

The Southern Sierra Nevada Drip and the Mantle Wind Direction Beneath the Southwestern United States

GEORGE ZANDT¹

Department of Geosciences, University of Arizona, Tucson, Arizona 85721

Abstract

The Miocene–Pliocene convective removal of the southern Sierra Nevada batholithic root and its sinking through the upper mantle provides a natural experiment to estimate the direction and velocity of mantle flow beneath the southwestern United States. Xenolith data, volcanism patterns, and geologic evidence are used to constrain the location and timing of the initial detachment. Seismic tomography images of the upper mantle are used to determine the displacement of the downwelling “tail” by the background mantle flow. The “mantle wind” direction based on this analysis is estimated to be SSW, in contradiction to another recent estimate based on a combination of geodetic data and shear-wave splitting measurements. The conflicting conclusions can be reconciled if the splitting measurements are dominated by anisotropy in the shallow mantle imposed by lithospheric motion. The SSW direction is approximately consistent with global models of asthenospheric counterflow directions, and therefore supports the idea that self-driving plate forces can explain the absolute motion of the North American plate.

Introduction

AN UNUSUAL MANTLE seismic anomaly is situated beneath the southern San Joaquin Valley in central California. It is a high-velocity body, 5% in maximum V_p magnitude, with the general shape of a vertical cylinder about 100 km in diameter and extending from near the base of the crust to about 250 km depth (Fig. 1). In map view it is almost circular in shape, with its center located beneath the town of Visalia, near the eastern edge of the southern Great Valley (Fig. 2). Thus the anomaly is situated partially beneath the Great Valley and partially beneath the western flank of the southern Sierra Nevada. It was imaged by seismic tomography studies in the early 1990s (Biasi and Humphreys, 1992; Benz and Zandt, 1993; Jones et al., 1994) and later interpreted as a downwelling associated with a local convective instability, or in simpler terms a “mantle drip” (Zandt and Carrigan, 1993; Jones et al., 1994). Recently, xenolith studies from the southern Sierra Nevada were published, making the case for delamination of the dense residual root of the central Sierra Nevada granitic batholith (Ducea and Saleeby, 1996, 1998). It has been recently proposed that the mantle anomaly marks the downwelling track of the delaminated Sierran root sinking

through the mantle (Ruppert et al., 1998; Saleeby et al., 2003). Making some inferences about the location and timing of the delamination, the mantle anomaly provides a direct measurement of the mantle flow direction that has partially entrained the “drip.” The analysis indicates the dominant flow direction is SSW, in general agreement with predictions of global models of asthenospheric counterflow (Chase, 1979; Hager and O’Connell, 1979), and consistent with self-driving forces dominating the motion of North America.

The Sierran Batholith Root

The fundamental assumption of the mantle flow analysis in this paper is that the mantle seismic anomaly is related to the convective removal of the southern Sierra Nevada batholith root. Therefore, it is important to review the interdisciplinary evidence for this inference. In 1993 the Southern Sierra Continental Dynamics (SSCD) project initiated multidisciplinary studies to investigate the crust and mantle of the region, and the ensuing reports from these investigations make a strong case for the late Cenozoic delamination of an eclogitic lower crust (Wernicke et al., 1996; Ducea and Saleeby, 1996, 1998). Seismic studies conducted during the SSCD project show that the Sierran crust is on average only 35 km thick with a small, localized root that

¹Email: zandt@geo.arizona.edu

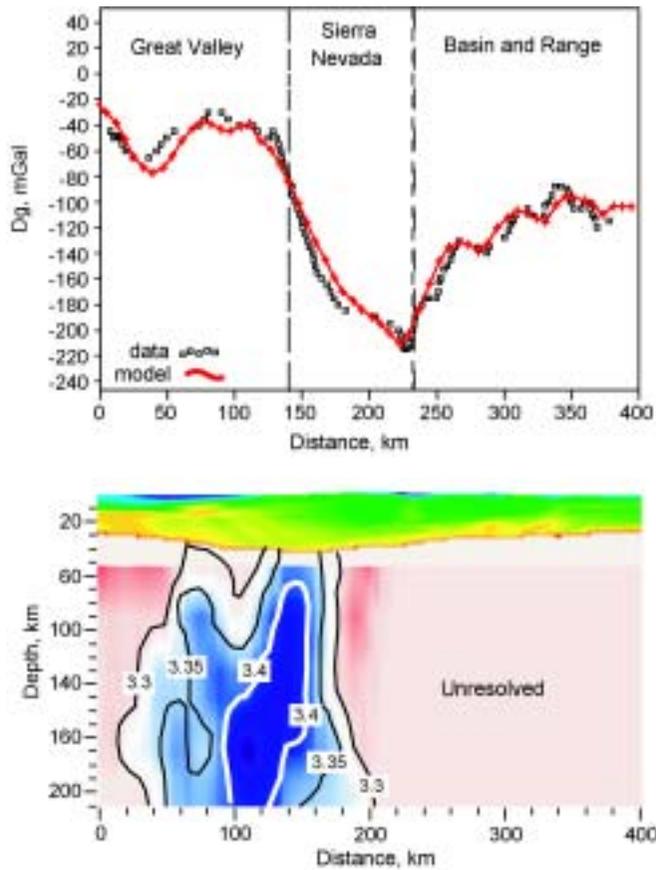


FIG. 1. Observed Bouguer gravity data and predicted gravity across the southern Sierra Nevada based on the combined crustal and mantle density model shown below. Mantle density contour labels in gm/cc. Location of cross section is shown in Figure 2. Modified from Ruppert et al. (1998).

reaches a depth of 42 km under the western flank of the range (Fleider et al., 1996, 2000; Ruppert et al., 1998). The crustal seismic velocities in the Sierra Nevada are remarkably low (<6.2 km/s) to nearly the base of the crust, implying a 30 km thick granitic batholith (Fleider et al., 2000; Ducea, 2002). The uppermost mantle velocities exhibit a large range (7.4–8.2 km/s) but are low (7.8 km/s) on average, implying the presence of asthenospheric material at shallow mantle depths. Part of the large range of uppermost mantle velocities may be due to the presence of anisotropy or the presence of slivers of relict lower-crustal eclogites below the Moho (Fleider et al., 2000).

Crustal and mantle xenoliths brought up in low-volume Miocene through Quaternary volcanism in the central Sierra Nevada provide the most direct

constraints on the composition of the Sierran lithosphere through time (Ducea and Saleeby, 1998). Miocene age xenoliths reveal a lithospheric column consisting of a ~30 to 35 km thick granitic batholith underlain by a lower crustal root ~40 km thick of mafic to ultramafic cumulates and residues, underlain by a peridotitic mantle. In contrast, Pliocene and Quaternary volcanics that sample the Sierras lack garnet-bearing xenoliths; instead, xenoliths from 35 to 70 km depth indicate the presence of a hot peridotitic mantle. The available xenoliths constrain this change in the lithospheric column to have occurred between 10 and 3 Ma, and are strong evidence for the delamination of the eclogitic lower crust during this time period.

Ducea (2001) suggested that the thick granitic crust and its eclogitic root were built in Late Creta-

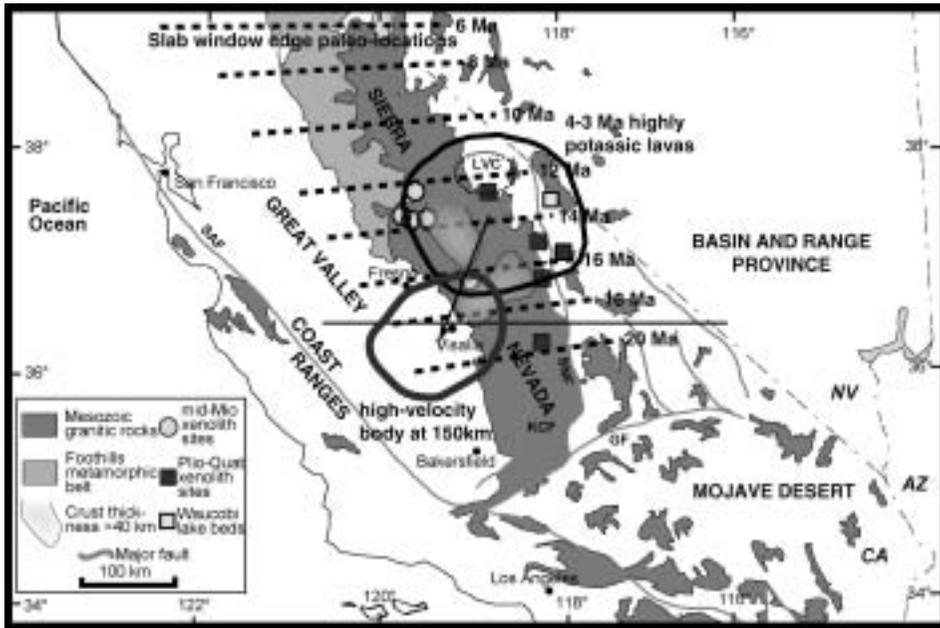


FIG. 2. Location map of major geologic, tectonic, and geophysical features discussed in text. The smaller, heavier circle is the surface projection of the upper mantle seismic anomaly cross section at 150 km depth. The larger, thinner circle is the area of Pliocene volcanism suggested as the initial delamination location (Manley et al., 2000). Dashed lines indicate paleo-locations of the slab window based on the plate reconstructions by Atwater and Stock (1998). Abbreviations: LVC = Long Valley caldera. The solid thin line is the location for the cross-section in Figure 1.

ceous time during a magmatic flare-up that produced most of the Sierra Nevada batholith. The production of a thick granitic batholith requires the concomitant production of a mafic to ultramafic residue that is one to two times the granitic layer thickness (Ducea, 2002). This residual root should have an eclogitic composition dominated by garnet pyroxenite at depths below ~35 to 40 km. Because the formation of the eclogite root is primarily a liquid-crystal fractionation process, it is less affected by kinetic factors associated with a purely metamorphic transformation to eclogite. Residual pyroxenites are extremely dense rocks, due to their garnet-rich (50% by volume compared to about 15% in typical subduction-related basaltic eclogites) and Fe-rich composition (Ducea, 2002). The measured densities of the pyroxenite xenoliths are 150–250 kg/m³ more dense than mantle peridotites, suggesting that the batholithic root must reside in a metastable state within the surrounding continental mantle lithosphere (Ducea, 2002). In addition, the compositional transition from granitic to eclogitic rocks is a major rheological transition that would be

a natural level for detachment in a delamination scenario (Ducea et al., 2003).

The upper mantle in this region has been imaged in a series of tomographic studies, ranging from larger scale regional or global scales to local studies. All the results consistently show the upper mantle drip anomaly from depths ~100 km to ~250 km. Even in the continental scale tomography results of Bijwaard et al. (1998), the drip anomaly shows up distinctly. Next to the southern edge of the subducting Juan de Fuca plate under northern California, the drip anomaly is the largest-magnitude positive anomaly in a sea of slow velocities that characterizes the southwestern United States. In the Bijwaard et al. results, the anomaly becomes indistinct below a depth of about 250 km. In the report by Ruppert et al. (1998), the detailed seismic crustal model from the SSCD project was combined with the upper mantle tomography model of Benz and Zandt (1993) and, using a standard velocity-density relationship, was shown to fit the observed gravity changes across the southern Sierra Nevada (Fig. 1). The density model in the upper mantle indicates

that the high-velocity body has, on average, a positive density contrast of about 100 kg/m^3 with the surrounding mantle. The close proximity of the mantle anomaly to the area of the proposed Sierran root delamination suggests the two phenomena are related.

Location and Timing of Detachment

The location and timing of the detachment of the lower crust is crucial to the mantle flow arguments in this paper. Fortunately, there are good constraints for both. The most direct constraints on the location of the initial delamination are the Miocene (12–8 Ma) xenoliths that represent samples of the then-present eclogitic root. Several Pliocene xenolith localities contain samples of high-temperature spinel peridotites and other clues that suggest the detachment began at least locally in the Miocene and was completed by ~3 Ma (Saleeby et al., 2003). A further clue is provided by a small-volume pulse of mafic potassic volcanism between 4 and 3 Ma that occurred in a circular area of ~200 km in diameter in the central Sierra Nevada (Figs. 2 and 3). This pulse of Pliocene magmatism has been suggested to indicate both the locality and timing of the main delamination event (Moore and Dodge, 1980; Manley et al., 2000; Farmer et al., 2002). The Miocene volcanic centers lie near the circumference of this circular area and may be related to an early phase of the delamination event.

Another clue that the completion of the detachment did not occur until ~3 Ma is the Pliocene–Pleistocene Waucobi Lake beds in the northern Owens Valley (Bachman, 1978). These lake deposits formed in a depression prior to crustal break-up and uplift of the Sierra Nevada–White–Inyo mountain blocks, and record the late Cenozoic tectonic evolution of this region. Based on published studies and his own investigations of the lake beds, Bachman pieced together the following sequence of events: In early and middle Pliocene time the area now occupied by the Sierra Nevada, Owens Valley, Long Valley, and the White–Inyo Mountains was a topographic high with westward drainage across the present divide. The Sierran escarpment in this area began to form in late Pliocene time (2.3–3.4 Ma) by downward flexure, followed by faulting and volcanism. Waucobi Lake formed 2.3–2.4 Ma in a depression and contains granitic debris from the newly formed Sierran escarpment. Soon afterward, uplift of the White–Inyo Mountains shifted the lake basin

westward to the present position of Owens Valley. The present topography developed over the past 2.3 m.y. as Owens Valley was downfaulted between the Sierra Nevada and the White–Inyo Mountains. This geologic history in conjunction with the Pliocene volcanism (Manley et al., 2000) suggests that, although the detachment of the batholithic root may have initiated in the Miocene, it was not completed until 3.5 Ma.

One question that arises after identifying the areal extent of the Miocene–Pliocene delamination is what happened to the batholithic root beneath the southernmost Sierra Nevada. Malin et al. (1995), Wood and Saleeby (1998), and Saleeby (2002) argued that the southernmost batholith root was removed in Laramide time during an episode of shallow subduction of a segmented slab. It has been proposed that a shallow dipping slab segment sheared off the lower crust beneath the southernmost Sierra Nevada and adjacent Mojave Desert, followed by tectonic underplating of the Pelona and Rand schists. But, farther north in the region of the younger convective removal, a steeper dipping slab segment left the lower crust intact.

The general temporal development of the convective removal event is consistent with the passage of the Mendocino Triple Junction through this region and the opening of the slab window in its wake (Dickinson and Snyder, 1979; Zandt and Furlong, 1982). According to the most recent plate motion reconstructions, the area delineated by the Pliocene volcanism was evacuated progressively between 17 and 10 Ma (Fig. 2) (Atwater and Stock, 1998). The passage of the slab had three important consequences: (1) it removed any underlying support by the subducting Farallon plate of the metastable root; (2) replacement of a cold subducting slab by hot asthenosphere initiated a thermal warming of the overlying lithosphere; and (3) it initiated a change from a compressional to an extensional backarc stress field that may have provided the perturbation necessary to trigger delamination of a metastable layer (Meissner and Mooney, 1998; Saleeby et al., 2003). Therefore, the opening of the slab window provides a natural explanation for the long delay between the formation of the eclogitic root in the Cretaceous arc environment and its eventual Miocene–Pliocene delamination.

The actual process of initiation of delamination, complete detachment of the batholithic root, and sinking of the detached root through the viscous mantle is still incompletely understood. However,

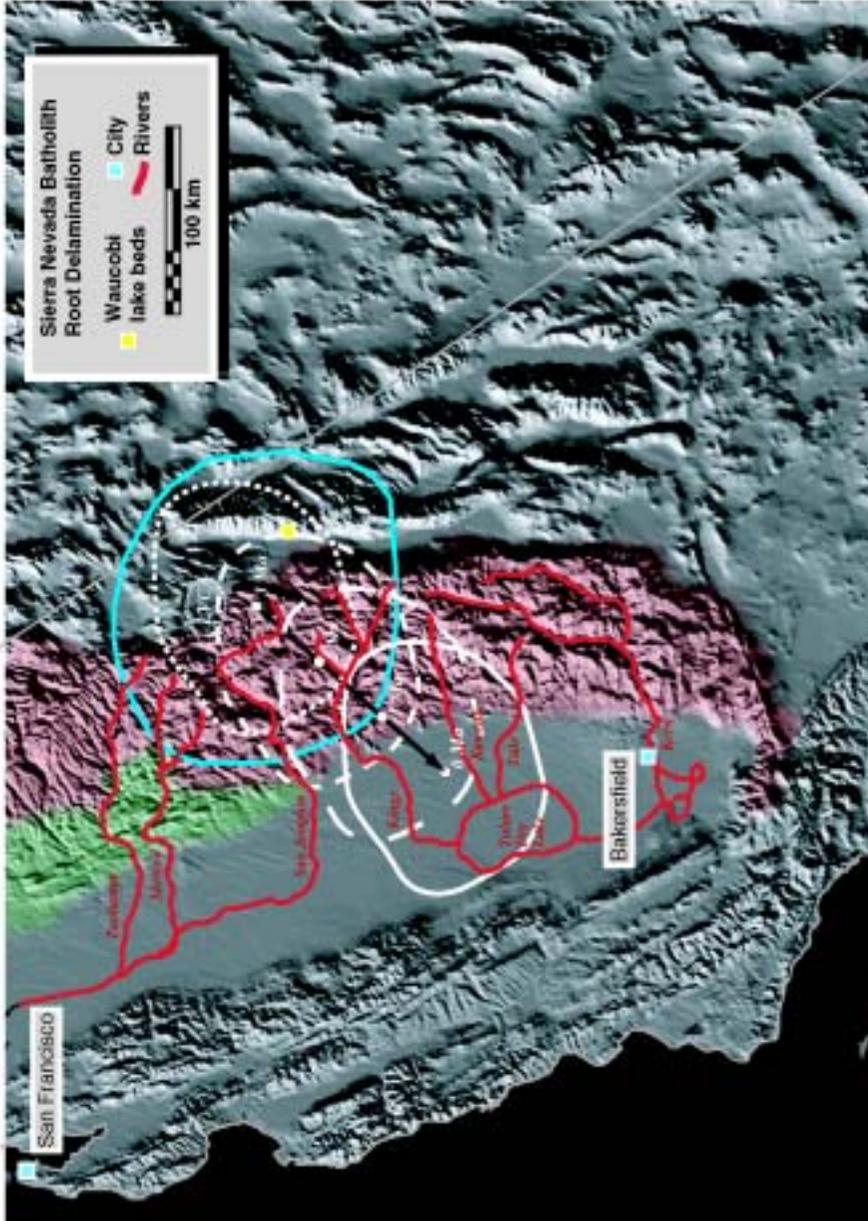


FIG. 3. Major features plotted on high-resolution topography. The blue circle is the proposed initial location of delamination, and the solid white circle is the current location of the downwelling mantle. The dotted and dashed circles are the back-projected locations of the downwelling at 1 m.y. intervals. Red lines indicate the major rivers in the Great Valley–Sierra Nevada (adapted from Unruh, 1991).

simplified analyses can provide a few basic constraints. The mantle anomaly can be viewed as a convective instability developing at the thermal boundary layer between the lithosphere and the asthenosphere. Zandt and Carrigan (1993) used thermal calculations and estimates of the local Rayleigh number to analyze the development of the southern Sierra anomaly as a convective instability from a growing thermal boundary layer. Their study was done prior to the recognition of the metastable batholithic root, and hence they hypothesized that the convective instability was due to the conductive cooling of asthenosphere upwelling into the slab window. Based solely on a conductive cooling model, the instability required 15–20 m.y. to initiate. This time period is clearly an overestimate because it did not take into account a preexisting metastable situation. However, the local Rayleigh number can still be used to relate the width of the anomaly to the dynamic viscosity of the mantle under the assumption that the seismic anomaly is primarily imaging a temperature anomaly. The viscosity of the mantle based on this analysis is $\sim 5 \times 10^{19}$ Pa-s (Zandt and Carrigan, 1993), a value that is within the range of other independent estimates of asthenospheric viscosity. So an important question is, does the mantle seismic anomaly represent an image of primarily a thermal anomaly or a compositional anomaly?

Stokes flow law can be used to place constraints on the sinking velocity of a spherical body with a positive density contrast in a viscous fluid (Turcotte and Schubert, 2002). A spherical body with a 50 km radius will have a sinking velocity (in mm/yr) given by

$$U = (\Delta\rho/\mu)(18 \times 10^{19}),$$

where $\Delta\rho$ is the density contrast in kg/m^3 , μ is the mantle viscosity in Pa-s, and the last term is a factor that includes the radius, gravitational acceleration, and a conversion factor. A 50 km radius body with a density contrast of 250 kg/m^3 in a mantle with a viscosity of 10^{20} Pa-s will have a sinking velocity of 450 mm/yr (or 450 km in 1 m.y.). This same equation can be used to calculate whether a body with radius r (in m) will be entrained in mantle flow of velocity U (in mm/yr):

$$r^2 = (U/\Delta\rho)(1.4 \times 10^9).$$

For a density contrast of 250 kg/m^3 with a mantle velocity of 25 mm/yr, the entrainment radius is

about 12 km. These simple calculations suggest that a thick garnet pyroxenite batholithic root, if it detaches as pieces larger than a few tens of kilometers in size, will sink rapidly through the asthenospheric mantle, reaching the mantle transition zone in less than 1 m.y. This analysis and the geologic evidence that the delamination was initiated at ~ 3.5 Ma suggest that the mantle seismic anomaly is primarily a thermal feature associated with cold mantle convective downwelling induced by the sinking pieces of the batholithic root. This idea is consistent with the average mantle density contrast of 100 kg/m^3 required by the gravity data. The smaller density contrast is more conducive to the possibility of partial entrainment of the drip by a moderately fast background mantle wind.

In summary, the following delamination scenario is envisioned. During the Late Cretaceous magmatic flare-up, the thick Sierran granitic batholith was generated and emplaced in the crust with an equally thick or even thicker residual root extending into the upper mantle. With continuing subduction through the mid-Cenozoic, the high-density root remained in place in a metastable state within the upper plate lithosphere. With the passage of the Mendocino Triple Junction, and the opening of the slab window, the lower subducting plate was completely replaced by high-temperature asthenosphere by about 10 Ma. The associated change in thermal and regional stress state was profound and initiated the delamination process, locally marked by Miocene volcanism. However, the breaking loose of the batholithic root from the surrounding lithosphere took some time after initiation of extension, and the detachment was not completed until Pliocene time, marked by a sudden pulse of mafic potassic volcanism. Once detached, however, the heavy root sank rapidly through the upper mantle to the base of the asthenosphere at 250–300 km depth, leaving a cold downwelling “tail” along its trail. It is this downwelling tail that is imaged in the seismic tomography and partially entrained and displaced by the background mantle flow. The offset between the current surface location of delamination and the current location of the mantle downwelling is the primary observation that is used in the following flow analysis.

Mantle Flow Analysis

To clarify the basic assumptions in the mantle flow analysis, consider the simple cases illustrated

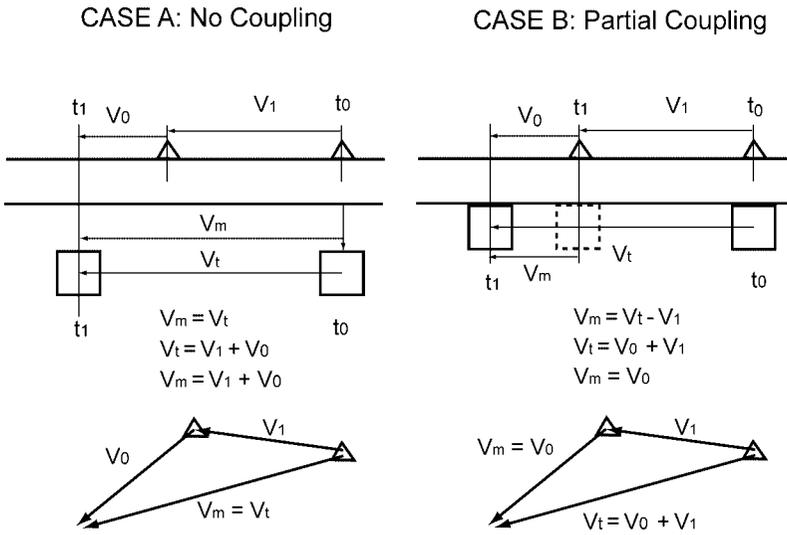


FIG. 4. Vector diagrams of displacement/velocity relationships for the Great Valley–Sierra Nevada block, the mantle seismic anomaly, and the background mantle flow. The four vectors used here are the absolute plate motion vector, V_1 ; the vector of the observed offset between the current surface location of delamination and the current location of the downwelling, V_0 ; the total displacement vector between the original surface location of delamination and the current location of the downwelling, V_t ; and the unknown mantle flow vector, V_m . Triangles represent the location of a surface feature at times t_0 and t_1 . The boxes represent the location of a marker body in the mantle at times t_0 and t_1 . The vector triangles in the second row represent map views of two-dimensional displacements. The two cases represent end-member sets of forces acting on the body. Further explanation is in the text.

by displacement/velocity vectors in Figure 4. The distances considered here are sufficiently small to utilize a Cartesian coordinate system. The four vectors required here are the absolute plate motion vector, V_1 ; the vector of the observed offset between the current surface location of delamination and the current location of the downwelling, V_0 ; the total displacement vector between the original surface location of delamination and the current location of the downwelling, V_t ; and the unknown mantle flow vector, V_m . If a body is dropped into the mantle, there are two end-member cases for forces acting on it. In Case A, there is no coupling between the dropped object and the overlying lithosphere, so the only force it responds to is the mantle flow. In this case the final total displacement of the object is a direct measure of the mantle wind, $V_w = V_t$. In terms of observables, the final displacement vector is the sum of the lithosphere motion vector and the final offset vector, so $V_m = V_1 + V_0$. In Case B, there is partial coupling between the body and the overlying lithosphere. This partial coupling case is defined in the simplest way such that the mantle wind vector is equal to the total displacement vector minus the

lithosphere motion vector, $V_m = V_t - V_1$. The total displacement vector is still the sum of the lithosphere motion vector and the offset vector, so the mantle wind vector, in this case, is the same as the final offset vector, $V_m = V_0$ (see Fig. 4). The case of complete coupling is not of interest here because no offset would occur and there is evidence for offset (i.e., V_0 is not zero).

There is evidence for viscous coupling between the mantle downwelling flow and the overlying crust. The surface projection of the current location of the anomaly coincides with a small crustal root (Fig. 1) and with a shallow embayment in the western edge of the batholith (Fig. 3), suggesting some downward force acting at the base of the crust. The present-day drainage patterns in the Sierra Nevada and Great Valley also appear to be influenced by a downward flexure centered near the anomaly center. Major rivers located north of the anomaly (San Joaquin, Merced, Tuolumne) flow westward into the valley and then turn northward to the Sacramento River and eventually reach the ocean; in contrast, the major rivers that cross the anomaly (Kings, Kaweah, Tule) continue flowing westward toward the

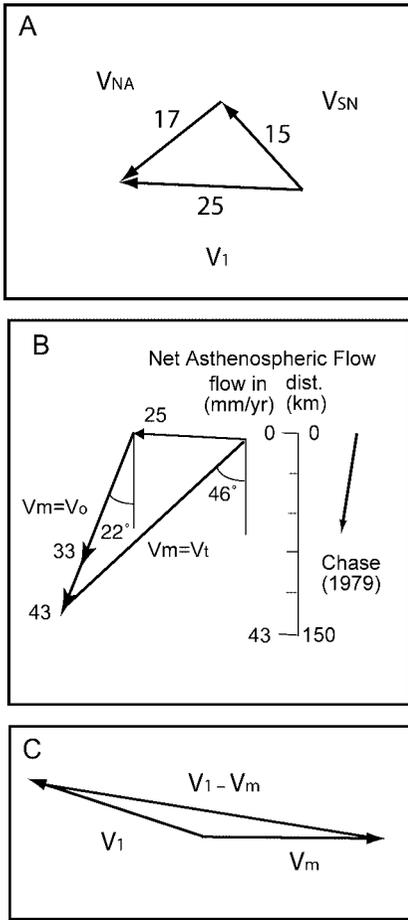


FIG. 5. Vector relationships discussed in text. All magnitudes are in mm/yr. A. The absolute motion of the Great Valley–Sierra Nevada block (V_1) is the sum of the absolute motion of North America (V_{NA}) and the motion of the GV–SN block with respect to NA (V_{SN}). B. Possible range of mantle flow vectors (V_m) based on no coupling ($V_m = V_0$) and partial coupling ($V_m = V_t$) models, and the predicted flow direction in the counterflow model of Chase (1979). C. In the Silver and Holt (2002) study, the anisotropy orientation is given by the difference between the lithospheric motion and the mantle flow ($V_1 - V_m$). In the case where the two vectors are nearly oppositely directed, the anisotropy direction is very similar to the direction of V_1 . See text for further discussions.

internal drainage basin of Tulare Lake (Fig. 3). Consistent with this drainage pattern, the rivers north of the anomaly are still actively downcutting, whereas the rivers flowing into the basin are aggrading upriver as if the basin is filling with sediments faster than it is subsiding (Jason Saleeby, pers. commun.,

2002). This geomorphic change is apparent even at the scale of the topography shown in Figure 3 by the occurrence of bedrock islands in the eastern edge of the Great Valley only within the area where the anomaly circle intersects the range. It is also probably not a coincidence that the highest peak in the Sierra Nevada, Mount Whitney, is located on the eastern edge of the range adjacent to the anomaly. The downward force acting in the middle of a broken plate in conjunction with an upward buoyancy force on the edge would cause a flexural uplift on its edge (Zandt and Carrigan, 1993).

The viscous coupling of the downwelling beneath the western Sierra Nevada and the buoyancy force of the asthenospheric upwelling beneath the Owens Valley (Crough and Thompson, 1977) would produce an additional component of flexural uplift of the eastern Sierra Nevada scarp. The mantle downwelling and upwelling flows are clearly not the sole cause of the westward tilting of the entire Sierra Nevada range; however, it appears to produce an observable perturbation to the regional patterns (Unruh, 1991; Small and Anderson, 1995). Finally, the southwestward migration of the viscous drag on the base of the crust over the past 3–4 m.y. (Fig. 3) may help to unify explanations for diverse volcanic and tectonic features in south-central California such as Long Valley volcanism, along-strike variations in drainage patterns in the Sierra Nevada, Plio-Pleistocene San Joaquin Valley sedimentation, and uplift of the Mount Whitney portion of the eastern Sierran scarp.

The absolute plate motion of the Great Valley–Sierra Nevada block is the vector sum of the absolute motion of stable North America, V_{NA} , and the relative motion of the Great Valley–Sierra Nevada block with respect to North America, V_{SN} . Using the Nuvel-1A NNR model (DeMets et al., 1990, 1994; Argus and Gordon, 1991) and geologic constraints on the Great Valley–Sierra Nevada block motion (Wernicke and Snow, 1998), the absolute motion of the Great Valley–Sierra Nevada block, V_1 , is approximately west at 25 mm/yr (Fig. 5A). The observed offset between the present-day surface location of delamination and the current location of the downwelling is a vector oriented SSW with magnitude 150 km. Assuming the complete detachment and sinking initiated at 3.5 Ma, the vector $V_0 = V_m$ has a magnitude of 43 mm/yr (Fig 5B). If the partial coupling with the lithosphere is negligible, the mantle flow vector would rotate toward the SW-oriented total displacement vector, V_t (Fig. 5B). For

the reasons outlined earlier, I prefer the partial coupling case, and therefore the SSW flow direction. Although the direction of this vector is relatively robust, its magnitude is dependent on the time of delamination initiation; for example, if the downwelling occurred at 4.5 Ma, then the vector would have a magnitude of 33 mm/yr. Based on these arguments, I conclude the mantle wind direction is SSW with a magnitude ranging between 33 to 43 mm/yr (Fig. 5B). This vector is approximately parallel to the dominantly S to SSW net flow direction in the southwestern United States predicted by global asthenospheric counterflow models and within a factor of two for the magnitude (Chase, 1979; Hager and O'Connell, 1981).

Discussion

The direction of mantle flow beneath the lithospheric plates has been debated for decades, and the importance of this question lies in the nature of the forces that drive plate tectonics. A succinct summary of the recent literature on this topic was given in the introduction of a paper by Liu and Bird (2002). The basic assumption in counterflow models is that asthenospheric mantle motions (down to about 350 km) are governed by fluxes generated at plate boundaries and the drag of the plates on the underlying mantle (Fig. 6); therefore, these models implicitly assume self-driving plate tectonic forces (Chase, 1979). An alternative model of plate tectonic driving forces is that density anomalies in the mantle, associated with past subduction and mantle plumes, drive large-scale convection that in turn drags the plates (Lithgow-Bertelloni and Richards, 1998). The two models predict somewhat paradoxical and opposite directions of mantle flow beneath western North America. In the counterflow model, mantle flow beneath most plates is in the opposite direction of plate motion (the return flow direction in Fig. 6), but subduction beneath Alaska and upwelling beneath the East Pacific Rise drives a SSE mantle flow beneath western North America. The net flow, incorporating the shear drag of the WSW-moving North American plate, is SSW (Fig. 5B). In the convection-driven model, most plates are dragged in the same direction as the underlying convection current, but the Farallon slab sinking beneath mid-North America entrains an eastward mantle flow beneath western North America. The conclusion reached in this paper is that mantle flow beneath western North America is dominantly

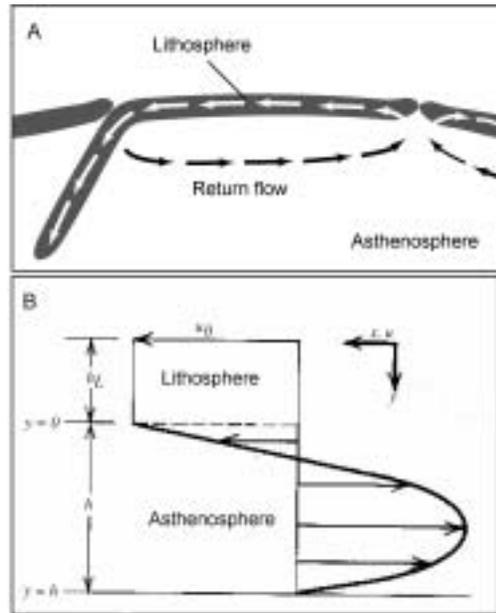


FIG. 6. A. The counterflow model involves a return flow from the subduction zone to the oceanic spreading center in a low viscosity channel beneath the lithosphere. B. The net flow in the mantle is a combination of shear flow concentrated beneath the lithosphere and a counterflow that dominates in the deeper part of the flow channel (figure from Turcotte and Schubert, 2002). In the two-dimensional case shown, the shear flow and counterflow are always in opposite directions. In a fully three-dimensional case, the shear flow remains in the same direction as the lithospheric motion, but the return flow can be in any direction required to balance the sources and sinks of asthenospheric material (Chase, 1979).

southward, rotating clockwise to a SSW direction towards the western coastline. This conclusion implicitly supports the self-driving model for plate tectonics.

In a recent contribution, Silver and Holt (2002) combined GPS observations of surface motions and upper mantle seismic anisotropy measurements to estimate the mantle flow field for the western United States. Geodetic coverage for the western U.S. is excellent, so the surface motion is well determined. The seismic anisotropy measurements in the southwestern United States are also plentiful and generally consistent, showing fast directions that vary between E-W and SW-NE (Fig. 2 in Silver and Holt, 2002). The fundamental assumption they make is that the seismic anisotropy is aligned parallel to the differential horizontal motion between the

lithosphere and the underlying mantle. This differential motion generates a simple shear deformation that aligns olivine fast axes in the asthenosphere. In terms of the vectors defined earlier, the anisotropy orientation is parallel to $V_1 - V_m$, where V_m now refers to the mantle flow direction at the base of the asthenosphere. Based on these observations and assumptions, Silver and Holt concluded that the mantle flow velocity is 55 mm/yr due east, nearly the opposite of my result. There are several possibilities to explain this discrepancy: (1) assumptions in this paper are wrong and Silver and Holt are correct; (2) seismic anisotropy is affected by the presence of water and consistently rotated from the true stress directions (Jung and Karato, 2001); (3) seismic anisotropy is dominated by shallow lithospheric motion and is insensitive to the mantle flow direction at the base of the asthenosphere; or (4) seismic anisotropy is dominated by deeper mantle flow and is insensitive to lithospheric motion. Next, I review two independent lines of evidence that provide evidence on which of these choices is most likely.

The migration of the Mendocino Triple Junction along the California coast was accompanied by northward-younging centers of volcanism related to influx of asthenosphere into the slab window. The flow of asthenosphere could be vertical from directly beneath the window, eastward from beneath the Pacific plate (as predicted by Silver and Holt), or westward from beneath the Sierra Nevada block (as predicted in this paper). The source regions directly beneath the window or from the Pacific side would have signatures of oceanic or mid-ocean ridge (OIB or MORB) environments, whereas the North American source would have the signature of a subduction-zone arc environment. A recent study of the geochemistry of samples from nine localities of young Coast Range volcanic fields consistently shows the unique signature of arc volcanics (calc-alkaline composition, low TiO_2 , high Ba/Ta, low Nb/Ta), consistent with a subduction mantle wedge source to the east or northeast (Whitlock, 2002). Seismic anisotropy measurements in northern California are sparse, but are consistent with the NE-SW subduction direction of the Juan de Fuca plate under North America. South of the current location of the triple junction, the anisotropy direction rotates clockwise to a more E-W direction with a moderate eastward dip, consistent with a shallow mantle flow westward and up into the slab window (Hartog and Schwartz, 2000).

The Yellowstone plume, located about 1000 km northeast of the Sierra Nevada, represents another natural experiment in mantle flow, except in this case a hot upwelling is interacting with the horizontal mantle wind. Recent numerical studies of plumes in a convecting mantle show that deep-rooted thermal plumes are subject to significant deviations of their volcanic tracks by mantle convection. In a recent global study, a better agreement of the predicted track of the Yellowstone plume with the Snake River Plain requires a fast southward flow in the asthenosphere of ~ 100 mm/yr (Steinberger, 2000), a direction predicted by global asthenospheric counterflow models (Chase, 1979). Yet the dense seismic anisotropy measurements across the Snake River Plain show a generally consistent SW-NE orientation, parallel to plate motion direction (Schutt et al., 1998).

Both of these examples support the third hypothesis that S-wave splitting measurements of anisotropy in the western U.S. are most sensitive to the shallow mantle where the effects of lithospheric shear dominate (Fig. 6B), and are relatively insensitive to deeper mantle flow. Shear-wave measurements of anisotropy average effects along the entire raypath and the sensitivity kernels are still poorly understood. Some initial numerical studies of the sensitivity indicate a greater sensitivity to shallower portions of the raypath (Saltzer et al., 2000). This is supported by empirical evidence in the form of dense spatial measurements of anisotropy such as the studies across the Snake River Plain and the Oregon Cascades (Silver and Holt, 2002). In these closely spaced measurements, systematic variations up to 10° are present in the anisotropy orientations. Variations on such small length scales are likely caused in the shallow mantle, or even by crustal anisotropy, perturbing the regional pattern. Silver and Holt's estimated mantle velocity flow vectors point in nearly opposite directions from the lithospheric vectors (Fig. 4 of Silver and Holt, 2002). Because the orientation of the predicted anisotropy is the difference between these two vectors (Fig. 5C), the predicted anisotropy orientations are very similar to the orientations of the lithospheric motion vectors (most are within about 10°).

In conclusion, the apparently disparate results from seismic anisotropy measurements and the drip displacement analysis can be reconciled if the seismic anisotropy measurements are mostly sensitive to the shallow mantle. Then the seismic anisotropy could be consistent with a shallow westward shear

flow, whereas the downwelling displacement observation is consistent with the net flow combining the effects of westward shear flow and a deeper southward counterflow (Fig. 6).

Acknowledgments

George Thompson was among the first geophysicists to set his sights on understanding the upper mantle influence on the Sierra Nevada. He set an example throughout his career that geophysicists should pay attention to geology. I thank Mihai Ducea and Clem Chase for many stimulating discussions about Sierra Nevada geology and western North American tectonics, and to Mihai Ducea, George Gehrels, and Jason Saleeby for leading an educational and inspirational field trip through the Sierra Nevada and California Coast Ranges. Mihai Ducea, Clem Chase, and Tom Owens reviewed early drafts of this paper. Mihai Ducea and Gary Ernst reviewed the final manuscript. This paper is dedicated to the memories of Doug Nelson and Guenter Bock, two geophysicists lost in the prime of their careers, who epitomized the best aspects of collaborative research. The research was supported in part by NSF grants #9805149 and #0125121.

REFERENCES

- Argus, D. R., and Gordon, R. G., 1991, No-net-rotation model of current plate velocities incorporating plate motion model NUVEL-1: *Geophysical Research Letters*, v. 18, p. 2039.
- Atwater, T., and Stock, J., 1998, Pacific–North America plate tectonics of the Neogene southwestern United States: An update: *International Geology Review*, v. 40, p. 575–402.
- Bachman, S. B., 1978, Pliocene–Pleistocene break-up of the Sierra Nevada–White–Inyo mountains block and the formation of Owens Valley: *Geology*, v. 6, p. 461–463.
- Benz, H. M., and Zandt, G., 1993, Teleseismic tomography: Lithospheric structure of the San Andreas Fault system in northern and central California, *in* Iyer, H. M., and Hirahara, K., eds., *Seismic tomography: Theory and practice*: New York, NY, Chapman and Hall, p. 440–465.
- Biasi, G. P., and Humphreys, E. D., 1992, P-wave image of the upper mantle structure of Central California and southern Nevada: *Geophysical Research Letters*, v. 19, p. 1161–1165.
- Bijwaard, H., Spakman, W., and Engdahl, E. R., 1998, Closing the gap between regional and global travel time tomography: *Journal of Geophysical Research*, v. 103, p. 30,055–30,078.
- Chase, C. G., 1979, Asthenospheric counterflow: A kinematic model: *Geophysical Journal of the Royal Astronomical Society*, v. 56, p. 1–18.
- Crough, S. T., and Thompson, G. A., 1977, Upper mantle origin of the Sierra Nevada uplift: *Geology*, v. 5, p. 396–399.
- DeMets, C., Gordon, R. G., Argus, D. F., and Stein, S., 1990, Current plate motions: *Geophysical Journal International*, v. 101, p. 425–478.
- _____, 1994, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions: *Geophysical Research Letters*, v. 21, p. 2191–2194.
- Dickinson, W. R., and Snyder, W. S., 1979, Geometry of subducted slabs related to San Andreas transform: *Journal of Geology*, v. 87, p. 609–627.
- Ducea, M. N., 2001, The California arc: Thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups: *Geological Society of America Today*, v. 11, p. 4–10.
- Ducea, M. N., 2002, Constraints on the bulk composition and root foundering rates of continental arcs: A California arc perspective: *Journal of Geophysical Research*, v. 107, no. B11, 2304, DOI 10.1029/2001JB000643.
- Ducea, M., Kidder, S., and Zandt, G., 2003, Arc composition at mid-crustal depths: Insights from the Coast Ridge Belt, Santa Lucia Mountains, California: *Geophysical Research Letters*, in press.
- Ducea, M., and Saleeby, J., 1996, Buoyancy sources for a large, unrooted mountain range, the Sierra Nevada, California: Evidence from xenolith thermobarometry: *Journal of Geophysical Research*, v. 101, p. 8229–8244.
- _____, 1998, A case for delamination of the deep batholithic crust beneath the Sierra Nevada, California: *International Geology Review*, v. 40, p. 78–93.
- Farmer, G. L., Glazner, A. F., and Manley, C., 2002, Did lithospheric delamination trigger late Cenozoic potassic volcanism in the Sierra Nevada, California?: *Geological Society of America Bulletin*, v. 114, p. 754–768.
- Fliedner, M., Klemperer, S. L., and Chrisyensen, N. I., 2000, Three-dimensional seismic model of the Sierra Nevada arc, California, and its implications for crustal and upper mantle composition: *Journal of Geophysical Research*, v. 105, p. 10,899–10,921.
- Fliedner, M., Ruppert, S., and SSCD Working Group, 1996, Three-dimensional crustal structure of the southern Sierra Nevada from seismic fan profiles and gravity modeling: *Geology*, v. 24, p. 367–370.
- Hager, B. H., and O’Connell, R. J., 1979, Kinematic models of large-scale flow in the Earth’s mantle: *Journal of Geophysical Research*, v. 84, p. 1031–1048.

- Hartog, R., and Schwartz, S. Y., 2000, Subduction induced strain in the upper mantle east of the Mendocino triple junction, California: *Journal of Geophysical Research*, v. 105, p. 7909–7930.
- Jones, C. H., Kanamori, H., and Roecker, S. W., 1994, Missing roots and mantle “drips”: Regional Pn and teleseismic arrival times in the southern Sierra Nevada and vicinity, California: *Journal of Geophysical Research*, v. 99, p. 4567–4601.
- Jung, H., and Karato, S.-I., 2001, Water-induced fabric transitions in olivine: *Science*, v. 293, p. 1460–1463.
- Lithgow-Bertelloni, C., and Richards, M. A., 1998, The dynamics of Cenozoic and Mesozoic plate motions: *Reviews in Geophysics*, v. 36, p. 27–78.
- Liu, Z., and Bird, P., 2002, North America plate is driven westward by lower mantle flow: *Geophysical Research Letters*, v. 29, no. 24, 21–64 [DOI 10.1029/2002GL016002].
- Manley, C. R., Glazner, A. F., and Farmer, G. L., 2000, Timing of volcanism in the Sierra Nevada of California: Evidence for Pliocene delamination of the batholithic root?: *Geology*, v. 28, p. 811–814.
- Malin, P. E., Goodman, E. D., Henyey, T. L., Li, Y. G., Okaya, D. A., and Saleeby, J. B., 1995, Significance of seismic reflections beneath a tilted exposure of deep continental crust, Tehachapi Mountains, California: *Journal of Geophysical Research*, v. 100, p. 2069–2087.
- Meissner, R. and Mooney, W., 1998, Weakness of lower continental crust, a condition for delamination, uplift, and escape: *Tectonophysics*, v. 296, p. 47–60.
- Moore, J. G., and Dodge, F. C. W., 1980, Late Cenozoic volcanic rocks of the southern Sierra Nevada, California: I. Geology and Petrology: *Geological Society of America Bulletin*, Part II, v. 91, p. 1995–2038.
- Ruppert, S., Fliedner, M., and Zandt, G., 1998, Thin crust and active upper mantle beneath the Southern Sierra Nevada in the western United States: *Tectonophysics*, v. 286, p. 237–252.
- Saleeby, J. B., 2002, Segmentation of the Laramide slab—Evidence from the southern Sierra Nevada region: *Geological Society of America Bulletin*, in press.
- Saleeby, J., Ducea, M., and Clemens-Knott, D., 2003, Production and loss of high-density batholithic root—Sierra Nevada, California: *Tectonics*, in press.
- Saltzer, R. L., Gaherty, J. B., and Jordan, T. H., 2000, How are vertical shear wave splitting measurements affected by variations in the orientation of azimuthal anisotropy with depth?: *Geophysical Journal International*, v. 141, p. 374–390.
- Schutt, D., Humphreys, E. D., and Dueker, K., 1998, Anisotropy of the Yellowstone Hotspot wake, eastern Snake River Plain, Idaho: *Pure and Applied Geophysics*, v. 151, p. 443–462.
- Silver, P. G., and Holt, W. E., 2002, The mantle flow field beneath western North America: *Science*, v. 295, p. 1054–1057.
- Small, E. E., and Anderson, R. S., 1995, Geomorphically driven late Cenozoic rock uplift in the Sierra Nevada, California: *Science*, v. 270, p. 277–280.
- Steinberger, B., 2000, Plumes in a convecting mantle: Models and observations for individual hotspots: *Journal of Geophysical Research*, v. 105, p. 11,127–11,152.
- Turcotte, D. L., and Schubert, G., 2002, *Geodynamics*, second ed.: Cambridge, UK, Cambridge University Press.
- Unruh, J. R., 1991, The uplift of the Sierra Nevada and implications for late Cenozoic epeirogeny in the western Cordillera: *Geological Society of America Bulletin*, v. 103, p. 1395–1404.
- Wernicke, B., et al., 1996, Origin of high mountains in the continents: The Southern Sierra Nevada: *Science*, v. 271, p. 190–193.
- Wernicke, B., and Snow, J. K., 1998, Cenozoic tectonism in the central Basin and Range: Motion of the Sierran-Greta Valley Block: *International Geology Review*, v. 40, p. 111–118.
- Whitlock, J. S., 2002, Evidence of a mantle wedge source for slab window volcanism in the northern California Coast Ranges: Unpubl. M.S. thesis, The Pennsylvania State University.
- Wood, D. J., and Saleeby, J. B., 1998, Late Cretaceous–Paleocene extensional collapse and disaggregation of the southernmost Sierra Nevada batholith: *International Geology Review*, v. 40, p. 289–325.
- Zandt, G., and Carrigan, C. R., 1993, Small-scale convective instability and upper mantle viscosity under California: *Science*, v. 261, p. 460–463.
- Zandt, G., and Furlong, K. P., 1982, Evolution and thickness of the lithosphere beneath coastal California: *Geology*, v. 10, p. 376–381.