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Formation of the frontal thrust zone of accretionary wedges

Jonathan R. Weiss [a,b,*], Garrett Ito [a], Benjamin A. Brooks [c], Jean-Arthur Olive [d], Gregory F. Moore [b], James H. Foster [e]

[a] COMET, School of Earth and Environment, University of Leeds, Leeds, United Kingdom
[b] Department of Geology and Geophysics, University of Hawai'i, Honolulu, HI, USA
[c] U.S. Geological Survey Earthquake Science Center, Menlo Park, CA, USA
[d] Laboratoire de Géologie, Ecole Normale Supérieure/CNRS UMR 8538, PSL Research University, Paris, France
[e] Hawai'i Institute of Geophysics and Planetology, University of Hawai'i Honolulu, HI, USA

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ABSTRACT

The combination of recent megathrust earthquakes that have ruptured the frontal portions of accretionary prisms and historical evidence for large wedge-front, fold-and-thrust belt events has sparked interest in the development of wedge-front fault systems. Here we explore the formation of these faults using two-dimensional finite-difference models of spontaneous thrust fault formation and wedge accretion. A reference model with uniform material strength parameters predicts wedge-front thrusts to nucleate near the surface of the sedimentary layer and propagate down towards the basal décollement. The formation of a new frontal thrust is preceded by incipient faulting over a zone several kilometers wide forward of the wedge toe, resembling the protothrust zone (PTZ) imaged in seismic reflection data from the front of submarine accretionary prisms. Similar behavior, with a new frontal thrust forming from top to bottom, occurs if the fraction (λ) of pore-fluid pressure relative to the total (dynamic) pressure is uniform and <0.8 throughout the sediment section, or if λ increases with depth and is <0.7 at the base of the décollement. For greater values of λ, models predict more frontal thrusts to form from the bottom to top. These results are reasonably well explained by a simple elastic stress analysis. Models that simulate cohesive brittle strength that is negligible in the shallow sediments and increases with depth also predict new thrust faults to form from top to bottom. Models in which viscous flow at shallow depths represents creep of sediments predict bottom-up thrust nucleation when viscous stresses due to plate convergence remain lower than the brittle yield stress in the top ~15–50% of the sediment section. Top-down nucleation is otherwise favored when viscous stresses exceed the brittle yield strength throughout most of the sediments. Our study illuminates key controls on the mechanical and temporal links between the PTZ, the forward propagation of slip along the underlying décollement, and the formation of a new frontal thrust.

1. Introduction

In the aftermath of recent large earthquakes associated with low-angle megathrust faults that underlie accretionary wedges, our understanding of how and where wedges rupture has begun to change. Previously, the frictional properties of the shallow up-dip portions of megathrusts were thought to be more likely to facilitate aseismic rather than coseismic slip (Scholz, 1998). The 2010 M_W 7.8 Mentawai, 2011 M_W 9.0 Tohoku-Oki, and the 1999 M_W 7.6 Chi-Chi earthquakes (Fujiwara et al., 2011; Hill et al., 2012; Yue et al., 2005), however, are just a few examples of recent events characterized by coseismic slip that advanced to the wedge toe and, in the case of the Japan and Sumatra earthquakes, resulted in devastating tsunamis. These events demonstrate the need to better understand the mechanics of the wedge toe including the formation of the décollement and steeply dipping thrust faults that facilitate surface uplift (e.g. Hubbard et al., 2015).

Our knowledge of wedge-front structures comes primarily from seismic reflection and well-log data, and in the case of fold-and-thrust belts, outcropping faults, folds, and geomorphic indicators. Such observations are often interpreted with geometric and kinematic models (e.g. fault propagation folding, trishear) that assume

* Corresponding author at: COMET, School of Earth and Environment, University of Leeds, Leeds, United Kingdom.
E-mail address: j.r.weiss@leeds.ac.uk (J.R. Weiss).

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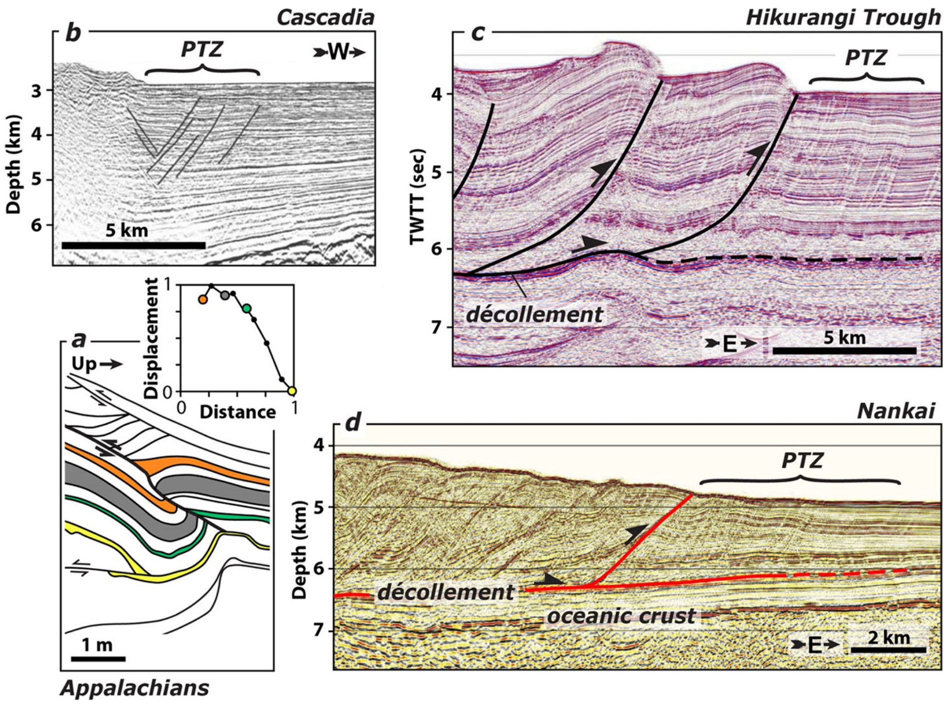

Fig. 1. Evidence of thrust faults initiating at or near the surface. (a) Line drawing from the Appalachian Valley and Ridge fold-and-thrust belt, showing an outcropping thrust fault where measured displacement (inset) decreases down-section into the footwall syncline (redrawn from McConnell et al., 1997). (b–d) Multi-channel seismic reflection images showing the protothrust zones (PTZ) in front of the (b) Cascadia accretionary prism (MacKay, 1995), (c) Hikurangi subduction zone (Barnes et al., 2010), and (d) Nankai Trough (Moore et al., 1990). Karig (1986) define the PTZ as a region forward of the main thrust characterized by disrupted reflection horizons, diffuse thickening, shortening, and porosity reduction that occurs prior to thrusting. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

thrusts initiate near the tip of the basal décollement, propagate upward towards the surface, and are linked to a décollement at depth (e.g. Allmendinger and Shaw, 2000; Hughes and Shaw, 2015; Suppe and Medwedeff, 1990). In contrast, an observation that has received relatively limited attention is the faulting associated with incipient deformation forward of the main frontal thrusts. High-resolution seismic reflection data outboard of accretionary prisms including Cascadia, Nankai, and New Zealand, for example, image a "protothrust zone" (PTZ), characterized by numerous cross-cutting faults midway through the sediment section that often offset the seafloor but do not clearly intersect the décollement (e.g. Barnes et al., 2018; Karig, 1986; MacKay, 1995) (Fig. 1).

This paper investigates the mechanics and formation of the wedge-front thrust fault system using a combination of a simple stress analysis and finite-difference models of spontaneous fault nucleation and growth. Our results show that in the simplest case of a sediment layer with homogeneous material strength parameters, new wedge front faults initiate at shallow depths and then propagate down to the décollement. We then vary material properties to further map out the range of conditions needed to produce top-down versus bottom-up fault propagation. One group of models explores different uniform fractions (λ) of pore-fluid pressure relative to the total pressure, another group includes a more realistic increase in λ with depth, another considers an increasing cohesive brittle strength with depth. Finally, we explore models in which viscous creep is possible at shallow depths in the crust, and the strain rate-dependent strength increases with depth. We conclude with a discussion of the implications for natural systems.

2. Numerical approach

We model the formation and evolution of orogenic wedges using SiStER (Simple Stokes solver with Exotic Rheologies, Olive et al., 2016), a two-dimensional MATLAB®-based code that uses finite differences on a fully staggered mesh with the particle-in-cell method (Gerya, 2010) to solve for conservation of mass and momentum in an incompressible visco-elastic–plastic continuum. At each time step, Picard iterations are used to solve the non-linear terms in the governing equations based on updated estimates of the strain rate-dependent rheology, computed on the finite difference grid. This process is repeated until the L_2-norm of the strain rate field residual is $\leq 10^{-3}$, or a maximum of 75 iterations are performed. Between time steps (50% of the Courant condition), Lagrangian tracer particles passively track material properties and stresses as they are advected in the Eulerian velocity field using fourth-order Runge–Kutta. Material properties are passed between nodes/cells and particles using bilinear interpolation (Gerya, 2010). Cells have dimensions of 125 m $\times$ 125 m for all model runs unless otherwise noted in Table S1, which lists all important model parameters.

The Maxwell model is used for the visco-elastic deformation, but the stress is limited by the plastic strength, which leads to the formation of localized shear bands that represent faults. Plastic strength is defined by the Drucker–Prager form of the Mohr–Coulomb failure criterion in which brittle strength (as the second invariant of the 2-D deviatoric stress tensor) increases with total pressure P, friction angle ϕ, and cohesion C,

$$\sigma_{II} = P \sin\phi + C \cos\phi. \quad (1)$$

Brittle failure is computed on the mesh nodes rather than particles. Brittle strength reduction occurs as accumulated plastic strain ε_p increases from 0 to 0.05 (e.g. Lohrmann et al., 2003) by decreasing C linearly from $C_0 = 20$ MPa at $\varepsilon_p = 0.0$ to $C_{\min} = 0.01$ MPa at $\varepsilon_{crit} = 0.05$. In addition, fault healing is simulated by reducing ε_p over a time scale ($\tau \approx 63$ kyr) that is small compared to the duration individual faults are active. Shear bands typically localize to widths of 2–4 grid cells. Thus, with 125 m grids, the critical plastic strain required for full fault weakening roughly corresponds to 10–20 m of slip.