their evolution, subsurface geometry and optimising exploration efforts.

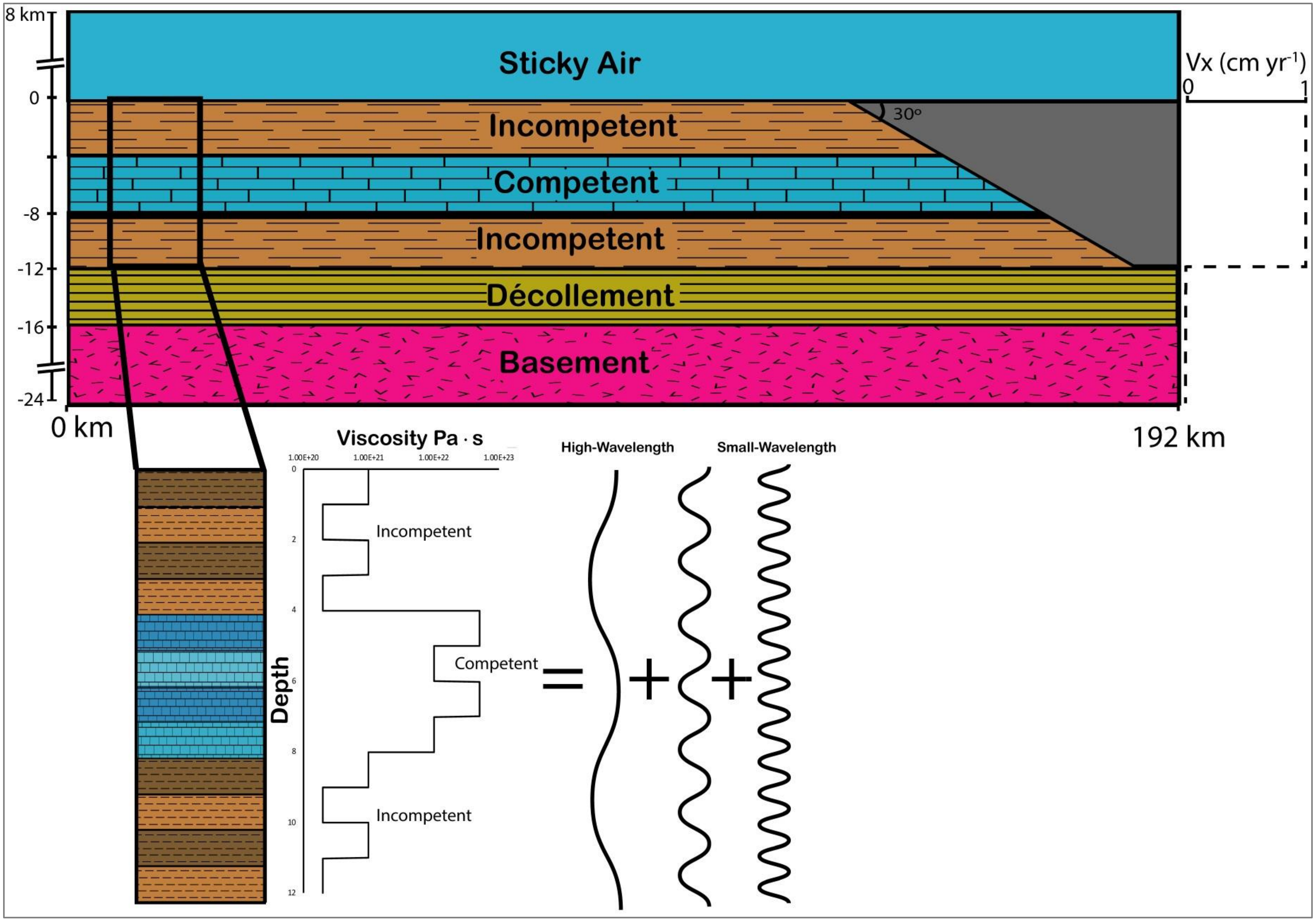

Figure 1. Model setup used to simulate the evolution of thin-skinned fold and thrust belts. A layer of competent rock (in blue) is sandwiched between two incompetent layers (in brown). Low wavelength oscillations in mechanical strength occur every 1 km and high wavelength oscillations occur every 4 km.

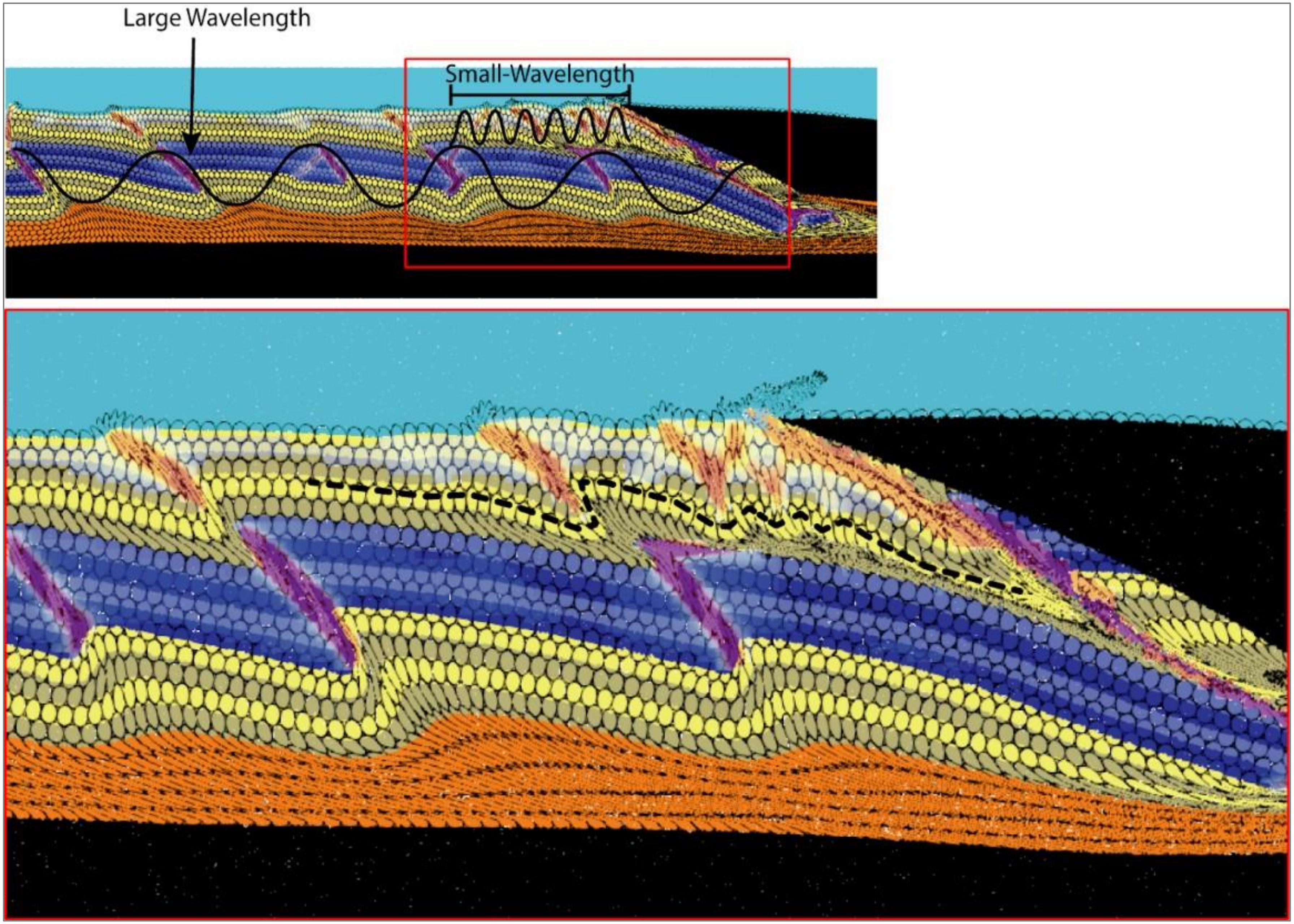

Figure 2. Model outputs showing both small strain wavelength and large strain wavelength. The blown-up portion illustrates the formation of small-scale heterogeneous structures. Finite strain ellipses illustrate the intensity, orientation and distribution of finite strain.

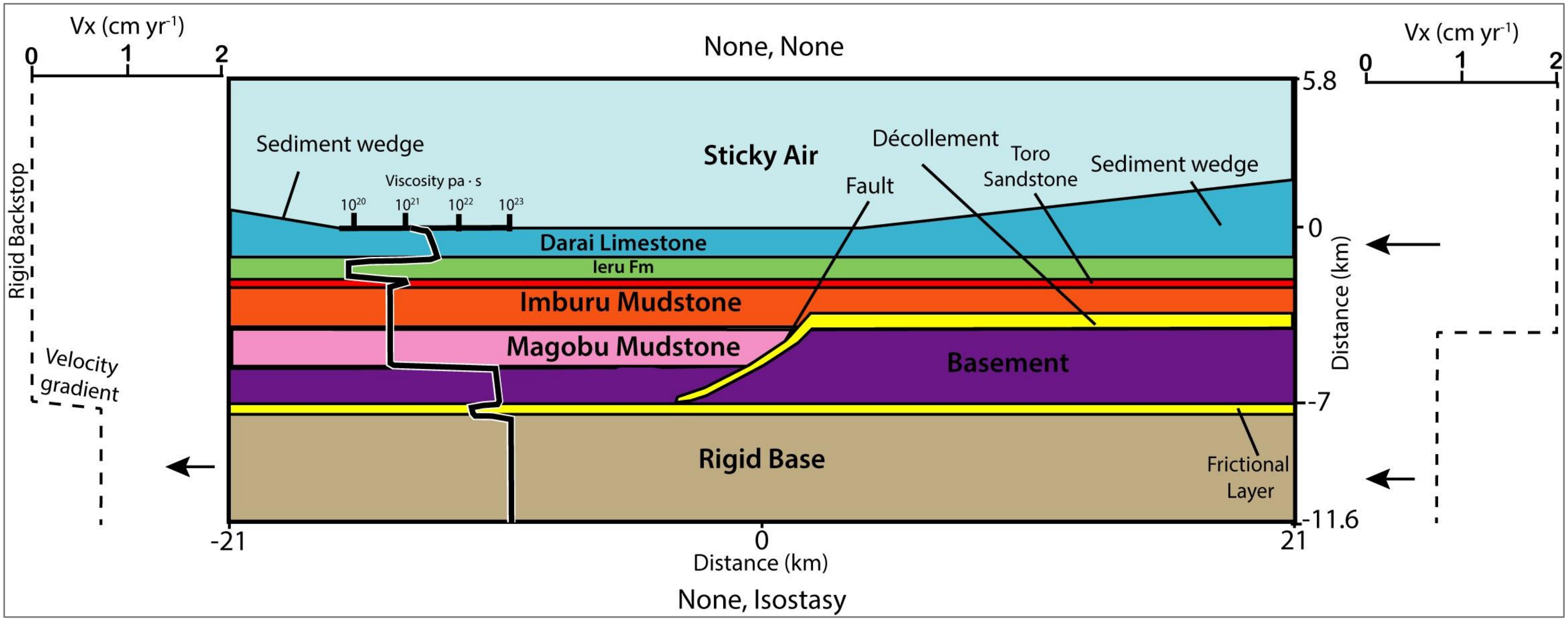

Figure 3. Initial model setup, boundary conditions, and viscosity for the reference model inspired by the Papuan Fold Belt.

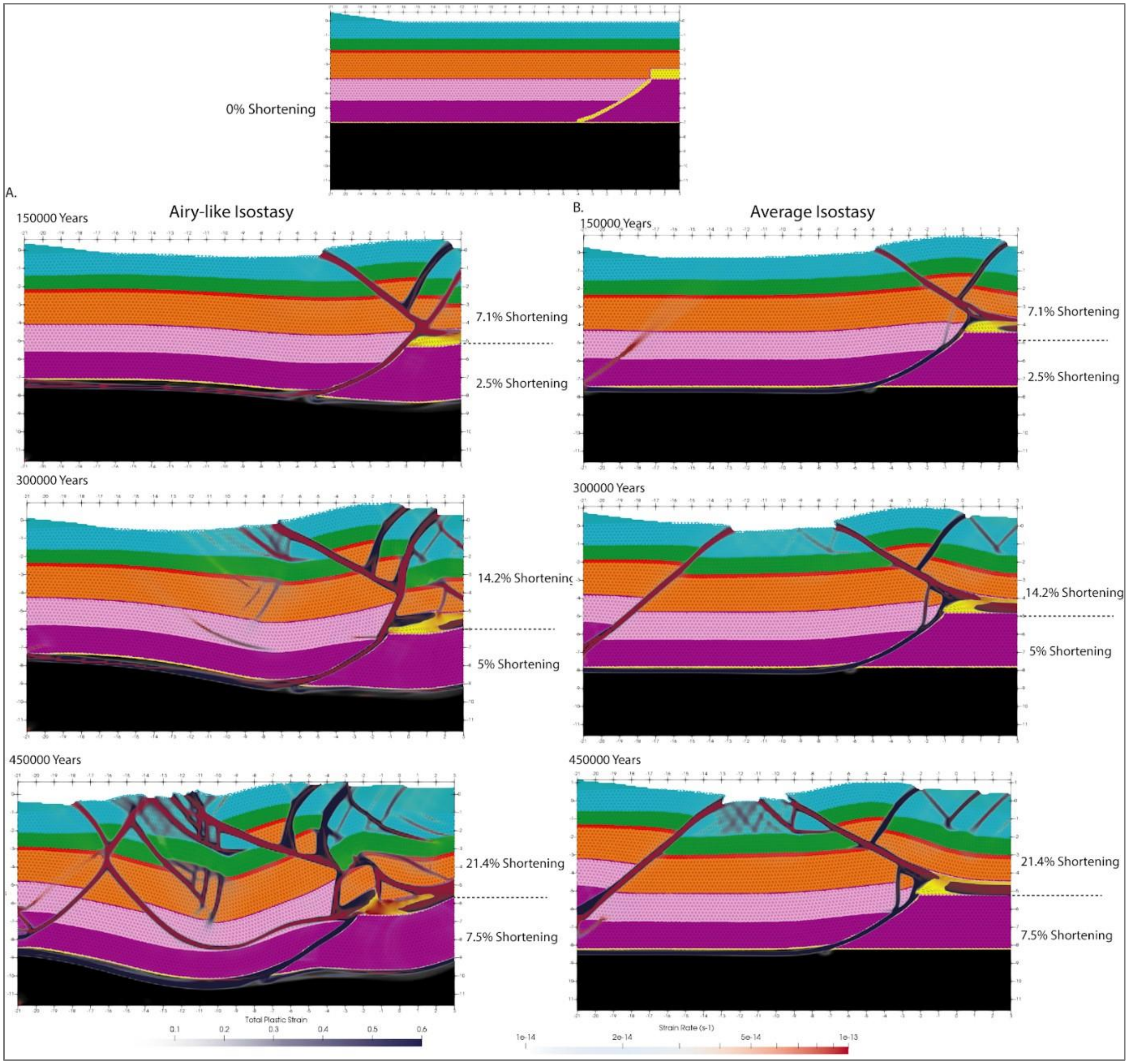

Figure 4. A. Models of the Papuan Fold Belt, with an Airy-like isostasy boundary condition (A) and an average isostasy boundary condition (B).