Supplementary Information for “Multiscale variations of the crustal stress field throughout North America”

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Supplementary Figure 1. Map of North America showing maximum horizontal stress ($S_{Hmax}$) orientations. Data that are newly presented here are in red (including those from Thompson$^{56,57}$ with new information added as part of this study), those from the World Stress Map$^{16}$ are in blue, and those compiled from recent Stanford Stress Group publications$^{12,13,55}$ and other public sources$^{54,101-115,102-109}$ are in green. New $S_{Hmax}$ orientations and those compiled from published sources are tabulated in Supplementary Data 1 and 2. World Stress Map data are freely available for download at [www.world-stress-map.org](http://www.world-stress-map.org). Supplementary Data 3 includes WSM data from North America that are pictured in this study (i.e., excluding single focal mechanism solutions and accounting for the 5 modifications indicated in Supplementary Data 2).
Supplementary Figure 2. Histograms illustrating the distributions of maximum horizontal stress ($S_{Hmax}$) orientation quality ratings with depth. a, Measurements from borehole techniques or aligned microseismic events from North America World Stress Map data included in Supplementary Data 3 (i.e., excluding single focal mechanism solutions), and from this and recent studies by the Stanford Stress Group\textsuperscript{12,13,17,55}. b, $S_{Hmax}$ orientations from formal focal mechanism stress inversions in North America from this study and the World Stress Map (FMF in Supplementary Data 3).
Supplementary Figure 3. Interpolated 1σ uncertainty range for \( A_\phi \) (relative principal stress magnitude) measurements in North America. Dots are \( A_\phi \) measurement control points colored by 1σ uncertainty, indicating \( A_\phi \) measurement density. These data are reported in Supplementary Data 4.
Supplementary Figure 4. Maps of $A_\phi$ (relative stress magnitude) in North America illustrating the effects of changing the interpolation algorithm. Unlike in the figures presented in the main body text, none of these interpolations were subsequently smoothed. Additional information is provided in the Supplementary Notes. a, Empirical Bayesian Kriging (the method employed for the main body figures); b, Ordinary Kriging; c, Inverse Distance Weighting; d, Natural Neighbor.
Supplementary Figure 5. Map of North America showing the difference between our $A_\phi$ (relative stress magnitude) values (e.g., Fig. 1) and those from the preferred global combined (GPE plus mantle flow) model (Model 4) reported by Ghosh et al.\textsuperscript{4}. Positive values indicate areas where the predicted $A_\phi$ exceeds our interpolated observations. Note that uncertainties in $A_\phi$ that are illustrated in Supplementary Fig. 3 will affect the true misfits.
Supplementary Figure 6. Data grids used to create Fig. 2b. a, Maximum horizontal stress ($S_{\text{Hmax}}$) orientation interpolated from only A and B quality measurements. b, Calculated divergence angle $\alpha$ between $S_{\text{Hmax}}$ and NNR-MORVEL56 absolute plate motion.
### STRESS INDICATOR:*

|                  | A                                                                 | B                                                                 | C                                                                 |
|------------------|------------------------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------|
| Drilling-Induced Tensile Fractures (DIF) | Ten or more distinct tensile fractures in a single well with standard deviation (sd) ≤ 12° and with highest and lowest observations at least 300 m apart | At least six distinct tensile fractures in a single well with sd ≤ 20° and with highest and lowest observations at least 100 m apart | At least four distinct tensile fractures in a single well with sd ≤ 25° and with highest and lowest observations at least 30 m apart |
| Focal Mechanism Inversions (FMF) | Formal inversion of ≥ 35 reasonably well-constrained focal mechanisms resulting in stress directions with sd ≤ 12° | Formal inversion of ≥ 25 reasonably well-constrained focal mechanisms resulting in stress directions with sd ≤ 20° | Formal inversion of ≥ 20 reasonably well-constrained focal mechanisms resulting in stress directions with sd ≤ 25° |
| Wellbore Breakouts (BO) | Ten or more distinct breakout zones in a single well (or breakouts in two or more wells in close proximity) with sd ≤ 12° and with highest and lowest observations at least 300 m apart | At least six distinct breakout zones in a single well with sd ≤ 20° and with highest and lowest observations at least 100 m apart | At least four distinct breakout zones in a single well with sd ≤ 25° and with highest and lowest observations at least 30 m apart |
| Open-hole Hydraulic Fracturing Stress Orientation (HF) | Four or more hydraulic fractures in a single well (or average of hydraulic fracture orientations for two or more wells in close geographic proximity) with sd ≤ 12° | Three or more hydraulic fractures in a single well (or average of hydraulic fracture orientations for two or more wells in close geographic proximity) with sd ≤ 20° | Two or more hydraulic fracture orientations in a single well with 20° < sd ≤ 25°. If a distinct orientation change with depth, the deepest measurements assumed valid. |
| Hydraulic Fractures Observed in Nearby Sub-horizontal Wellbores (HFH) | Twelve or more distinct hydraulic fractures in a single well (or average of hydraulic fracture orientations for two or more wells in close geographic proximity) with sd ≤ 12° | Eight or more distinct hydraulic fractures in a single well (or average of hydraulic fracture orientations for two or more wells in close geographic proximity) with sd ≤ 20° | Six or more distinct hydraulic fractures in a single well (or average of hydraulic fracture orientations for two or more wells in close geographic proximity) with sd ≤ 25° |
| Microseismic Alignments Along Hydraulic Fractures (HFM) | Twelve or more distinct linear zones associated with HF stages, with sd ≤ 12° | Eight or more distinct linear zones associated with HF stages, with sd ≤ 20° | Six or more distinct linear zones associated with HF stages, with sd ≤ 25° |
| Shear Velocity Anisotropy from Crossed-Dipole Logs (SWA)† | Anisotropy ≥ 2% present at a consistent azimuth, with highest and lowest observations at least 300 m apart, and with sd of fast azimuth ≤ 12° | Anisotropy ≥ 2% present at a consistent azimuth, with highest and lowest observations at least 100 m apart, and with sd of fast azimuth ≤ 20° | Anisotropy ≥ 2% present at a consistent azimuth, with highest and lowest observations at least 30 m apart, and with sd of fast azimuth ≤ 25° |

**Supplementary Table 1.** Quality criteria for $S_{H max}$ orientations and relative stress magnitudes ($R$, $\phi$, or $A_b$)
Supplementary Notes

Supplementary Note 1. In situ (wellbore) measurements of $S_{H\text{max}}$ orientations

We employed established methods to obtain most in situ measurements of the orientation of $S_{H\text{max}}$ that are newly presented in this study (Supplementary Data 1). These are supplemented by data compiled from recently published sources\textsuperscript{12,13,16,55}. Use of such methods are explained in detail by Zoback\textsuperscript{62}. In general, one principal stress is approximately vertical and the other two sub-horizontal because shear tractions cannot be transmitted across the interface between the solid Earth and water or air\textsuperscript{63,64}. All $S_{H\text{max}}$ orientations are shown in Supplementary Fig. 1, with symbol colors indicating data sources. Data from the World Stress Map (WSM)\textsuperscript{16}, are shown in the figures and included in Supplementary Data 3. WSM data are freely available from www.world-stress-map.org.

We applied quality ratings ranging from A (best) to D (lowest) to each $S_{H\text{max}}$ orientation and to $A_\phi$ measurements obtained from earthquake focal mechanism inversions. Only A–C-quality measurements are considered sufficiently reliable to be plotted on stress maps (Fig. 1). Supplementary Table 1 provides the quality criteria used to apply these ratings, which are updated from previously published quality criteria\textsuperscript{6,13,55} and newly include criteria for earthquake focal mechanism inversions. These quality criteria are very similar to those employed by the WSM\textsuperscript{65}. The depth distributions of $S_{H\text{max}}$ orientation measurements and their quality ratings throughout the continent are shown in Supplementary Fig. 2.

The bulk of the 271 reliable (A–C-quality) new $S_{H\text{max}}$ orientations included in Supplementary Data 1 are from azimuths of drilling-induced tensile fractures (DIF) or borehole breakouts (BO) measured in the walls of subvertical wellbores. Such fractures, which are types of wellbore failure that often occur during drilling, develop in predictable orientations relative to the maximum and minimum horizontal principal stresses, with DIF parallel to $S_{H\text{max}}$ and BO parallel to the minimum horizontal principal stress, $S_{h\text{min}}$ (perpendicular to $S_{H\text{max}}$). Of the new $S_{H\text{max}}$ orientations, a single measurement was made from azimuths of fast shear-wave polarization measured in a subvertical well, following criteria established by Boness and Zoback\textsuperscript{66}. This technique is based on the observation that fluid-filled fractures parallel to $S_{H\text{max}}$ are typically closed, whereas those oriented perpendicular to $S_{H\text{max}}$ may be slightly dilated, potentially resulting in higher shear-wave polarization velocities parallel to $S_{H\text{max}}$. An additional 64 new
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$S_{H\text{max}}$ orientations were obtained by averaging the azimuths of aligned groups of microseismic events produced during hydrocarbon reservoir stimulation that were thought to define propagating hydraulic fractures, as described by Warpinski et al.\textsuperscript{67} and following techniques outlined by Lund Snee (Lundstern) and Zoback\textsuperscript{13}. This method is based upon the expectation that hydraulic fractures open in the direction of the least principal stress, $S_3$, and propagate in the direction of the intermediate and maximum principal stresses, $S_2$ and $S_1$\textsuperscript{[59]}. Some of these measurements were obtained from figures included in previously published papers, as referenced in Supplementary Data 1.

It is convenient that principal stress orientations and relative magnitudes generally do not vary significantly with depth below levels affected by topography\textsuperscript{16,64,68,69}. Exceptions are typically due to changes to horizontal stress magnitudes due to differential fluid pressure across an impermeable fault or relaxation of the horizontal stresses due to viscous creep in ductile sedimentary layers. In addition, $A_\phi$ and $S_{H\text{max}}$ can vary significantly within a certain distance of faults that have recently slipped\textsuperscript{51,70}. In cases of significant variability with depth, $S_{H\text{max}}$ orientations would carry high standard deviations, resulting in low ratings using the quality criteria presented in Supplementary Table 1.

**Supplementary Note 2. Compilation of the focal mechanism catalog**

Earthquake focal mechanisms were employed to estimate both $S_{H\text{max}}$ orientations and $A_\phi$, as described below. The catalog presented in Supplementary Data 1 consists of 58,709 source mechanisms from earthquakes that occurred dominantly between January 1970–March 2019, which were compiled from the sources listed below and tabulated in Supplementary Data 5. Duplicates within the merged catalog were identified by occurrence within 10 s and 0.2° latitude and longitude of one another. To ensure only crustal events, we retained only those with depths $\leq$ 25 km (relative to mean sea level if specified) for all catalogs except those provided by Mazzotti and Townend\textsuperscript{71} and Singh et al.\textsuperscript{72}, and we also omitted shallower events near subduction zones that could have occurred on or below the plate interface. We applied the following additional filters to individual catalogs in order to ensure the use of only reliable mechanisms:

- Retain only $M \geq 3.0$: For International Seismological Centre (ISC) Bulletin (http://www.isc.ac.uk/iscbulletin/search/fmechanisms/);
• Use only events from Reviewed ISC Bulletin from February 1976–July 2016, and unreviewed events thereafter;
  • Retain only $M \geq 3.0$: For Global Centroid Moment Tensor Project (GCMT) catalog available via the Global CMT Catalog Search (https://www.globalcmt.org/CMTsearch.html) and the Incorporated Research Institutions for Seismology (IRIS) DMC Data Products search;
  • Retain only $M \geq 3.5$: For U.S. Geological Survey Comprehensive Earthquake Catalog (ComCat) focal mechanisms;
  • Retain all U.S. Geological Survey ComCat moment tensors;
  • Retain only $M \geq 2.4$: For Texas Seismological Network (TexNet) mechanisms;
  • Retain only depths $\leq 10$ km in West Texas;
  • Retain all Saint Louis University moment tensors;
  • Retain only A and B quality: For Southern California earthquakes;
  • Retain only $M \geq 3.0$, azimuthal gap $\leq 90^\circ$, and nearest station distance $\leq 50$ km: For earthquakes from the Northern California Earthquake Data Center;
  • Retain only misfit $\leq 0.5$: For Canadian moment tensors;
  • Retain all events from individual studies.

Supplementary Note 3. Stress measurements from earthquake focal mechanism inversions

We conducted 50 formal stress inversions using the earthquake focal mechanism catalog presented in Supplementary Data 1, yielding 46 reliable (A–C-quality) $S_{Hmax}$ orientations (Supplementary Data 1) and 40 reliable $A_\phi$ (relative stress magnitude) estimates (Supplementary Data 4). These inversions were subjected to the new quality criteria set forth in Supplementary Data 1, which are informed by indications that at least 20 focal mechanisms (and often $> 30$), are needed to yield reliable results, particularly for $A_\phi$.

Our new quality ratings additionally include a criterion for inversion uncertainties, which can be estimated using bootstrap sampling.

Formal stress inversions of earthquake focal mechanisms rely upon assumptions that the slip vector is parallel to the direction of maximum shear stress resolved on the slipping fault, that all mechanisms are reliable representations of the earthquake source geometry, that the active plane can be differentiated from the nodal plane, and that all events included as part of the same inversion occurred in a uniform stress field. We conducted our inversions using Vavryčuk’s algorithm, which iteratively inverts for the active fault plane in order to maximize the accuracy.
of differentiating the active and nodal planes. The 1σ error ranges and minimum and maximum values of $S_{H_{\text{max}}}$ orientations and $A_\phi$ were quantified using bootstrap sampling ($B = 1000$). The focal mechanism catalogs were filtered as described above in order to employ only reliable mechanisms. To ensure a uniform stress field for each inversion, we sought small geographic areas of events sampled for each inversion, and we avoided conducting inversions where groups of mechanisms displayed clear spatial rotations in their $P$- or $T$-axes. The conservative style of our approach to identifying sampling areas is illustrated by the relatively small number of inversions (50) that we conducted across this large region.

In our mapping, we additionally included 594 reliable $A_\phi$ estimates from prior focal mechanism inversions in North America made by Yang and Hauksson\textsuperscript{10} in Southern California (their G10N30 model with 10 km squares and $\geq 30$ mechanisms per square) and two by Quinones et al.\textsuperscript{90} in the Fort Worth Basin, Texas. We applied our new quality criteria to these previously published inversions, excluding from our map a number of inversion results that are considered unreliable (D quality). We further excluded 3 inversions by Yang and Hauksson\textsuperscript{10} with $A_\phi < 0.5$ (radial normal faulting) in the southern Sierra Nevada where numerous strike-slip and normal faulting earthquakes are present, as well as 1 inversion result in eastern California (in the vicinity of Owens Valley) that indicates strongly reverse faulting in spite of normal, strike-slip, and reverse faulting focal mechanisms and dominantly normal and strike-slip Quaternary fault offsets in the area. We suspect that these inversions may be unreliable due to the presence of either poorly constrained focal mechanisms or changes in the stress field within the grid boxes. The new data supersede inversion results by Mazzotti and Townend\textsuperscript{71} in southeast Canada and the central and eastern USA because the new inversions in these areas applied the latest focal mechanisms, subject to stricter filtering criteria described above. Because of adoption of the new quality criteria, which stipulate a minimum number of focal mechanisms and maximum uncertainty bounds for inversions to be considered reliable, we did not conduct inversions in some areas for which those authors previously obtained formal $A_\phi$ estimates, and older inversions in those areas may be less reliable. Nevertheless, in such cases $A_\phi$ was interpreted informally based on the available mechanisms, using the techniques described below. In addition, we did not invert for specifically $A_\phi$ using TexNet mechanisms in Texas due to considerable variability in focal plane geometries in certain areas and other indications of elevated uncertainty. However,
we did formally invert for only $S_{H_{\text{max}}}$ orientations using the TexNet mechanisms based on evidence mentioned above that $S_{H_{\text{max}}}$ is less sensitive to nodal plane uncertainties\textsuperscript{91}.

Finally, because multiple plate-bounding fault zones cut North America, we note that estimates of faulting regime from earthquake focal mechanism stress inversions are unreliable if they include events that occurred on faults with anomalously low coefficients of friction. On such faults, the sense of slip (e.g., strike-slip) may differ from the faulting regime (e.g., reverse faulting), as is the case in some areas near the San Andreas fault zone\textsuperscript{96}. Perhaps related to this effect, as well as the very high rate of seismicity in the area, Abolfathian et al.\textsuperscript{97} have shown appreciable stress changes with depth near major faults associated with the plate boundary in Southern California. For these reasons, we do not include events that occurred within 10 km of plate bounding faults or major, potentially weak subsidiary structures near plate boundary zones. We also exclude previously published $A_\phi$ inversion results that include such earthquakes.

**Supplementary Note 4. Interpretation of relative stress magnitudes from earthquake focal mechanisms and Quaternary fault offsets**

Of the 1303 new estimates of $A_\phi$ (relative stress magnitudes), 1263 are based on the slip sense of Quaternary fault offsets, observations of fault slip sense from microseismic events and focal mechanisms monitored during hydraulic fracturing operations, or interpretations from individual earthquake focal plane mechanisms or groups of mechanisms (Supplementary Data 4). Earthquake focal mechanisms and paleoseismic indicators provide constraints on $A_\phi$ even in cases where there are too few indicators to conduct a formal inversion. Observation of a specific sense of fault slip (normal, strike-slip, reverse, or oblique) provides permissible and impermissible ranges of $A_\phi$; multiple observations in an area allow for interpretation of increasingly well-constrained permissible $A_\phi$ ranges. For example, nearby occurrence of both normal and strike-slip faulting (and/or oblique normal/strike-slip events) indicates a faulting regime between normal faulting ($A_\phi = 0.5$) and strike-slip faulting ($A_\phi = 1.5$), bounding $A_\phi$ between 0.5–1.5. Similarly, the presence of a single normal faulting mechanism indicates a faulting regime between normal/strike-slip faulting ($A_\phi \leq 1.25$) and the extremely rare condition of radial normal faulting ($A_\phi = 0$). The uncertainty bounds can be narrowed considerably in cases where multiple slip sense observations are available. For example, numerous events distributed
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roughly equally between normal to strike-slip faulting sense (or numerous oblique normal/strike-slip events) suggest that $A_\phi$ is likely near 1.0.

Based on this framework, we interpreted $A_\phi$ and its uncertainty using the information provided by earthquake focal mechanisms and Quaternary fault offsets, with interpretations informed by formal focal mechanism stress inversions. We assumed normal uncertainty distributions for each $A_\phi$ measurement, for which we interpret the mean ($\mu$, presented in Fig. 1), standard deviation (1σ, illustrated in Supplementary Fig. 3), and minimum and maximum truncation bounds ($t_{\min}$ and $t_{\max}$) for the distribution.

Data for recent fault slip sense were drawn from the U.S. Geological Survey Quaternary Fault and Fold Database\textsuperscript{60}, as well as evidence for reverse–strike-slip faulting in the paleoseismic record of the Meers Fault, southwest Oklahoma\textsuperscript{98,99}, and extensional growth faulting along the Gulf Coast margin\textsuperscript{64}. Focal mechanisms were compiled as described above. In general, focal mechanisms were considered more reliable than Quaternary offsets due to the lower precision of the fault offset record (e.g., slip vectors are not typically recorded for Quaternary offsets, limiting the potential to recognize oblique slip) and a potential bias against sampling strike-slip faults due to greater challenges identifying offsets without significant vertical components.

$A_\phi$ was interpolated using the Empirical Bayesian Kriging (EBK) algorithm supplied in the ESRI ArcGIS v.10.6.1 software program (Geostatistical Analyst toolbox), using a power variogram model and standard circular search neighborhood with a minimum of 10 neighbors and a maximum of 15 neighbors. The interpolation was made on the mean $A_\phi$ value ($\mu$) given in Supplementary Data 4. To illustrate the uncertainty range (Supplementary Fig. 3), the 1σ measurement-point uncertainties given in Supplementary Data 1 were interpolated using the same algorithm. Both interpolations were smoothed slightly using a low-pass filter with a $3 \times 3$ window. Supplementary Fig. 4 compares the interpolation using EBK to other options such as Natural Neighbor, Inverse Distance Weighted (IDW), and Ordinary Kriging. The latter three algorithms are those provided by ArcGIS v.10.6.1 (Spatial Analyst toolbox), and default parameters were employed for each. Unlike in the figures presented in the main body text, the $A_\phi$ interpolations in this comparison figure were not subsequently smoothed. The difference between our interpolated mean $A_\phi$ values and the $A_\phi$ values predicted from the preferred global combined (GPE plus mantle flow) model (Model 4) reported by Ghosh et al.\textsuperscript{4} are shown in Supplementary Fig. 5.
Supplementary Note 5. Estimation of divergence angle $\alpha$ between $S_{H\text{max}}$ orientations and absolute plate motion directions

$S_{H\text{max}}$ orientations were gridded using EBK with the same parameters as in the interpolation of $A_\phi$ (see above). To reduce noise, only higher (A and B) quality $S_{H\text{max}}$ orientations were used for the interpolation. The resulting grid is presented in Supplementary Fig. 6a. The $S_{H\text{max}}$ orientation raster was subtracted from a grid of orientations of NNR-MORVEL56 absolute plate motions\textsuperscript{19} using the ArcGIS Raster Calculator. The resulting grid of divergence angles (Supplementary Fig. 6b) was smoothed slightly using a $3 \times 3$ low-pass filter. Divergence angles were extracted from this grid along three $2^\circ$-wide swath profiles (Fig. 2) that were constructed approximately parallel to plate motion using TopoToolbox v.2.3\textsuperscript{100} in MATLAB. Divergence angles were sampled every $0.1^\circ$ along and across the swath profiles. The negative mean across-profile value for each point along the profile is shown in Fig. 2b.
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