Mechanical model for the tectonics of doubly vergent compressional orogens

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ABSTRACT

A mechanical model of crustal shortening and deformation driven by the relative convergence of rigid, underlying mantle plates explains many features of convergent orogens. Results based on numerical models and supported by sandbox models show that a Coulomb crustal layer subject to basal velocity boundary conditions corresponding to asymmetric detachment and subduction of the underlying mantle passes through three stages of orogenic growth: (1) block uplift bounded by step-up shear zones; (2) development of a low-taper wedge over the underthrusting mantle plate; and (3) development of a low-taper wedge overlying the overthrusting mantle plate and verging in the opposite direction. When modified by isostasy, basal viscous flow, surface erosion and denudation, and sedimentation, the resultant model orogens exhibit a variety of styles with characteristics in common with small, rapidly denuded orogens, large orogens with plateaus and extensional characteristics, and active subduction margins with doubly vergent accretionary wedges and deformed fore-arc basins.

INTRODUCTION

The doubly vergent nature of continental collision zones was noted early in this century (Argand, 1916) and more recently for active margins (e.g., Silver and Reed, 1988; Byrne et al., 1988) (Fig. 1, A and B). Investigation of the underlying mechanics has, however, been confined mainly to sandbox experiments (Malavieille, 1984). Critical Coulomb wedge models (e.g., Davis et al., 1983; Dahlen, 1984, 1990) can explain the geometry of accretionary wedges but are limited in their applicability to the structure of the orogen as a whole. We present results from a mechanical model, based on more general numerical techniques, in which a crustal layer with a rigid-plastic rheology is deformed by the motion of two nearly rigid, underlying plates. Calculations were made with a velocity-based, Eulerian, finite-element technique (Willett, 1992; Beaumont et al., 1992a), but results presented here are restricted to interpretive descriptions.

BASIC MODEL: DOUBLY VERGENT CRITICAL MECHANICS

Description of Basic Model

We consider first the two-dimensional, plane-strain deformation of a laterally uniform, rigid-plastic layer attached to two converging, rigid underlying plates. One underlying plate is assumed to slide below the other at point S, and their motion imposes constant-velocity boundary conditions on the base of the overlying layer (Fig. 1C). Left of S the velocity is constant and positive (moving from left to right), whereas to the right of S it is zero (Fig. 1C). The discontinuity in the horizontal boundary velocity at S results in a singularity in the strain rate field within the layer. The model layer is infinite in lateral extent (X direction, Fig. 1C). These boundary conditions are fundamentally asymmetric, as illustrated by the model results.

The deforming layer has a noncohesive Coulomb yield criterion with a coefficient of friction ϕ. The base of the layer is weaker than the overlying material and has a coefficient of friction ϕ_b. The flow rule that governs the post-yield deformation is isotropic and incompressible, and the material does not strain harden or soften. With these properties and boundary conditions, the problem is scale independent and so is applicable for any layer thickness H.

Results of the Basic Model

Initially, the basic model shows two conjugate zones of shear deformation that "step up" deformation from the stress singularity to the surface (Fig. 1C). Consistent with the incompressible Coulomb plastic rheology, the shear zones initially form at 45° relative to the direction of maximum compressive stress, which is approximately horizontal. The initial stress and strain rate fields are symmetric, but subsequent growth is distinctly asymmetric and remains so through three stages of development (Fig. 2).

In stage 1 (Fig. 2A), the step-up shear zones remain rooted at the singularity. The region between the shear zones forms a nearly undeforming triangular plug that is lifted and translated to the right to form a block uplift.

In stage 2 (Fig. 2B), deformation propagates beyond the step-up

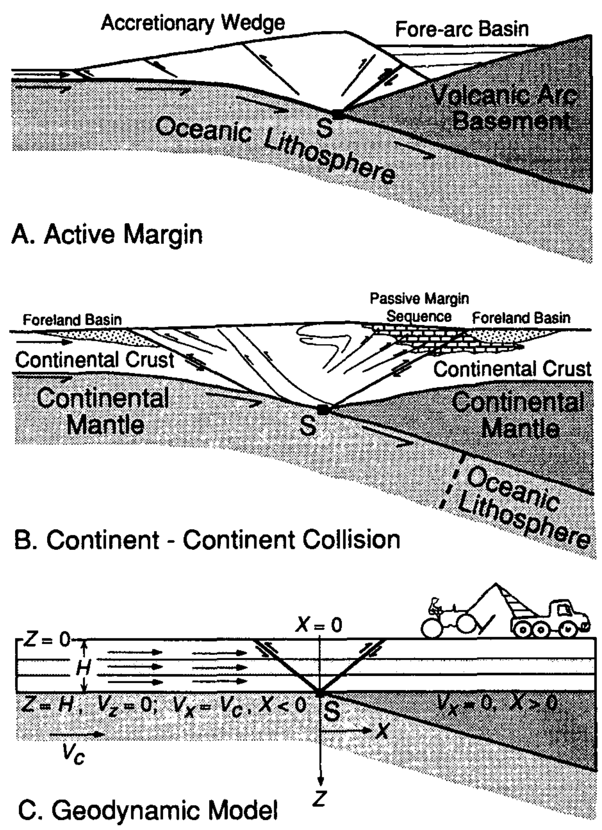

Figure 1. Illustration of active margin (A) and continent-continent collision (B). Crustal deformation is focused above point S, where mantle of left plate detaches and is underthrust. C: Geodynamic model in which uniform crust, extending from surface to depth *H*, is deformed under basal velocity boundary conditions. Underlying domain (gray regions) is not modeled. For these boundary conditions there is no requirement for "bulldozer" backstop.