Yellowstone Plume Drives Neogene North American Plate Motion Change

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Abstract Plate motion changes provide powerful constrains on plate tectonic forces. North America is ideal to explore these forces. We use recently published high-temporal resolution plate reconstructions of North America, which reveal a velocity slow-down at ~17 Ma, roughly coeval with the eruption of the Yellowstone plume, together with a stratigraphic analysis of hiatus surfaces across the continent, which provides proxy information for paleotopography. Using a simple Couette/Poiseuille flow models we estimate asthenosphere flow beneath North America and its impact on Neogene plate motion. We find that North America's Neogene plate motion change can be explained by Poiseuille flow in the asthenosphere generated upon the arrival of the Yellowstone plume and that the flow length-scale matches the extent of hiatus surfaces. While plume driven upper mantle flow constitutes a geodynamically viable model to explain North America's Neogene plate motion change it provides an intrinsic link between vertical and horizontal plate motions.

Plain Language Summary Plate motion changes are increasingly well documented in the geologic record. However, the underlying forces that initiate these plate motion changes remain poorly understood. Over the past years a pressure driven, so-called Poiseuille flow, model for upper mantle flux in the asthenosphere has gained increasing geodynamic attention–for a number of fluid dynamic arguments. This elegantly simple model makes a powerful testable prediction: Plate motion changes should coincide with regional scale mantle convection induced elevation changes. The latter are best inferred for continents from stratigraphic evidence. In this study we analyse newly available constrains on the Neogene kinematic plate history of North America together with a novel stratigraphic frame-work based on the principle of hiatus analysis. The stratigraphic frame work provides proxy information for paleo elevation. Combining these newly available constrains we show for the first time that: (a) Poiseuille flow induced by the arrival of the Yellowstone hotspot provides a compelling explanation for the observed coeval velocity and topographic change of North America, and (b) the Yellowstone plume push force is sufficient to initiate a plate motion change of North America under considerations of a quantitative geodynamic force balance analysis.

1. Introduction

Earth's surface moves in response to a combination of tectonic forces from the thermally convective mantle and/or plate boundary forces. The former arise from the time-evolving mantle buoyancy field (e.g., Lithgow-Bertelloni & Richards, 1998), while the latter arise from the brittle interaction between two or more tectonic plates (e.g., Bird et al., 2008; Flesch et al., 2000; Houseman & England, 1986; Iaffaldano et al., 2006). For mantle related forces Morgan and Smith (1992) and Morgan et al. (1995) argued that plumes can trigger sufficient pressure driven upper mantle flow to drive plate motions. The validity of this concept has been shown recently in numerical simulations for the Pacific plate (Stotz et al., 2018). In addition to affecting horizontal plate motion, the plume mode of convection (e.g., Davies & Richards, 1992) also generates significant topographic signals, known as dynamically sustained topography (e.g., Hager et al., 1985). In the continents plume related uplift signals have been described as domal uplifts with corresponding expressions in the sedimentary record (e.g., Campbell, 2007; Friedrich et al., 2018; Rainbird & Ernst, 2001; Saunders et al., 2007; Şengör, 2001). This allows continents to preserve a stratigraphic signal of past dynamic topography.
Western North America is well suited to identify plume related dynamic topography from the stratigraphic record. The presence of late Cretaceous shoreline deposits at ~2,000 m provides evidence for Tertiary uplift (Pederson et al., 2002), reported to have occurred in two episodes in the Eocene and Miocene, respectively (e.g., Flowers et al., 2008; Karlstrom et al., 2012; Wolfe et al., 1998). The younger uplift events coincide with the eruptions of the Columbia River flood-basalts of the Yellowstone plume system at ~17–14 Ma in northern Nevada and southern Oregon (Reidel et al., 2013; Zoback et al., 1994). These events took place while North America was moving westward as a consequence of the Tertiary opening of the North Atlantic as seen, for example, in the reconstructions by Gaina et al. (2002). Such reconstructions have a coarse temporal resolution with time stages of ~10 Myrs or longer. However, high-temporal resolution reconstructions (of ~1 Myr-long-stages) for North American plate motion with respect to Eurasia and Nubia (i.e., Africa) are now available for the Neogene (DeMets et al., 2015; Merkouriev & DeMets, 2014a, 2014b). This allows one to link the spreading record in the North Atlantic with the tectonic forces that helped in shaping the North American continental lithosphere.

Global and regional plate models (e.g., DeMets et al., 2015; Eagles, 2016; Müller et al., 1997, 2008; Torsvik et al., 2008) hold crucial information on the dynamics of plate motions. Among this information the record of temporal plate motion changes stands out, revealing variations that occur on short time scales relative to the time it takes for the large-scale structure associated with mantle buoyancy to evolve, which is ~100–200 Myrs (Bunge et al., 1998). A compact format to record plate motions and their changes is done through an Euler vector representation which describes rigid instantaneous rotations on a sphere. The vector is aligned with the axis of rotation. Its magnitude represents the angular velocity, while the position where the rotation axis intersects Earth's surface is referred to as the Euler pole. Euler vector representations hold key geodynamic constraints on the driving and resisting forces of tectonic plates—as some plate motion changes have been linked to evolving plate boundary forces (e.g., Faccenna et al., 2012; Iaffaldano, 2012; Stotz et al., 2017), while others have been linked to variations in sublithospheric mantle flow (e.g., Cande & Stegman, 2011; Colli et al., 2014; Stotz et al., 2021). Short-term mantle flow fluctuations can be induced by mantle plumes as a pressure driven flow—also known as a Poiseuille flow. For instance, Parnell-Turner et al. (2014) reported short-term activity fluctuations of the Iceland plume on time scales of about 3–8 Myrs. Numerical simulations reveal that pressure driven Poiseuille flow within the asthenosphere increases lithosphere-asthenosphere coupling (Hoeink et al., 2012) and yields rapid horizontal asthenosphere flow velocities of ~10–20 cm/yr (Weismüller et al., 2015), allowing it to provide significant driving shear stress beneath the lithosphere (e.g., Brune, 2018). Importantly, Poiseuille flow in the asthenosphere links changes in dynamically maintained topography and horizontal plate motion changes through a geodynamically plausible model (e.g., Iaffaldano et al., 2018; Stotz et al., 2018). Simultaneous availability of stratigraphic and high resolution plate motion records then makes North America a prime location to test this model.

2. Neogene Kinematics of the North American Plate

We estimated Neogene North American absolute plate motion using two reference frames. We based our analysis on recently publish data by DeMets et al. (2015, see their Supporting Information Tables 1 and 3) build on the work of Merkouriev and DeMets (2014a, 2014b), whose finite rotations describe the motion of North America relative to Nubia and Eurasia with mitigated noise via Redback open-source software (Iaffaldano et al., 2014). First we assume that Eurasia remained fix relative to the mantle throughout the Neogene and compute a set of Euler vectors that describe the absolute velocity of North America (see Figure 1a), which reveals slow-downs between ~15 and ~12 Ma and ~8 and ~5 Ma—as noted by previously DeMets et al. (2015), Iaffaldano and DeMets (2016) and Merkouriev and DeMets (2014a). Second, we reconstruct the absolute motion of North America with respect to the hotspots in the South Atlantic. We combine finite rotations of North America with respect to Nubia (DeMets et al., 2015, their Supporting Information Table 3) with Nubia with respect to the South Atlantic hotspots based on three different studies by Müller et al. (1993), O’Neill et al. (2005), and Maher et al. (2015). Note that such finite rotations of Nubia with respect to hotspots agree with each other within the uncertainty level—see Supporting Information S1. In there, we also show an extended analysis and note that due to the large uncertainties and the coarse temporal resolution those reconstructions are prone to artifacts—however such analysis is out of the scope of this study. Our preferred reconstruction of North America with respect to the South Atlantic hotspots is the one encompassing Müller et al. (1993) and is displayed in Figure 1b. In all estimated absolute reference frames
the Euler pole is located in the Southern Hemisphere close to Chile and remains relatively stable throughout the Neogene—see Figure 1. Thus we interpret the North America kinematic record as a slow-down that begins at ~15 Ma, lasted ~3 to ~10 Myrs and is largely independent of the choice of absolute reference frame—see Figure 1 and Supporting Information S1.

3. Yellowstone Plume Uplift Signal in the Stratigraphic Record

Friedrich et al. (2018) developed a stratigraphic framework to analyse continent scale geological maps to map the full extent of the surface expression of mantle plumes. As a plume rises from the core mantle boundary toward the surface it generates dynamic topography and thus leaves an imprint in the sedimentary record. Specifically, while the plume is within the lower mantle it generates a dynamic topography signal of low amplitude but significant areal extent. Then, as it gets closer to the surface the dynamic topography signal grows in amplitude but reduces in areal extent. A quantitative description of this process in terms of geodynamic uplift kernels is given in Colli et al. (2016). Finally, as the plume enters the asthenosphere it
spreads out laterally. This succession of events leaves a distinct sedimentary signature as described in Friedr

ich et al. (2018). Hereby, the stratigraphic record of the North American plate holds important constrains on the evolution of the Yellowstone plume rise.

We use a recently derived inventory of Base Hiatus Surfaces (BHS) collected by Hayek et al. (2020), where they mapped conformable and unconformable contacts at the temporal resolution of geological series (Cohen et al., 2018) for the Atlantic realm (i.e., North America, Europe, Africa, and South America) and Australia. The BHS are provided as spherical harmonic representation of no-/hiatus scattered contacts convolved in a Gaussian filter with a cut off at degree 15. They serve as a proxy for paleotopography, as suggested by Friedrich et al. (2018). Figure 2 shows the BHS for the North American continent. Red/blue colors depict un/conformable (hiatus/no hiatus) contacts, respectively, indicative of high/low topography in the preceding series. Blank regions reveal the absence of the considered series and its immediately preceding unit. Such regions may have undergone intense and/or long-lasting erosion or non-deposition, indicative of intense and/or persistent exhumation and surface uplift. Recent examples of continent scale hiatus mapping for Europe and Africa are given in Carena et al. (2019) and Vibe et al. (2018). Figure 2 shows BHS for the Oligocene to Pliocene. Much of the eastern half of the North American continent shows blank regions, reflecting the absence of Eocene to Pleistocene series. In the western half BHS changes at interregional scales while North America approaches the Yellowstone hotspot. A prominent change occurs from the Base of Oligocene to Base of Miocene when the hiatus signals extend deep into the continental interior, indicative of growing topography. In particular the BHS extends from the northeast of the current plume location into the Interior Plains, indicative of growing regional scale topography.

4. Yellowstone Plume Flow Pattern

Figure 3 shows a simple analytic estimate of upper mantle flow beneath North America derived from the assumption of Couette flow, Poiseuille flow and the superposition of both, at the time at which the Yellowstone plume presumably arrives in the asthenosphere, as evidenced by the onset of widespread volcanism in the Miocene (Reidel et al., 2013). In a first step, we calculate the Couette flow (~17 Ma), which is induced in the underlying asthenosphere by the motion of tectonic plates. The latter is obtained from the global collection of Mueller et al. (2016). Assuming an asthenosphere thickness of 110 km (see text below), this flow is half the surface velocity at mid-asthenosphere depth. The Couette flow pattern (Figure 3a) displays fast velocities of about 4 cm/yr underneath the Pacific, Cocos and Nazca plates. However, beneath the North American plate the flow velocity is slow (less than 1 cm/yr). In the next step, we estimate the Poiseuille flow generated by the arrival of the Yellowstone plume in the asthenosphere following the equation...
where, $D$ is the asthenosphere thickness and $\mu$ its viscosity. The two values are tied together by inferences from post-glacial rebound (e.g., Paulson & Richards, 2009). Thus we choose a thickness of 110 km and a viscosity of $5 \times 10^{19}$ Pa s. The expression $\frac{\Delta p}{\Delta x}$ is the pressure gradient, which we estimate from density contrast, gravity and topographic height in the following relationship $\Delta p = \rho gh$. We use a density contrast of $3,300 \text{ kg m}^{-1}$ and a topographic height of 1,400 m. The latter is in agreement with observational estimates of dynamic topography (e.g., Hoggard et al., 2017) and theoretical considerations of geodynamic response functions (e.g., Colli et al., 2016; Hager et al., 1985). $\Delta x$ is the distance away from the plume center—we use the present-day geographical location of Yellowstone at ($111^\circ$ W, $44^\circ$ N). The plume driven Poiseuille flow (Figure 3b) spreads away radially from the plume center, achieves velocities of ~20 cm/yr and extends throughout much of the upper mantle beneath North America, reaching Eurasia and Africa, albeit at very small velocities of less than 0.1 cm/yr.

The combined flow is obtained by summing up the Couette and Poiseuille flow, as done by Stotz et al. (2018), and shown in Figure 3c. Underneath the North American plate it displays an outward shape in the vicinity of the plume center. Further East the flow displays a divergent flow pattern toward the North and South.

The area affected by Yellowstone plume driven Poiseuille flow is calculated by taking the difference between the magnitudes of the Poiseuille (Figure 3b) and Couette flow (Figure 3a). We highlight the region where the Poiseuille flow exceeds the Couette flow by at least 0.5 cm/yr (Figure 3c). This serves as a proxy for the area that contributes as active mantle flow (i.e., driving plate tectonics) to the force balance of the North American plate. We note that it extends from the West Coast far into the Interior Plains of the North American continent, a distance of over 2,500 km.

### 5. Yellowstone Plume Tectonic Force Model

To evaluate geometrically if the Poiseuille flow generated by the Yellowstone plume may explain the Neogene slow-down of the North American plate, we make use of the Euler vector representation consisting of an angular velocity and an Euler pole as noted before. The latter provides information whether a torque applied in a particular location of the plate will slow it down, change its direction or speed it up. Figure 4a plots the paleocontour, plate boundaries (i.e., Mueller et al., 2016) and paleo-position of the Yellowstone plume at ~17 Ma, assuming the Yellowstone plume has remained fixed at its present-day position throughout the Neogene. We calculated the geometrical center of the North American plate to be at $83^\circ$W and $49^\circ$N and highlight with a black arrow the direction of motion of North America. A great circle connects the average position of the
Euler pole at ~17 Ma and the geometrical center of the North American plate. Because our projection centers on North America and the Yellowstone plume we don’t show the Euler Pole (which is located near Chile as noted before) but rather its anti-pole, with purple and orange arrows. The great circle in Figure 4a is shown with a dashed purple line for the reconstruction with respect to Eurasia fix and in dashed orange line for the reconstruction with respect to fix South Atlantic hotspots. We refer to this as the pole-line. We also draw solid lines (purple and orange) in the direction of North American plate motion and call this the motion-line. The motion- and pole-lines define four quadrants (labeled I, II, III, IV in Figure 4a) and reveal how torques affect plate motions, in our case for the North American plate. For instance, a change in plate boundary forces induced by increased plate coupling along the northwest margin of the North American plate (quadrant I) will slow the plate down but also change its direction by rotating it clockwise.

We calculate the linear force density that the Poiseuille flow due to arrival of the Yellowstone plume in the asthenosphere will exert upon the North American plate. To do so, we estimate the shear stresses at the plate base using the following relationship

$$\tau = \mu \frac{\delta V_{\text{plume}}}{\delta x}$$

(2)

where $\mu$ is the asthenosphere viscosity, $V_{\text{plume}}$ is the asthenosphere flow velocity due to the arrival of the Yellowstone plume and $\delta x$ is half of the asthenosphere channel thickness. We use a plume related Poiseuille flow velocity between 2 and 4 cm/yr, based on Figure 3b, take an asthenosphere viscosity of $5 \cdot 10^{19}$ Pa s and a half-thickness of 55 km, as noted before. This yields shear stresses of ~0.6 to ~1.3 MPa at the base of the North American lithosphere. By integrating it over a distance of 2,500 km, which is the extent of the Yellowstone-related Poiseuille flow dominated area (Figure 3d), we get a linear force density ranging from $\sim 1.6 \cdot 10^{12}$ to $\sim 3.2 \cdot 10^{12}$ N/m. This is displayed in Figure 4b with a dashed black box.

The Euler vector change and plate torque variations are linked by a linear operator that accounts for the length scale of the tectonic process and the viscosity/thickness of the underlying asthenosphere (see Iaffaldano & Bunge, 2015, for a review). We calculate the magnitude of linear force density required to explain the observed plate motion change of North America displayed in Figure 1 with the following equation

$$F_b = \frac{\Delta V_c}{D} L$$

(3)
L is the length of the plate along the geometrical center of 7,000 km and \( V = R \times \Delta \omega \) is the velocity change, where \( R \) is the radius of Earth at the geometrical center of the North American plate (83°W, 49°N) and \( \Delta \omega \) is the Euler vector change magnitude, while the other parameters are as listed before. We calculate the linear force density from the reconstructed Euler vector of North America with respect to Eurasia if it had experienced two distinct slow-downs, between ~15 Ma and ~12 Ma, or if it had lasted for 10 Myrs between ~15 Ma and ~5 Ma. Using a distribution of 10^6 samples from the reconstructed Euler vector covariance matrices we get an average linear force density of ~0.5 \cdot 10^{12} and ~1 \cdot 10^{12} N/m. They are shown with their associated uncertainties in Figure 4b in purple dashed and solid lines, respectively. For the reference frame of North America with respect to fix hotspots we get an average linear force density of ~2 \cdot 10^{12} N/m, shown with its associated uncertainties in Figure 4b in orange solid line for a continuous velocity change between ~15 Ma and ~5 Ma.

6. Discussion and Conclusions

It is well accepted that convection in the Earth's mantle provides the forces to drive plate motions (see Davies & Richards, 1992). However, the precise nature of the interaction between flow and plates remains incomplete, because the strength of plates allows them to integrate over a presumably complex flow field in the mantle beneath--making it difficult to get a glimpse even on the recent Cenozoic mantle flow. The description by Hoeink and Lenardic (2008); Hoeink and Lenardic (2010); Hoeink et al. (2011, 2012); Morgan et al. (1995) of mantle convection explicitly in terms of Poiseuille and Couette flow offers an opportunity to overcome this difficulty. It motivated us to link North American plate motion changes, driven by evolving basal shear forces, and nonisostatic vertical motion of the North American continent, by building upon our earlier work (Stotz et al., 2018) and exploiting growing observational constraints on both.

The Neogene North American plate tectonic history is well suited for this approach for three reasons. First, recent advances in high-temporal-resolution studies of the ocean floor magnetization pattern reveal the North American plate motion in great detail, elucidating slow-downs in its absolute velocity (DeMets et al., 2015; Merkouriev & DeMets, 2014a, 2014b, and this study). The tectonic force associated with the slow-down is on average at most ~2 \cdot 10^{12} N/m within uncertainties of the reconstructions (Figure 4). Second, the deep origin of the Yellowstone plume has been imaged by a recent shear wave tomography model for the mantle beneath the western United States based on seismic observations of the dense US Array seismic network (Nelson & Grand, 2018), so that a plume-like structure extending from the core mantle boundary to the surface is revealed clearly now. Growing seismic evidence for the existence of mantle plumes is consistent with geodynamic arguments for a significant contribution of plumes to the mantle heat budget (Bunge, 2005). Last, a novel approach by Friedrich et al. (2018) for the analysis of hiatus surfaces at continental scale makes it possible to exploit stratigraphic constraints on past dynamic topography generated by plumes. Taken together these advances offer the possibility to explore the dynamic effects of mantle plumes on plate motion in the context of geodynamically plausible Couette and Poiseuille flow models.

Our analytical flow calculations provide a theoretical estimate of upper mantle flow beneath the North American plate induced by a combination of Couette and Poiseuille flow. In our calculations the latter arises solely from the pressure gradient generated by the arrival of the Yellowstone plume in the asthenosphere. The plume flow dominated area, estimated based on the ratio between Couette and Poiseuille flow to be in range of ~1.2 \cdot 10^{2} km² (Figure 3c), agrees well in size with the area affected by hiatus as defined by the hiatus/no-hiatus red contours (Figure 2b). Importantly, both involve a comparable length-scale of ~2,500 km, provided by their diameter. Active plume driven upper mantle flow at the base of the North American plate integrated over such distance yields sufficient force to explain its slow down (~2.4 \pm 0.6 \cdot 10^{12} N/m, see Figure 4). Thus, linking vertical and horizontal plate motions. Earlier studies have argued for significant plume push force to drive plate motions and intra-plate stress deformation, for instance, in the Indian Ocean realm (i.e., Cande & Stegman, 2011; Iaffaldano et al., 2018). Our results agree with this notion. But they demonstrate that theoretical considerations on the plume flow affected area are in good agreement with entirely independent geological estimates based on hiatus surface area and that both suggest that the plume affected area can supply tectonically relevant forcing upon plate motion. While some plate motion changes have been attributed to variations in plate boundary forces (Iaffaldano et al., 2006), these forces have failed to explain the geometry, timing, or the extent of events in North America during the Cenozoic (e.g., English &
Johnston, 2004). Plume push force instead provides a dynamically viable mechanism to affect North America’s plate motions. We note that North America’s Neogene plate kinematic history is complex and could involve two individual slow-downs, as stated earlier, for which time variable plume flux or plate boundary forces (Iaffaldano & DeMets, 2016) could be responsible.

We close by noting that our flow calculations involve the choice of three key parameters: asthenosphere viscosity/thickness and amplitude of dynamic topography. The former two are tied together by inferences from post-glacial rebound (Paulson & Richards, 2009), as noted before. But the latter, while understood from theoretical geodynamic considerations (Colli et al., 2016; Hager et al., 1985), entails uncertainty in its amplitude (e.g., Hoggard et al., 2017). We test this uncertainty with a second calculation where we reduce the assumed dynamic topography by a factor of 2. The result (Figure 3c black contour) yields a reduction in the length-scale of the Poiseuille dominated area by a factor of 2, bringing the plume push force into the range of $-1.2 \pm 0.3 \times 10^{12}$ N/m–still sufficient to slow-down North America. We emphasize that our analytical calculations are kept deliberately simple, to bring out the effects of key parameters. More sophisticated global dynamic Earth models could be applied. But they require the definition of a suitable initial condition for Neogene mantle heterogeneity, derived either from forward mantle circulation modeling (e.g., Coltice & Shephard, 2018) or a geodynamic adjoint approach (e.g., Colli et al., 2018), as well as a tectonic model for the strength and structure of the lithosphere (e.g., Stotz et al., 2017). Our results suggest to pursue such modeling in the future, to further elucidate the effects of the Yellowstone plume on North American plate motion.

Data Availability Statement

Finite rotation datasets are available through Merkouriev and DeMets (2014a), Merkouriev and DeMets (2014b), DeMets et al. (2015), Müller et al. (1993), O’Neill et al. (2005) and Maher et al. (2015). The inventory of Base Hiatus Surface data set is available through Hayek et al. (2020).

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