Flow of Mantle Fluids Through the Ductile Lower Crust: Helium Isotope Trends
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can be expected that $\mathbf{E} \propto \mathbf{B}_{\text{ext}}$. In that experiment, no coherent oscillations were observed, which is consistent with the considerations here.

An important characteristic of spin orbit-mediated driving is the linear dependence of the effective driving field on the external magnetic field, which follows from Eq. 1 and is predicted in (12, 13, 29). We aim to verify this dependence by measuring the Rabi frequency as a function of the resonant excitation frequency (Fig. 4A), which is proportional to the external magnetic field. Each point is rescaled by the estimated applied electric field (Fig. 4B). Even at fixed output power of the microwave source, the electric field at the dot depends on the microwave frequency due to various resonances in the line between the microwave source and the gate (caused by reflections at the bonding wires and microwave components). However, we use the photon-assisted-tunneling response as a probe for the ac voltage drop across the interdot tunnel barrier, which we convert into an electric field amplitude by assuming a typical interdot distance of 100 nm. This allows us to roughly estimate the electric field at the dot for each frequency (17). Despite the large error bars, which predominantly result from the error made in estimating the electric field, an overall upward trend is visible in Fig. 4A.

For a quantitative comparison with theory, we extract the spin-orbit strength in GaAs, via the expression of the effective field $\mathbf{B}_{\text{eff}}$ perpendicular to $\mathbf{B}_{\text{ext}}$ for the geometry of this experiment (12)

$$|\mathbf{B}_{\text{eff}}(t)| = 2 |\mathbf{B}_{\text{ext}}| \frac{|E(t)| |\Delta|}{I_{\text{SO}}}$$

with $I_{\text{SO}}$ the spin-orbit length (for the other definitions, see Fig. 1B). Here, $I_{\text{SO}}^{-1} = m^* (\alpha + \beta) / h$ for the case with the gate symmetry axis along [110] or [110], respectively. Via $f_{\text{Rabi}} = (g_{\text{Rabi}} B_{\text{eff}}) / 2\hbar$, the confidence interval of the slope in Fig. 4A gives a spin-orbit length of 28 to 37 nm (with a level splitting $\Delta$ in the right dot of 0.9 meV extracted from high-bias transport measurements). Additional uncertainty in $I_{\text{SO}}$ is due to the estimate of the interdot distance and the assumption of a homogeneous electric field, deformation effects of the dot potential (15), and extra cubic terms in the Hamiltonian (7). Still, the extracted spin-orbit length is of the same order of magnitude as other reported values for GaAs quantum dots (18).

Both the observed trend of $\mathbf{B}_{\text{eff}}$ with $f_{\text{Rabi}}$ and the extracted range for $I_{\text{SO}}$ are consistent with our supposition (by elimination of other mechanisms) that spin transitions are mediated by spin-orbit interaction. We note that also for relaxation of single electron spins in which electric field fluctuations from phonons couple to the spin, it is by now well established that the spin-orbit interaction is dominant at fields higher than a few 100 mT (12, 18, 28, 29). It can thus be expected to be dominant for coherent driving as well.

The electrically driven single-spin resonance reported here, combined with the so-called $\sqrt{\text{SWAP}}$ gate based on the exchange interaction between two neighboring spins (30), brings all-electrical universal control of electron spins within reach. Whereas the $\sqrt{\text{SWAP}}$ gate already operates on subnanosecond time scales, single-spin rotations still take about 100 ns (the main limitation is photon-assisted tunneling). Faster operations could be achieved by suppressing photon-assisted tunneling (e.g., by increasing the tunnel barrier or operating deeper into Coulomb blockade), by working at still higher magnetic fields, by using materials with stronger spin-orbit interaction, or through optimized gate designs. Furthermore, the electrical control offers the potential for spatially selective addressing of individual spins in a quantum dot array, because the electric field is produced by a local gate. Finally, the spin rotations were realized at magnetic fields high enough to allow for single-shot read-out of a single spin (31), so that both elements can be integrated in a single experiment.

**References and Notes**

17. Supporting material is available on Science Online.

**Supporting Online Material**

www.sciencemag.org/cgi/content/full/1148092/DC1

Materials and Methods

SOM Text

Figs. S1 and S2

References

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**Flow of Mantle Fluids Through the Ductile Lower Crust: Helium Isotope Trends**

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Heat and mass are injected into the shallow crust when mantle fluids are able to flow through the ductile lower crust. Minimum $^{4}He/^{3}He$ ratios in surface fluids from the northern Basin and Range Province, western North America, increase systematically from low crustal values in the east to high mantle values in the west, a regional trend that correlates with the rates of active crustal deformation. The highest ratios occur where the extension and shear strain rates are greatest. The correspondence of helium isotope ratios and active transtensional deformation indicates a deformation-enhanced permeability and that mantle fluids can penetrate the ductile lithosphere, even in regions where there is no substantial magmatism. Superimposed on the regional trend are local, high $^{4}He/^{3}He$ anomalies indicating hidden magmatic activity and/or deep fluid production with locally enhanced permeability, identifying zones with high resource potential, particularly for geothermal energy development.

Mantle volatiles, principally water and CO$_{2}$, play an important role in lithospheric rheology and the production of buoyant fluids that can be injected into the shallow crust. Regional and local trends in the

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such as ore minerals and oil, gas, and geo-
thermal fluids (6). Mantle-derived volatiles in
the crust are traceable through He isotopic com-
positions of hydrologic fluids (7). Once injected
into a crustal-fluid system, mantle He will be
continuously diluted with radiogenic helium-4
(\(^{3} \text{He}\)) acquired from the U, Th–rich crust, and
therefore surface-fluid He isotopic compositions
also provide a measure of the mantle He flux
and the integrated permeability-fluid pressure
gradient (flow rate) through the crust (1). To
enter the hydrologic system, mantle He must
pass through a ductile lower crust, which is
believed to be an impermeable boundary
because of an inability to maintain open frac-
tures on long time scales (8–10). A general
assumption is that the passage of fluids through
this boundary must occur either by direct in-
trusion and degassing of mantle-derived mag-
mas (6) or by diffusion through the ductile
boundary layer (11). However, two recent studies
in areas void of recent volcanism (1, 12) have
found evidence for fault-controlled advective
flow of mantle fluids through the ductile
boundary. How and why this occurs is not well
understood.

We conducted a regional study of He iso-
topic compositions of thermal fluids collected
from surface features and wells throughout the
northern Basin and Range Province (B&R), west-
ern North America (Fig. 1 and table S1) (13). As
a result of the tectonic influence exerted by
the relative motion of the Pacific and North
American Plates (14, 15), the B&R is a vast ex-
tended region of anomalous thermal gradients,
large heat flux, high regional elevation, thin
(ned) crust, and lithospheric- and asthenospheric-
mantle melting. Presently, extension is accom-
modated by high-angle normal faults, and the
locus of major extension and its associated
magmatism occurs at the margins of the
province (16), primarily within the Walker Lane,
a narrow 100-to-200-km–wide transtensional
volcanic zone along the eastern side of the
Sierra Nevada that extends north into a tran-
tensional zone between the Sierra Nevada and the
subduction-related volcanic arc of the Cascades.

Collectively, the minimum \(^{3} \text{He}/^{4} \text{He}\) ratios de-
cine a regional baseline trend of decreasing ratios
from west to east, as illustrated by the shaded

Fig. 1. Sample location map of the B&R and surrounding areas. The
symbol colors delineate \(^{3} \text{He}/^{4} \text{He}\) ratios, expressed as \(R_{c}/R_{a}\) (the air-
corrected sample ratio normalized to the ratio in air), and the symbol
shapes identify the type of thermal area. Tectonic zones are outlined: red,
northern B&R; yellow, the Walker Lane transtensional zone (WL) and the
CNSB; green, the Sierra Nevada batholith (SN); and light blue, the
Cascades volcanic zone. TZ, transition zone between the Cascades, WL,
and B&R.
Fig. 2. Air-corrected He isotopic composition of geothermal fluids above 38°N latitude in the B&R, TZ, and Cascades, plotted as a function of longitude. The shaded curve depicts an east-to-west baseline trend defined by minima in the local $^3$He/$^4$He ratios.

Fig. 3. Compilation of present-day GPS strain rates across the northern B&R, relative to the North America reference frame. The data are from GPS networks located in a band from 38°N to 41°N latitude (15, 16). West of 242°E to 242.5°E longitude, the data show a combined increase in total magnitude of strain and an increase in lateral dextral shear strain superimposed on the east-west extension. This is most evident in the Walker Lane, but it impacts most of the B&R in and to the northwest of the CNSB, as illustrated by the Fig. 3 insert taken from (19). The broad colored band is the regional baseline He isotope trend from Fig. 2, shown superimposed on the trends in strain rate. CP, Colorado Plateau; GV, Great Valley.
band in Fig. 2. East of the Walker Lane and Cascades, the occurrence of mantle He—as indicated by baseline $^3\text{He}/^4\text{He}$ ratios (~0.2 to 2.0 Ra) that are much greater than those of average crustal He (~0.02 Ra)—is not supported by magma intrusion, as this region has no evidence for current or recent volcanic activity. Instead, the baseline trend is strongly correlated with a change in the direction and magnitude of strain detected by present-day Global Positioning System (GPS) velocities (Fig. 3) (17, 18). West of the CNSB, a nearly pure east-west extension rate of ~3 mm/year shifts to N40°W and increases to 12 to 13 mm/year. The accelerating dextral shear component is driven by a drag force due to the relative movement of the Pacific and North American Plates (19). We hypothesize that the increase in total strain and, specifically, the northwest-orientated dextral shear component greatly enhance average fluid-flow rates, allowing for a more rapid flow of mantle fluids through the crust. We propose that the preserving the high $^3\text{He}/^4\text{He}$ ratios observed at the surface. The enhanced flow rate must persist through the ductile zone at, or near, lithostatic pressure, then the east-west increase in the flow rate is primarily governed by an east-to-west increase in average permeability.

The high-angle normal faults that presently accommodate B&K extension and that are probably fluid-flow pathways are not expected to penetrate the ductile lower crust. In extensional regimes, because of gravitational loading, the maximum principle stress is perpendicular to the geoid. With increasing depth, the brittle-ductile transition in rheology refraacts the maximum stress acting on the fault, resulting in nearly horizontal shear zones or detachment faults at the boundary. Without mantle influence, the high-permeability crust of the San Andreas fault (3) and a recent observed series of novel volcanic tremors deep (20 to 40 km) beneath the same section of the fault provide additional support for the evolution of deep-mantle fluids, their potential importance in fault mechanisms (27), and nonmagnetic fluid flow through the ductile zone. The high $^3\text{He}/^4\text{He}$ ratios superimposed on the regional trend indicate enhanced crustal permeability coupled with local zones of deep fluid production and/or hidden magmatic activity. These local anomalies may be indicative of a heterogeneous distribution of mantle volatiles that promote melt production. Assuming a CO$_2$/$^3\text{He}$ of ~10$^{-6}$ M (characteristic of mid-ocean ridge basalt) as a proxy for mantle-derived volatiles, the calculated fluid-flow rate through the Dixie Valley geothermal system (24) translates into a mantle CO$_2$ flux of ~10$^{-6}$ to 10$^{-5}$ mol cm$^{-2}$ year$^{-1}$. As of yet, no definitive geochemical or isotopic evidence for the presence of mantle CO$_2$ has been found, other than carbon isotopic compositions ($^{13}$C = 65 ± 2.5 per mil) (22) that is not dissimilar from those of mantle CO$_2$ (6). An estimated CO$_2$/$^3\text{He}$ ratio in Dixie Valley fluids of ~40 × 10$^{-6}$ (13) is ~20 times the mid-ocean ridge value, suggesting that most (~95%) of the CO$_2$ is not mantle-derived or, alternatively, that the subcontinental mantle CO$_2$/$^3\text{He}$ ratio is much greater than that observed at mid-ocean ridges.

Earth’s crust stores an enormous reserve of thermal energy produced primarily from the radiative decay of U, Th, and K that is dispersed throughout Earth. It has been estimated that, within the United States (excluding Hawaii and Alaska), there are ~9 × 10$^{16}$ kilowatt-hours (kWh) of accessible geothermal energy. This is a sizable resource compared to the total energy consumption in the United States of 3 × 10$^{20}$ kWh annually. In order for geothermal systems to develop and mine the heat source naturally, adequate fluid sources and deep permeable pathways are a necessity. The deep pathways provide access to high temperatures that can drive fluid convection cells. Isotopes provide a quantitative or, at least, a qualitative estimate of deep permeability from surface measurements, and anomalies superimposed on regional trends can identify potential resources.

References and Notes

7. Without mantle influence, crustal fluids are dominated by $^4\text{He}$ released from the natural radioactivity of U and Th and characterized by very low $^3\text{He}/^4\text{He}$ ratios of ~0.02 Ra (where Ra = 1.4 × 10$^{-6}$, the ratio in air). Mantle fluids without substantial crustal influence are strongly enriched in $^4\text{He}$, with typical ratios ranging from ~6 to 35 Ra, depending on the mantle source (e.g., plume volcanism versus mid-ocean ridge basin versus back-arc volcanism).
13. Materials and methods are available as supporting material on Science Online.
28. This work was supported by the U. S. Department of Energy, Office of Basic Energy Sciences and Office of Geothermal Technologies under contract DE-AC02-05CH11231.

Supporting Online Material

www.sciencemag.org/cgi/content/full/318/5855/1433/DC1

Materials and Methods

Table S1

References

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