Tectonophysics 684 (2016) 76–91

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Three-dimensional finite-element models on the deformation of forearcs caused by aseismic ridge subduction: The role of ridge shape, friction coefficient of the plate interface and mechanical properties of the forearc

Stefanie Zeumann *, Andrea Hampel

Institut für Geologie, Leibniz Universität Hannover, Germany

ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form 25 November 2015
Accepted 23 December 2015
Available online 6 January 2016

Keywords:
Aseismic ridge subduction
Forearc deformation
3D finite-element modelling
Ridge shape
Friction coefficient
Forearc strength

ABSTRACT

Geological and geophysical data show that the forearc of subduction zones experiences strong deformation during the subduction of aseismic oceanic ridges. In order to better understand ridge-related forearc deformation patterns, we performed a series of three-dimensional finite-element models, in which we varied the ridge shape, the friction coefficient of the plate interface and the mechanical strength of the forearc. Experiments were carried out for migrating/non-migrating ridges and accretive/erosive margins, respectively. Our results show that the subducting ridge uplifts the forearc and induces horizontal displacements that alter the strain regime of both erosive and accretive forearcs. Generally, shortening prevails in front of the ridge, while domains of shortening and extension exist above the ridge. Models with stationary ridges show high uplift rates only above the ridge tip, whereas the forearc above migrating ridges experiences uplift above the leading ridge flank and subsequent subsidence above the trailing flank. The height and width of the ridge as well as the friction coefficient of the plate interface have the largest effect on the forearc deformation patterns, whereas the mechanical strength of the forearc plays a lesser role. Forearc indentation at the trench is largest for high and broad ridges, high friction coefficients and/or weak forearc material. Shortening and extension of the forearc above the ridge are more intense for high and narrow ridges. Our model results provide information about the distribution of ridge-induced displacements and strain fields and hence help to identify deformation patterns caused by subducting aseismic ridges in nature.

1. Introduction

When bathymetric highs such as seamount chains or aseismic ridges enter a subduction zone, they can considerably affect the tectonic evolution of the forearc region (e.g. Lallemand et al., 1994; McCann and Habermann, 1989; Spikings and Simpson, 2014; von Huene et al., 1997). Geological data from convergent margins worldwide document that ridge subduction may lead to uplift of the forearc, with the possible formation of marine terraces at the coast (e.g. Bouysse and Westercamp, 1990; Corrigan et al., 1990; Gardner et al., 1992; Hsu, 1992; Macharé and Ortlieb, 1992; Saillard et al., 2011). Furthermore, the subducting bathymetric high may alter the strain regime in the forearc, for example, by causing enhanced shortening (e.g. Sitchler et al., 2007) or by inducing strike-slip or normal faulting (e.g. Dominguez et al., 1998; Sébrier et al., 1985, 1988).

Although geological and geophysical data can provide many constraints on the impact of a subducting ridge on a forearc, the shape of the subducted part of the ridge can only be roughly inferred from deformation patterns (e.g. Dominguez et al., 1998; Gardner et al., 1992, 2013) or mirror images of the ridge on other plates (e.g. Gutscher et al., 1999; Hampel, 2002). Furthermore, it may be difficult to identify ridge-related displacement and strain patterns if the ridge has migrated along the margin, which is commonly the case. Against this background, modelling studies can help to gain a better understanding of the deformation patterns caused by ridge subduction because models allow the analysis of the spatio-temporal forearc evolution during ridge subduction and also the variation of parameters like the geometry and orientation of the ridge or the structure of the forearc. So far, however, the range of parameters explored by analogue or numerical modelling studies is rather limited, which may be partly due to the fact that capturing the effects of ridge subduction requires a demanding three-dimensional setup. For example, the relationship between the geometry of the ridge and the resulting shape of the deformed forearc area has never been quantitatively investigated despite the fact that natural collision zones show a wide range of different shapes of subducting ridges (e.g. McCann and Habermann, 1989; Spikings and Simpson, 2014). Similarly, the friction coefficient of the plate interface has not been varied in experiments of ridge subduction, although it is known from analogue and numerical models without a subducting bathymetric high that the friction coefficient of the plate

* Corresponding author at: Institut für Geologie, Leibniz Universität Hannover, Callinstraße 30, 30167 Hannover, Germany.

E-mail address: zeumann@geowi.uni-hannover.de (S. Zeumann).

http://dx.doi.org/10.1016/j.tecto.2015.12.022

interface exerts a fundamental control on the forearc evolution (Buiter et al., 2001; Cailleau and Oncken, 2008; Cattin et al., 1997; Gutscher et al., 1998; Hampel and Pfiffner, 2006; Hassani et al., 1997; Lohrmann et al., 2003).

The available analogue and numerical models of ridge subduction were mostly designed to investigate the ridge-induced forearc deformation at a specific margin. The three-dimensional analogue models by Dominguez et al. (1998) and Hampel et al. (2004a) were adjusted to the tectonic setting of the Ryukyu and Peruvian margins, respectively. Based on a comparison of two experiments, Hampel et al. (2004a) showed that the mechanical strength of the forearc influences the style of ridge-induced deformation. In a more general approach, Martinod et al. (2013) used three-dimensional analogue experiments to explore the feedback mechanisms between a subducting ridge (oriented either perpendicular or oblique to the trench), the deformation of the upper plate and the downgoing slab for different plate convergence velocities, but with a plate convergence direction that was always perpendicular to the margin. Compared to the analogue models, the existing three-dimensional numerical models have a simplified setup, in which the ridge is implemented as a boundary condition and the plate interface as a vertical boundary (Geist et al., 1993; Wallace et al., 2009). Both studies used model setups adjusted to specific margins and hence did not include a sensitivity analysis of model parameters. Other numerical models on ridge subduction were restricted to a 2D setup and investigated, on a lithospheric scale, the effect of the subducting ridge on the slab geometry (e.g. Gerya et al., 2009; van Hunen et al., 2002) or the evolution of the vertical displacement of the Andean forearc (Martinod et al., 2015).

Here we present a parameter study with three-dimensional numerical models, in which an oceanic plate carrying the ridge subducts beneath a forearc wedge (note that we consider only "aseismic" ridges, i.e. active spreading ridges are excluded). In different experiments, we varied the height and width of the ridge, the friction coefficient of the plate interface and the material properties of the forearc wedge. Also varied are the angles between ridge, trench and plate convergence. Our models, which we analyse in terms of the ridge-induced displacement and strain fields, help to gain a better understanding into patterns of forearc deformation during ridge subduction.

2. Model setup

The three-dimensional models, which were constructed and computed using the commercial finite-element software package ABAQUS, consist of a forearc wedge and an oceanic plate that carries the aseismic ridge (Fig. 1a). Ridge and oceanic plate are modelled as rigid parts, whereas the forearc is deformable and has an elastoplastic rheology (see below). Following Cailleau and Oncken (2008), who implemented the subducting oceanic plate in their two-dimensional models as a rotating segment of a circle, the oceanic plate in our three-dimensional models is included as a rotating cylinder segment with a radius of 225 km (cf. Zeumann and Hampel, 2015). On this cylinder, an arc-shaped model ridge is positioned, whose frontal part has a circular shape with a radius of 25 km. This setup has the advantage that we can consider the curvature of the oceanic plate, the wedge shape of the forearc and a frictional plate interface. Also, gravity can be included based on a well established procedure for models with non-horizontal layers (see below). Our chosen setup further has the advantage that it is computationally stable for many orientations of the subducting ridge, for different directions of the plate convergence as well as for a

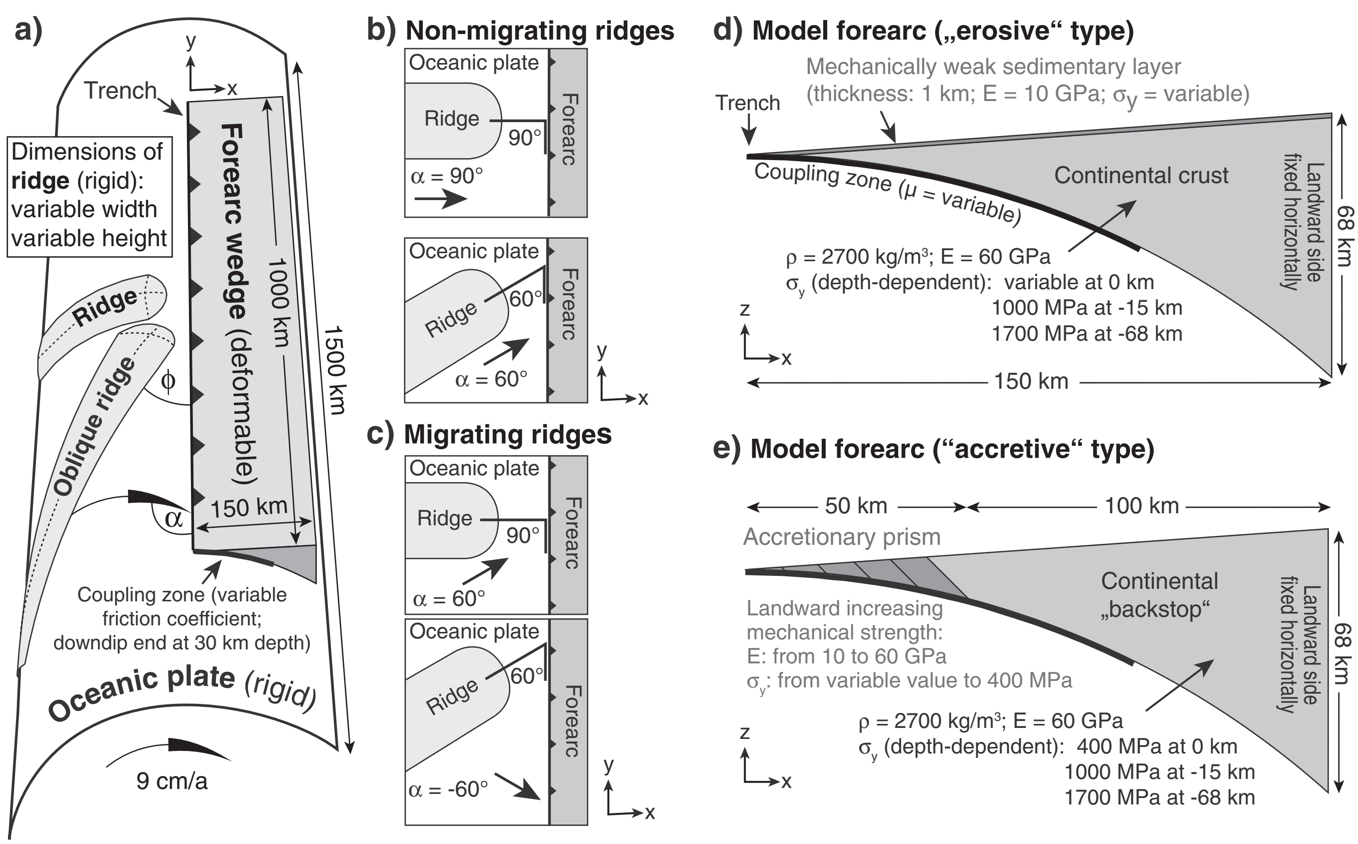

Fig. 1. Model setup. a) Perspective view of the model with a rigid oceanic plate carrying the aseismic ridge and a deformable forearc. The oceanic plate is implemented as a rotating cylinder with a diameter of 225 km (cf. Cailleau and Oncken, 2008). α and ϕ denote the angles between ridge axis and plate convergence direction and between ridge axis and margin, respectively. Thick black line along the plate interface indicates the coupling zone with variable friction coefficient and a downdip end of 30 km. The lower part of the plate interface is frictionless. b) Schematic sketches of the setup with non-migrating ridges. c) Schematic sketches of the setup with migrating ridges. d) Cross section of the erosive forearc. e) Cross section of the accretive forearc. Rheological parameters are Young's modulus (E), density (ρ) and plastic yield stress (σ_y). Density is 2700 kg/m^3 and Poisson ratio is 0.25 for the forearc in all experiments.