North America plate is driven westward by lower mantle flow

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Received 29 July 2002; accepted 7 October 2002; published 19 December 2002.

[1] The sense of shear traction which the deeper mantle exerts on the North America plate is controversial. To test this, we compute laterally-varying thin-shell models. Fault elements are used to outline the plate, so the velocity of North America is not fixed. The basal boundary condition is set in one of three ways: (a) for resistive drag, we assume that the lower mantle is static with respect to Africa; (b) we test models with no basal traction; (c) for active drag, we assume that the lower mantle moves as a rigid plate but 10% faster than North America. Each model is scored by comparison with sea-floor spreading rates, geodetic velocities, stress directions, and NUVEL-1A. Only models with active drag are successful. While these results do not determine the exact azimuth or pattern of basal drag on the North America plate, they establish the modal sense as active. *INDEX TERMS:* 3210 Mathematical Geophysics: Modeling; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 9350 Information Related to Geographic Region: North America. **Citation:** Liu, Z., and P. Bird, North America plate is driven westward by lower mantle flow, *Geophys. Res. Lett.*, *29*(24), 2164, doi:10.1029/2002GL016002, 2002.

1. Introduction

[2] The shear traction which the sub-asthenospheric mantle exerts on the base of the North America plate has been controversial: is it generally eastward (resistive or passive drag) or westward (forward or active drag)? *Grand* [1987] used seismic tomography to identify subducted Farallon plate more than 400 km below the eastern United States and Caribbean; this would seem to imply resistive drag at those latitudes. *Richardson and Reding* [1991] used an elastic-plate finite element model with parameterized boundary forces, and found that either strong ridge-push or active basal drag is required to explain stress directions. *Wang and Wang* [1999] treated the plate as a viscous shell (ignoring topography and faults) and found that successful models were driven from the edges, with resistive basal drag. *Schutt and Humphreys* [2001] summarized SKS splitting observations that suggest a strain-fabric in the asthenosphere with a stretching direction near 060–240° (but ambiguous as to the sense of shear). *Silver and Holt* [2002] used known deformation rates in the Basin and Range province to break this symmetry, and to show that there the lower mantle flow is eastward and the traction is resistive. But, *Bokelmann* [2002] found P-wave anisotropy fabrics under the Canadian shield which suggest active (southwestward) mantle drag on the base of the cratonic part of the North American continent.

2. Construction of Model

[3] To help resolve this controversy, we construct a laterally-varying thin-shell model of the lithosphere of the entire North America plate, with realistic nonlinear rheology and faults, and use it in a set of neotectonic simulations with both senses of basal drag (or none). To build a model with the greatest possible realism (within the thin-shell approximation), and the smallest possible number of free parameters: (1) Topographic plate-driving forces of ridge-push and trench-suction are incorporated in a 3-D density model, not treated as adjustable parameters. (2) Dislocation-creep flow laws are calibrated to olivine rheology (mantle) or maximum earthquake depth (crust), so the only free rheologic parameters are effective fault friction and subduction-zone shear traction. (3) Lateral boundaries with other plates are represented by plate-boundary faults, with the velocity of the adjacent plate prescribed along the outside. Thus, all sides have velocity boundary conditions, and there are no side-boundary traction parameters to adjust.

[4] We base our grid (Figure 1) on the outline of the North America plate in the NUVEL-1(A) model of *DeMets et al.* [1990; 1994]. Adjacent parts of the Pacific plate which are deforming are included in the domain (Alaska, British Columbia, California, Baja California). Flat and rigid regions of the craton are represented with large finite elements (~500 km) for economy, while plate margins are represented by smaller elements (60–120 km) to better represent fault shapes and short-wavelength topography. Fault elements are used to outline the plate; we assign fault dips of 90° to transform faults, 65° to normal faults along spreading ridges, and 20° to subduction zones. Additional fault elements are used to represent active intraplate faults in the West. The resulting finite element grid NAP2 has 5399 nodes, 7953 triangular continuum elements, and 1223 linear fault elements.

[5] Topography within the plate is taken from the ETOPO5 data set. We created a map of estimated heat flow from 3 sources: (1) contours from the map of *Blackwell and Steele* [1992] in western North America; (2) 5°-mean values from *Pollack et al.* [1993] in other continental areas; and (3) model heat flows in oceanic lithosphere based on the theory of *Stein and Stein* [1992] and the digital age grid of *Mueller et al.* [1997]. A 3-D thermal and density model was computed from the topography and heat flow maps by assuming local isostasy (with respect to mid-ocean ridges of 2700 m depth) and steady-state heat conduction. Critical thermal and isostatic constants include: crustal reference density (at 0 K) of 2816 kg m^{-3}; mantle reference density 3332 kg m^{-3}; thermal expansion coefficient 2.4×10^{-5}

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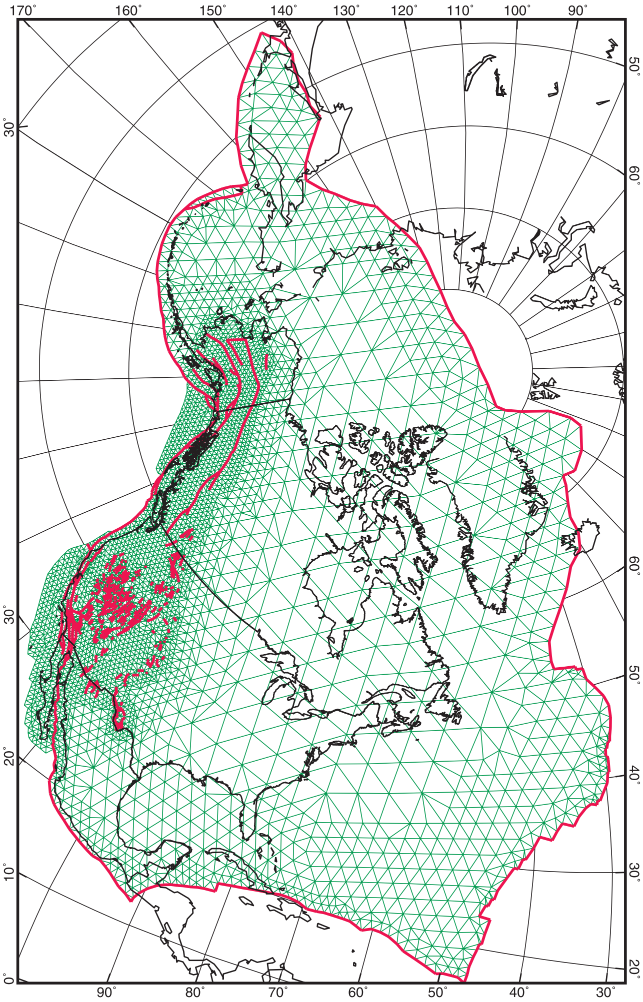

Figure 1. Thin-shell finite element grid NAP2 used in these experiments. The model domain is the entire North America plate plus adjacent deforming regions of the Pacific plate. Heavy lines are fault elements; light lines are boundaries of continuum elements. Oblique Mercator projection.

K^{-1} in crust and 3.94×10^{-5} K^{-1} in mantle; thermal conductivity 2.7 W m^{-1} K^{-1} in crust and 3.2 W m^{-1} K^{-1} in mantle; radioactive heat production 6.2×10^{-7} W m^{-3} in crust and 3.2×10^{-8} W m^{-3} in mantle; adiabatic gradient in asthenosphere 6.1×10^{-4} K m^{-1}. The most uncertain parameter in this group is the crustal radioactivity, which was adjusted to achieve a rough match of model crustal thicknesses with thicknesses measured by seismic refraction.

[6] An anelastic rheology including frictional plasticity and thermally-activated dislocation creep was chosen for both crust and mantle-lithosphere layers, based on laboratory results and previous modeling studies [*Bird and Kong*, 1994; *Bird*, 1998; *Bird and Liu*, 1999]. Critical rheologic constants include: continuum friction 0.85; hydrostatic pore pressure (except in subduction zones); dislocation creep strength of crust (in Pa) of $2.3 \times 10^9\ \varepsilon^{1/3} \exp(4000/T)$; and dislocation creep strength of mantle lithosphere and asthenosphere of $9.5 \times 10^4\ \varepsilon^{1/3} \exp((18314 + 0.0171\ z)/T)$, where ε is strain rate in s^{-1}, T is temperature in K, and z is depth in m.

[7] Subduction zones almost certainly have super-hydrostatic pore pressures which lubricate them, and we approximate this effect through one additional rheologic parameter, an imposed upper limit on the down-dip integral of shear tractions in all fault elements representing the Aleutian, Cascadia, and Central America subduction zones. This parameter (TAUMAX of Table 1) has been variously estimated as $3 \sim 4 \times 10^{12}$ N/m [*Bird*, 1978], 4×10^{12} N/m [*Wang et al.*, 1995], $2 \sim 3 \times 10^{12}$ N/m [*Bird*, 1996], and 2×10^{12} N/m [*Geist*, 1996].

3. Boundary Conditions

[8] Since side-boundary nodes lie in adjacent plates, velocity boundary conditions are assigned based on the NUVEL-1A model, but the velocity of the North America plate is not fixed at any point. The basal boundary condition is located at 400 km depth (at the base of the asthenosphere) and is set in one of three ways: (a) for resistive drag, we assume that the deeper mantle is static with respect to the Africa plate [*Burke and Wilson*, 1972], and compute shear tractions from the rheology of an adiabatic asthenosphere of

Table 1. Parameters and Scores of Computed Models

FFRIC	TAUMAX (N/m)	Basal Drag	TADIAB (K)	Ideal Drag (MPa)	Velocity Error (mm/a)	Geodesy Error (mm/a)	Spreading Error (mm/a)	Stress Error (degree)
0.03	7.5×10^{11}	resistive	1412	−1.98	18.0	11.7	15.2	45.0
0.03	7.5×10^{11}	resistive	1512	−0.94	17.4	9.7	15.7	42.7
0.03	7.5×10^{11}	none	1512	0.00	17.2	15.6	17.7	40.2
0.03	7.5×10^{11}	active	1512	0.44	3.2	6.8	5.3	38.7
0.03	7.5×10^{11}	active	1412	0.92	1.1	5.7	2.8	35.8
0.03	7.5×10^{11}	active	1362	1.43	1.1	5.7	2.2	35.2
0.10	2.5×10^{12}	resistive	1412	−1.98	17.3	10.7	16.5	37.9
0.10	2.5×10^{12}	resistive	1512	−0.94	17.2	10.8	17.4	36.4
0.10	2.5×10^{12}	none	1512	0.00	18.4	16.5	19.7	37.2
0.10	2.5×10^{12}	active	1512	0.44	11.0	10.2	13.4	35.7
0.10	2.5×10^{12}	active	1412	0.92	2.0	6.3	6.1	32.2
0.10	2.5×10^{12}	active	1362	1.43	0.9	5.6	4.7	31.4
0.17	4.25×10^{12}	resistive	1412	−1.98	17.6	11.8	18.2	37.0
0.17	4.25×10^{12}	resistive	1512	−0.94	18.0	11.8	19.3	36.4
0.17	4.25×10^{12}	none	1512	0.00	20.2	14.6	21.2	37.0
0.17	4.25×10^{12}	active	1512	0.44	14.6	11.0	17.4	34.0
0.17	4.25×10^{12}	active	1412	0.92	4.7	7.6	10.4	32.1
0.17	4.25×10^{12}	active	1362	1.43	1.3	6.5	7.7	31.1

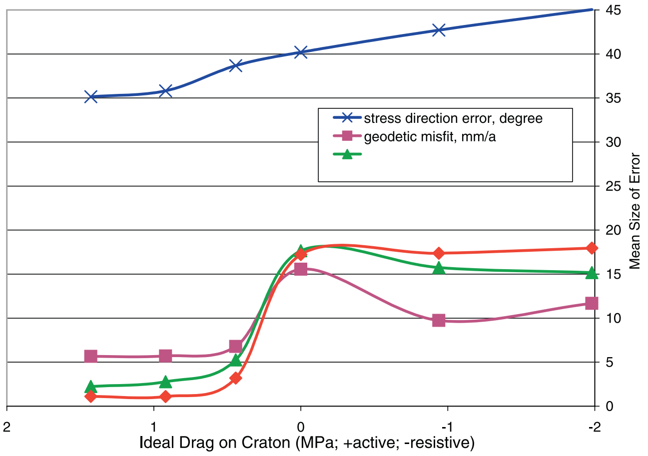

Figure 2. Results of 6 models with fault friction 0.03, as a function of magnitude and sense of shear traction applied to base of the lithosphere ("ideal drag" of Table 1). Active (westward) drag produces much smaller errors than zero or resistive drag.

olivine at either ~1200 or ~1300 C; (b) we also test models with no shear traction on the base; (c) for active drag, we assume that the lower mantle moves as a rigid plate but 10% (1–3 mm/a) faster than North America (with respect to Africa), and compute shear in an olivine asthenosphere of ~1150, ~1200, or ~1300 C. Note that basal tractions (when allowed) are based on the current local velocity of the model lithosphere, so this is a "mixed" boundary condition.

4. Scoring of Simulations

[9] The horizontal components of the momentum equation are solved with program SHELLS [*Kong and Bird*, 1995; *Bird*, 1999], which predicts long-term-average horizontal velocities, fault slip rates, anelastic strain rates, and vertically-integrated stress directions and magnitudes. Each simulation is scored by comparison with 3 geophysical data sets and one plate-tectonic model: (1) sea-floor spreading rates [*DeMets et al.*, 1990] along the Mid-Atlantic Ridge and Gulf of California, giving the "Spreading Error" column of Table 1; (2) geodetic velocities [*Bennett et al.*, 1999], giving the "Geodesy Error" column; and (3) stress directions [World Stress Map 1997], giving the "Stress Error" column. In addition, the "Velocity Error" column of Table 1 shows the error, with respect to the NUVEL-1A model, in the velocity of a central point in the plate (46°N, 84°W). This last measure of kinematic error is included because measures (1) and (2) give so much weight to complex plate-boundary regions, and it is useful to have a simple scalar measure of the velocity error in the plate interior.

5. Results

[10] To date, 18 models have been computed using 3 different values of effective fault friction (0.03, 0.10, or 0.17) and 3 different limits on the shear traction in subduction zones (7.5×10^{11}, 2.5×10^{12}, or 4.25×10^{12} N/m).

[11] The strength of coupling (when included) between the lithosphere and the sub-olivine mantle is regulated by asthenosphere strength, which is determined by the assumed temperature of the asthenosphere, which is modeled as adiabatic. The intercept (at zero pressure) of this adiabat is given by parameter TADIAB of Table 1, which takes values which give asthenosphere temperatures of 1150, 1200, or 1300 C at a reference depth of 100 km. The strength of coupling is best expressed by the "Ideal Drag" column of Table 1, which gives the intensity of basal shear traction that would have resulted under the cratonic part of North America (46°N, 84°W) if the model velocity at that point had been the NUVEL-1A velocity of the North America plate. (Negative values in this column indicate a resistive sense of drag.)

[12] All models with resistive drag, or no drag, predict only a few mm/a of spreading on the Mid-Atlantic Ridge, little or reversed slip on the North America/Caribbean plate transform boundary, and excessive spreading (~30 mm/a) in the Basin and Range province. Only models with active (westward) drag and an asthenosphere of ~1150 or ~1200 C are kinematically successful (Figure 2).

[13] The assumed values of fault friction and subduction zone traction have only a weak effect on the range of acceptable basal tractions. As might be expected, a model with stronger faults needs slightly more active basal traction to maintain the correct North America plate velocity with respect to neighboring plates (most of which move relatively eastward). Thus, when fault friction is 0.17, model misfit scores do not reach their lower plateau values until ideal drag reaches 1.4 MPa. However, even at the lowest plausible value of effective fault friction (0.03), active basal traction ($\geq$0.44 MPa of ideal drag) is still required.

[14] Models with active drag also have smaller mean errors in the directions of predicted stresses, although this difference is modest (31° in the best models vs. 45° in the worst). In the eastern United States, where abundant evidence has established a WSW-ENE direction of the most compressive horizontal principal stress, only active-drag models match well.

[15] The best models give a good approximation of northwestward flow in the Basin and Range province (Figure 3). Unphysical spreading of the Sierra Madre Oriental is a persistent problem in all models, which

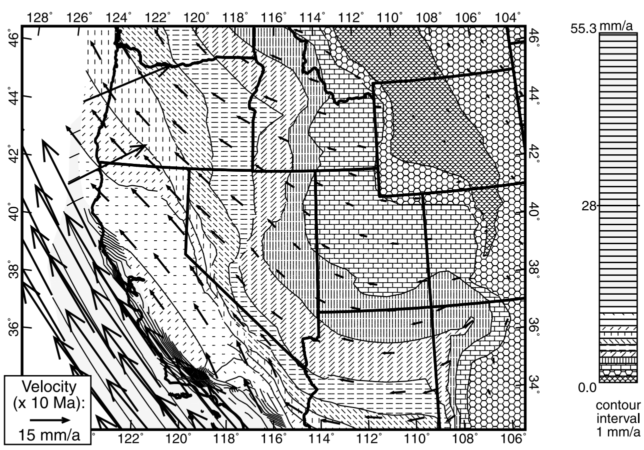

Figure 3. Detail of velocity in the western United States from one relatively successful model with westward mantle drag. Velocity shown at 1/4 of nodes for clarity. Agreement with geodesy [*Bennett et al.*, 1999] is good (6 mm/a RMS, after elastic corrections for fault locking).

probably indicates that in this province the basal shear traction is eastward and resistive [*Silver and Holt*, 2002].

[16] This detailed study of one plate supports the general conclusion of *Bird* [1998] that slow-moving continents are typically linked to, driven by, and indicators of the average lower mantle flow beneath them. While this set of models does not determine the exact azimuth or pattern of basal drag on the North America plate, it clearly establishes the sense as active.

[17] **Acknowledgments.** This work was supported by the National Science Foundation under grants EAR-9614263 and EAR-9902735, and by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 01HQGR0021. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either express or implied, of the U.S. Government.

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