Supplementary information

1. Calculation of single-crystal strain rates

Single-crystal strain rates are calculated based on published data for San Carlos olivine crystal rheology (Table S2), including corrections for water content and oxygen fugacity. The general flow law is

$$\dot{\varepsilon} = A\, \sigma^n\, f\mathrm{O}_2^m\, exp\left(\frac{E^*+PV^*}{RT}\right) \quad \text{Eq. S1}$$

where σ is the differential stress, fO_2 the oxygen fugacity, *P* the hydrostatic pressure, and *T* the temperature. R is the gas constant. *A*, *n*, *m*, *E**, and *V** are constants adjusted to previous experimental data (Table S2).

For a dry single crystal of olivine with the $[110]_c$ direction parallel to compression (promoting [100](010) dislocation slip), the crystal strain rate can be calculated according to

$$\dot{\varepsilon}_{[110]c} = B\,[\dot{\varepsilon}_1 + ((\dot{\varepsilon}_2)^{-1} + (\dot{\varepsilon}_3)^{-1})^{-1}] \quad \text{Eq. S2}$$

with $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$ calculated using Eq. S1 and the parameters of Table S2. For a dry single-crystal, *B* = 1. For a wet single-crystal *B* = 4.13 (see below).

For a single crystal with the $[011]_c$ direction parallel to compression (promoting [001](010) dislocation slip), the corresponding strain rate is

$$\dot{\varepsilon}_{[011]c} = B\,[\dot{\varepsilon}_1 + \dot{\varepsilon}_2]\,. \quad \text{Eq. S3}$$

with $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ calculated using Eq. S1 and the parameters of Table S2. For a dry single-crystal, *B* = 1. For a wet single-crystal *B* = 24.7 (see below).

Finally, for a dry single crystal with the $[101]_c$ direction parallel to compression (promoting [100](001) and [001](100) slips together), the corresponding strain rate is

$$\dot{\varepsilon}_{[101]c} = B[((\dot{\varepsilon}_1)^{-1} + (\dot{\varepsilon}_2)^{-1})^{-1}] \quad \text{Eq. S4.}$$

with $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ calculated using Eq. S1 and the parameters of Table S2. For a dry single-crystal, *B* = 1. For a wet single-crystal *B* = 11.3 (see below).

2. Effect of water

Wet olivine single crystals are weaker than dry crystals, respectively by factors of ~1.5, 2.5 and 2.0 on the differential stress when deformed along $[110]_c$, $[011]_c$ and $[101]_c$ directions [*Mackwell et al.*, 1985; *Girard et al.*, 2013]. When calculating $\dot{\varepsilon}_{IC}$ for wet aggregates, these weakening factors translate into factors of 4.13, 24.7 and 11.3 on crystal strain rates, accounting for olivine stress exponent *n* = 3.5 in classical power laws [*Bai et al.*, 1991].

3. Supplemental References

Peslier, A.H., Woodland, A.B., Bell, D.R., Lazarov, M. (2010) Olivine water contents in the continental lithosphere and the longevity of cratons, *Nature* **467**, 78-81.

Supplementary Material

Figure S1: plots of the 80-Ma and 20-Ma oceanic geotherms and the continental geotherm used in this study. Pressure increase with depth is calculated using the upper-mantle average density (3.35 g/cm^3), i.e. a 32.9 MPa/km vertical gradient.

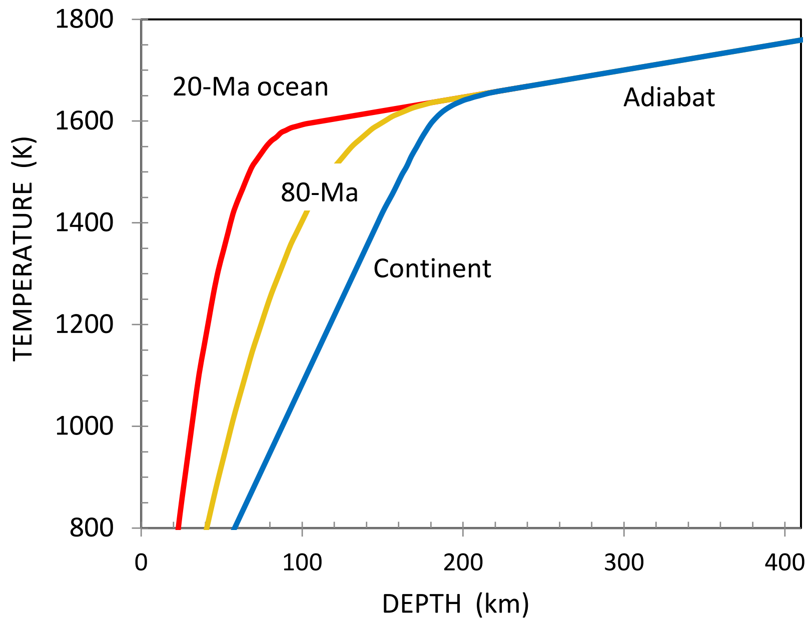

Figure S2: same as Figure 3.b, with σ = 50 MPa.

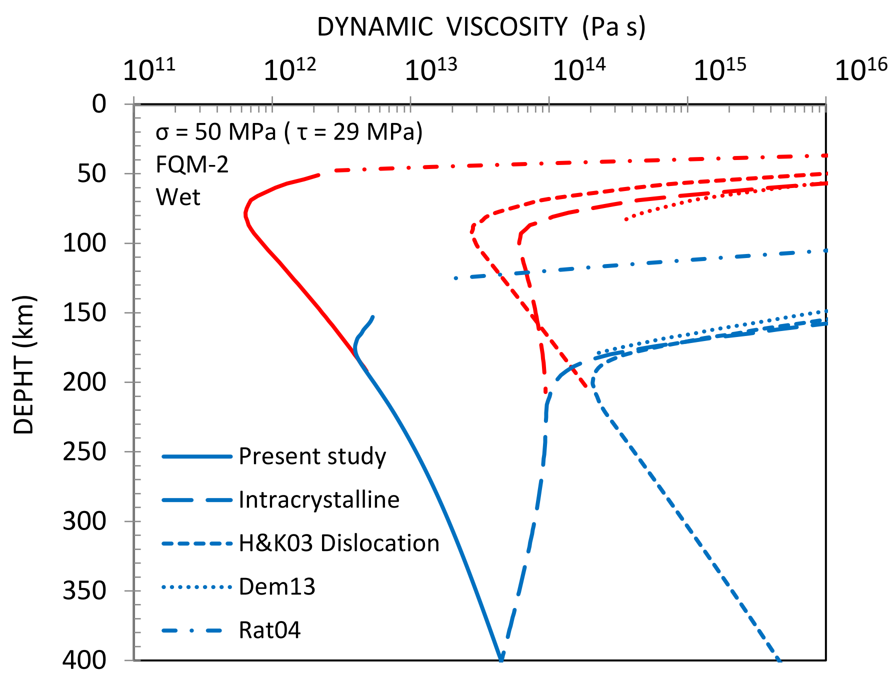

Table S1: Rheological data for olivine aggregates deformed in axial compression at high pressure and temperature. $\dot{\varepsilon}_{Agg}$ are raw experimental data. $\dot{\varepsilon}_{IC}$ are calculated from Eq. 3. For the unbuffered experiments, we assume either the iron-wüstite (IW) or the fayalite-magnetite-quartz (FMQ) buffer oxygen fugacity (fO_2).

Run #	P	ΔP	T	ΔT *	σ	$\Delta\sigma$ *	fO_2	fO_2	$\dot{\varepsilon}_{Agg}$	$\Delta\dot{\varepsilon}_{Agg}$	$\log(\dot{\varepsilon}_{Agg}/\dot{\varepsilon}_{IC})$	$\log(\dot{\varepsilon}_{Agg}/\dot{\varepsilon}_{IC})$	$\Delta\log(\dot{\varepsilon}_{Agg}/\dot{\varepsilon}_{IC})$
	GPa	GPa	K	K	MPa	MPa	atm	atm	s^{-1}	s^{-1}			
Durham et al. [2009] *: Dry.* Ni-NiO *buffered*							Ni-NiO				Ni-NiO		
140	4.2	0.05	1540	*25*	250	*50*	6.13E-09	-	1.50E-05	5.80E-07	1.18	-	0.44
144(1)	2.7	0.05	1477	*25*	300	*50*	1.33E-09	-	1.90E-05	7.60E-07	1.39	-	0.42
144(2)	4.8	0.05	1455	*25*	500	*50*	7.52E-10	-	1.60E-05	5.20E-07	1.63	-	0.39
145(1)	4.9	0.05	1453	*25*	250	*50*	7.14E-10	-	1.90E-06	7.50E-08	1.83	-	0.47
145(2)	4.9	0.05	1451	*25*	340	*50*	6.77E-10	-	3.20E-05	1.30E-06	2.61	-	0.43
Hilairet et al. [2012]: *Wet unbuffered*							IW	FMQ			IW	FMQ	
D0912-1	4.2	0.2	1373	*25*	1385	220	4.86E-14	2.90E-10	6.70E-06	1.50E-07	0.69	-0.16	0.48
D1040-2	7.9	0.2	1375	*25*	2895	400	5.20E-14	3.08E-10	1.10E-05	5.00E-08	0.51	0.19	0.49
D1040-3	6.2	0.2	1375	*25*	2910	500	5.20E-14	3.08E-10	1.49E-05	2.00E-07	0.36	-0.19	0.50
D1062-1	5.0	0.2	1506	*25*	76	25	2.85E-12	1.19E-08	3.44E-06	2.00E-08	2.92	2.42	0.61
D1062-3	5.8	0.2	1506	*25*	1465	260	2.85E-12	1.19E-08	1.24E-05	6.00E-07	-0.80	-1.25	0.45
D1040-1	6.8	0.2	1593	*25*	169	25	2.83E-11	9.69E-08	1.27E-05	9.00E-08	0.54	0.00	0.47
D0912-2	3.8	0.2	1600	*25*	212	50	3.36E-11	1.14E-07	3.42E-05	2.90E-06	0.29	-0.24	0.52
D0912-3	4.3	0.2	1600	*25*	215	60	3.36E-11	1.14E-07	1.40E-05	4.00E-07	1.47	1.01	0.40
Bollinger et al. [2014]*: Wet unbuffered*							IW	FMQ			IW	FMQ	
81	7.2	0.1	1373	*25*	382	212	4.86E-14	2.90E-10	3.80E-05	1.00E-06	4.06	3.66	0.95
81	6.0	0.1	1373	*25*	493	160	4.86E-14	2.90E-10	2.70E-05	1.00E-06	3.32	2.74	0.65
82	10.6	0.1	1373	*25*	831	285	4.86E-14	2.90E-10	2.60E-05	1.00E-06	3.17	2.99	0.70
87	5.9	0.2	1373	*25*	737	183	4.86E-14	2.90E-10	1.80E-05	6.00E-07	2.51	1.91	0.57
267	4.2	0.2	1373	*25*	800	217	4.86E-14	2.90E-10	4.30E-05	1.00E-06	2.34	1.49	0.58
267	4.9	0.2	1373	*25*	917	595	4.86E-14	2.90E-10	2.40E-05	7.00E-07	2.07	1.32	1.07
80	4.0	0.1	1473	*25*	262	143	1.11E-12	5.05E-09	3.40E-05	5.00E-06	2.24	1.64	0.90
88	8.6	0.2	1473	*25*	884	170	1.11E-12	5.05E-09	1.60E-05	6.00E-07	1.08	0.80	0.49
89	5.7	0.2	1473	*25*	535	172	1.11E-12	5.05E-09	1.30E-05	1.00E-06	1.21	0.74	0.61
89	5.9	0.2	1473	*25*	504	191	1.11E-12	5.05E-09	1.10E-05	2.00E-06	1.28	0.82	0.69
90	7.9	0.2	1473	*25*	796	190	1.11E-12	5.05E-09	1.70E-05	8.00E-07	1.16	0.85	0.53
81	4.2	0.1	1573	*25*	341	88	1.71E-11	6.11E-08	5.80E-05	2.00E-06	0.60	0.07	0.50
82	9.0	0.1	1573	*25*	163	83	1.71E-11	6.11E-08	2.50E-05	5.00E-06	2.52	2.18	0.85
87	5.2	0.2	1573	*25*	203	203	1.71E-11	6.11E-08	2.40E-05	3.00E-06	1.32	0.82	1.56
87	6.1	0.2	1573	*25*	276	113	1.71E-11	6.11E-08	2.50E-05	2.00E-06	1.13	0.66	0.71
88	7.8	0.2	1673	*25*	272	137	1.89E-10	5.49E-07	2.80E-05	3.00E-06	0.28	-0.22	0.82
89	5.5	0.1	1673	*25*	83	98	1.89E-10	5.49E-07	4.40E-05	6.00E-06	1.65	1.08	1.82
89	4.8	0.2	1673	*25*	248	137	1.89E-10	5.49E-07	5.30E-05	1.00E-06	-0.16	-0.74	0.88
90	7.2	0.1	1673	*25*	118	90	1.89E-10	5.49E-07	4.50E-05	1.00E-06	1.61	1.09	1.20

*ΔT is the estimated uncertainty on nominal T ; $\Delta\sigma$ provided by N. Hilairet for *Hilairet et al.* [2012] data, and arbitrarily set to 50 MPa for *Durham et al* [2009] data. Note that, within uncertainties, all data points but one verify $\log(\dot{\varepsilon}_{Agg}/\dot{\varepsilon}_{IC}) \geq 0$, i.e. $\dot{\varepsilon}_{Agg}/\dot{\varepsilon}_{IC} \geq 1$ in good agreement with Eq. 3; $\dot{\varepsilon}_{Agg}/\dot{\varepsilon}_{IC} < 1$ may occasionally result from the lower-bound approach used here to calculate the intracrystalline strain rate (overestimation of $\dot{\varepsilon}_{IC}$). See text for further explanations.

Table S2. Flow-law parameters[†] for orthopyroxene-buffer SC olivine single crystals

$$\text{Flow law}: \ \dot{\varepsilon} = A\,\sigma^{n}\, f\mathrm{O}_2^{m}\, exp\left(\frac{E^{*}+PV^{*}}{RT}\right)$$

Compression direction		*A* (MPa^{-n} atm^{-m} s^{-1})	*n*	*m*	*E** (kJ/mol)	*V** (cm^3/mol)
$[110]_c$ [††]	$\dot{\varepsilon}_1$	0.02	3.5	0.36	230	12
	$\dot{\varepsilon}_2$	1.3×10^{22}	3.5	0.10	1000	12
	$\dot{\varepsilon}_3$	1.2	3.5	0.15	290	12
$[011]_c$ [††]	$\dot{\varepsilon}_1$	2.1×10^{4}	3.5	0.02	540	3
	$\dot{\varepsilon}_2$	5.2×10^{5}	3.5	0.23	540	3
$[101]_c$ [††]	$\dot{\varepsilon}_2$	0.65	3.5	0.33	250	10.7
	$\dot{\varepsilon}_2$	5.3×10^{11}	3.5	0.06	690	10.7

[†] *A*, *n*, *m* and *E** from *Bai et al.* [1991], *V** from *Raterron et al.* [2009; 2012];
[††] $\dot{\varepsilon}_{[110]c} = \dot{\varepsilon}_1 + ((\dot{\varepsilon}_2)^{-1} + (\dot{\varepsilon}_3)^{-1})^{-1}$; $\dot{\varepsilon}_{[011]c} = \dot{\varepsilon}_1 + \dot{\varepsilon}_2$; $\dot{\varepsilon}_{[101]c} = ((\dot{\varepsilon}_1)^{-1} + (\dot{\varepsilon}_2)^{-1})^{-1}$; in wet conditions, strain rates must be multiplied by 4.13, 24.7 and 11.3, respectively [*Mackwell and Kohlstedt*, 1985; *Girard et al.*, 2013].