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Back-propagating super-shear rupture in the 2016 *M*7.1 Romanche transform fault earthquake

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How an earthquake rupture propagates strongly influences potentially destructive ground shaking. Complex ruptures often involve slip along multiple faults, masking information on the frictional behaviour of fault zones. Geometrically smooth ocean transform fault plate boundaries offer a favourable environment to study fault dynamics, because strain is accommodated along a single, wide fault zone that offsets homogeneous geology. Here we present an analysis of the 2016 M7.1 earthquake on the Romanche fracture zone in the equatorial Atlantic, using data from both nearby seafloor seismometers and global seismic networks. We show that this rupture had two phases: (1) upward and eastward propagation towards a weaker region where the transform fault intersects the mid-ocean ridge, then (2) unusual back-propagation westwards at super-shear speed toward the centre of the fault. We suggest that deep rupture into weak fault segments facilitated greater seismic slip on shallow locked zones. This highlights that even earthquakes along a single distinct fault zone can be highly dynamic. Observations of back-propagating ruptures are sparse, and the possibility of reverse propagation is largely absent in rupture simulations and unaccounted for in hazard assessments.

For large earthquakes, many complex configurations of seismic slip have been proposed, such as cascading rupture across multiple faults[1], including for intraplate ocean earthquakes[2], and closely-spaced doublets[3]. These configurations, however, are often dominated by pre-existing complex geometries of multiple faults[4]. In contrast, ocean transform faults (OTFs), which make up ~20% of the total length of global plate boundaries, have most strain accommodated along a single broad zone, a thermally controlled seismogenic width, and well-defined ridge-controlled slip rates, making them the simplest manifestation of transform faults on Earth. OTF faults are strongly bi-material, controlled by plate age variation across the fault, with hydrothermal alteration of mafic and ultramafic rocks[5]. Rupture behaviour along OTFs was thought to be influenced by strongly-coupled, velocity-weakening fault patches[6–8], with short recurrence times of moderate-sized earthquakes (M_w≤6.2) along faster-slipping OTFs in the Pacific[9], allowing for possible earthquake forecasting[9–11]. The wide fault damage zone along OTFs (~5–20 km)[12,13] likely affects seismogenic behaviour[8,14]. These concepts, however, have yet to be explored for larger ruptures along OTFs that offset slower-spreading, Atlantic-type ridges.

Using teleseismic data alone, past studies of OTF earthquakes suggested anomalously long rupture durations[15], with unilateral propagation after initiation closer to the ridge-transform intersection (RTI), then propagating toward the centre of the fault[16–18]. Although fast strike-slip earthquakes are found in continental[19], ocean-continent[20], and oceanic intraplate[2] settings, it remains unclear as to whether OTFs can host super-shear rupture. Fast ruptures might occur given the maturity[21], length, and linearity[22] of OTFs. Whilst OTFs offer a unique opportunity to investigate geological controls on rupture style and seismic cycle behaviour[14], there has been no documented capture and analysis of large earthquakes along OTFs using nearby (i.e. <1,000 km) seafloor sensors.

Uniquely, in August 2016, an M_w 7.1 earthquake at the eastern end of the Romanche OTF in the central Atlantic Ocean was captured by a local ocean-bottom seismometer (OBS) network (**Figure 1**). The 920 km-long Romanche OTF is the second longest globally, and large earthquakes along it are common, with 13 M_w 6.5+ events since 1970, including an M_w 7.1 rupture in 1994[16]. Using local OBS and teleseismic data of the earthquake and its aftershocks, we show that the 2016 earthquake ruptured at super-shear speed with back-propagating fronts along a single fault zone.

Rupture complexity from seafloor and teleseismic waveforms

The mainshock epicentre coincides with the 20-km wide Romanche axial valley, lying ~90 km WSW of the RTI (**Figure 1, Figure 2a**). The hypocentre depth is approximately 20 km below sea level (BSL), although this is poorly constrained due to network coverage (see **Methods**). The magnitude of the largest aftershock is M_L 4.8, consistent with the maximum aftershock magnitude decrement for OTF earthquakes globally of 2.2[5]. We find a high density of aftershocks (see **Methods**) ~20 km west of the mainshock epicentre, and some further east, up to 70 km away (**Figure 2a**). The aftershock distribution relative to the mainshock indicates a ~60-80 km-long bilateral rupture. Regional moment tensor (RMT) analysis (see **Methods**) using a single point-source approximation shows strongly double-couple (98%) right-lateral strike-slip faulting (**Figure 1**). The hypocentre-to-centroid time and epicentre shifts of 16 s and <20 km, respectively imply a slow[15] rupture velocity, $v_r \approx 1$ km/s.

To investigate this apparently slow rupture, we inverted waveforms at shorter periods to solve for multiple sub-events with variable deviatoric RMTs[23] (see **Methods**). Waveform fits and source configurations are shown in **Figure 2b** and described below. The largest pulse in waveforms is reproduced by an M_w 6.9 sub-event at $\Delta t = 21$ s located close to the epicentre.

In the residual waveforms, we fit an earlier pulse with an additional sub-event, which increases overall variance reduction by 20%, statistically significant at 95% confidence (**Note S4**). This M_w 6.7 sub-event ruptured earlier ($\Delta t = 13$ s) than the larger sub-event, with its centroid ~40 km east of the epicentre. We refer to the earlier, smaller sub-event as *SE1* and the later, larger sub-event as *SE2*. In contrast to early indications of a slow unilateral rupture, the location and timing of sub-events indicate a faster, more complex rupture. The resulting source-time function is similar to that from automated teleseismic analyses[24] (**Figure 2c**).

To verify our source model, we inverted teleseismic waveforms for a slip-rate model[25] of the Romanche earthquake (see **Methods**). This model requires a sub-vertical, south-dipping fault plane (~78° dip) with deep initiation, consistent with our RMTs and hypocentre estimate, respectively. The rupture evolution over time (**Figure 3a**) shows a low slip-rate (<2 cm/s) early on ($\Delta t = 0$–8 s), similar to other large OTF earthquakes[16]. At $\Delta t = 8$–14 s, an emergent phase of slip (4 cm/s) occurs ~35 km east of the hypocentre at shallow depth (SE1). Soon after, at $\Delta t > 16$ s, the rupture appears to travel west, toward, and beyond, the nucleation region - rupturing a large asperity ~50 km long in the crust (SE2) with high slip-rate (7 cm/s).

Verification of rupture reversal

The aftershock distribution, sub-event RMTs, and teleseismic slip inversion appear consistent, implying two rupture phases propagating in opposite directions. Two models can explain this: either bilateral rupture with vastly different v_r in each direction; or sequential back-propagating rupture with super-shear v_r.

Bilateral super- and sub-shear ruptures were inferred for the 2013 M_w 7.5 Craig, Alaska earthquake[20]. If we assume a similar configuration for the Romanche earthquake, failure of

the larger failed asperity (SE2) must have propagated very slowly ($v_r \approx 1$ km/s), requiring, for example, a dissipative mechanism in ductile mantle[26]; however, the earthquake ruptured above the 600°C isotherm (**Figure 4**).

Alternatively, if the rupture changed direction following SE1, then this part of the earthquake must have travelled at super-shear v_r (5–6 km/s). To validate this model, we used time-domain teleseismic back-projection (BP) imaging[27] with phase-weighted stacking of virtual seismic arrays (see **Methods**). We imaged the BP on two planar grids: one at 2.5 km depth and the other at 10 km depth below the seafloor. For the nucleation phase, we find a higher coherence of back-projected waves using the 10 km depth grid, consistent with rupture initiation in mantle. For the total rupture, the shallower grid has higher waveform coherence, indicating slip at crustal levels. The overall BP results (**Supplementary Video S1**) confirm an apparent reversal in rupture direction with an initial, eastwards propagation followed by a westerly-travelling phase travelling at 4–6 km/s (**Figure 3b).** Whilst the high-frequency radiators occur over a laterally more compact region than the sub-events and teleseismic slip-rate model, the overall pattern is consistent.

We verify this result by searching for far-field Rayleigh Mach waves[28,29] by comparing waveforms filtered at 10–20 s period from the Romanche mainshock with a co-located M_w 5.6 earthquake on 2018-02-15 that had an identical faulting mechanism[30] (**Figure 1**; see **Methods**). At azimuths of 35–65° relative to rupture direction, many stations have very high waveform similarity between the mainshock and aftershock with cross-correlations exceeding 0.9 (**Figure 1, Extended Data Figure 1**). Accounting for phase velocity variations over large epicentral distances of up to 90° (**Figure S14**), these azimuths demarcate a Mach cone with lower rupture directivity effects[28,29], similar to that predicted for a v_r of 5.7 km/s

(see **Methods**; **Extended Data Figure 2**). Outside of the predicted Mach cone azimuths, waveform similarity is lower with cross-correlation coefficients generally less than 0.80 (**Figure 3c**; **Extended Data Figure 1**). A relatively low density of aftershocks in the super-shear segment (**Figure 2a**) is similar to past observations of super-shear earthquakes[31]. These indications of super-shear rupture appear to rule out the possibility of bilateral rupture from the hypocentre.

A remaining issue is whether after nucleation ($\Delta t = 0$–9 s) the rupture front was continuous, or SE1 was dynamically triggered due to S-waves from the initiation phase. The latter model, in which rupture nucleation may be regarded as a foreshock, is supported by the along-fault nodal maximum in S-wave amplitude and apparent $v_r \approx 3.5$–4 km/s, similar to the shear-wave velocity (v_S) of mid-to-lower crust. Yet OBS waveforms show continuous seismic energy radiation over time following rupture nucleation (**Figure S15**), suggesting a spreading, continuous rupture as indicated by BP imaging, although we cannot completely rule out dynamic triggering at smaller scales[32].

Segmentation in fault stress controls rupture propagation

The unique spatio-temporal evolution of the 2016 Romanche earthquake adds new understanding to the geological controls on seismic slip along mature strike-slip faults, providing direct evidence of super-shear rupture along OTFs. Theoretical studies have suggested that earthquakes on inhomogeneous faults rupture in a preferred direction for sub- and super-shear propagation[33]. The segment that failed in 2016 is likely bi-material since it offsets crust with an age difference of ~27 Ma (**Figure 1**). If we assume higher seismic velocities on the older and cooler north side, the preferred super-shear direction[33] is east, opposite to our observations. This finding indicates that propagation direction might not be

147 simply controlled by broad plate age and thermal variations. Instead, rupture direction may
148 be more dependent on variable material properties within a wide (5–20 km) fault damage
149 zone[12,13]. One possibility is that greater fracturing and serpentinisation may exist on the older
150 side, possibly related to uplift of the transverse ridge to the north[34], reducing seismic velocity,
151 and resulting in preferred westward super-shear rupture.

152 The depth and lateral extent of rupture is likely determined in part by variations of
153 serpentinisation in the seismogenic zone. The OBS data, teleseismic slip rate inversion and BP
154 imaging imply deeper initiation at ~20 km depth. Therefore, the earthquake nucleated in the
155 oceanic mantle, at the base of the seismogenic zone[5,35] at 500–600°C temperature (**Figure 4**).
156 Nucleation was likely promoted by brittle failure in conditionally-stable serpentinised mantle
157 peridotite[6]. Most seismic slip occurred in the crust beneath a topographically smoother
158 segment of the Romanche axial valley (~6,200 m BSL; **Figure 2a**, **Figure 4**). At the rupture's
159 western end, a deeper valley (>6,500 m) may indicate greater hypothermal alteration and
160 serpentinsation[11,13], resulting in velocity-strengthening frictional behaviour[13,34]. The eastern
161 edge of the rupture lies where the seafloor steepens to shallower depths of <5,500 m at the
162 diffuse RTI (**Figure 2a**, **Figure 4**), which likely restricted slip due to a narrower seismogenic
163 zone[35]. These fault segments bounding the earthquake likely creep aseismically, contributing
164 to the overall low seismic coupling of OTFs[5].

165 Our preferred explanation for rupture reversal during the 2016 M_w 7.1 Romanche earthquake
166 is as follows and illustrated in **Figure 4**. Nucleation occurred at ~20 km depth, above the
167 brittle-ductile transition (**Figure 4**, Step 1-2). SE1 then ruptured along the ~500–600°C
168 isotherm towards the surface near the RTI, with relatively weak slip in conditionally-stable
169 serpentinised mantle peridotite[35] (**Figure 4**, Step 3-4). We speculate that the SE2 fault

segment was pre-seismically more strongly coupled than for SE1, but its potential reactivation from a vertically propagating rupture front with little strain energy release was buffered by altered mantle peridotite. SE1 then provided sufficient strain energy release to overcome the larger fracture energy of the locked SE2 segment, resulting in super-shear rupture and termination in an adjacent weak zone (**Figure 4**, Step 5-6). Either both fault patches were sufficiently pre-seismically stressed to promote seismogenic failure[36], or the deeper SE1 rupture instantaneously increased the static stress, immediately causing the shallow SE2 portion of the fault to fail.

Observations of back-propagating ruptures along single isolated faults are sparse[37,38], although rapid tremor reversals can occur in subduction settings[39]. Our observations are supported by dynamic simulations in which the presence of a wide, low-velocity damage zones, such as those along OTFs[12,13], promotes back-propagating rupture fronts[40]. Alternatively, multiple fault strands in such a wide damage zone may also help to facilitate a reversing earthquake. Another possible explanation for the Romanche earthquake is that a cascading rupture reversal can occur when a weak nucleation phase starts in the mantle, and away from a barrier on one side of the fault. In this case, rupture directionality depends on interactions between the nucleation point, strain release history, and fracture energy variations along the fault. Whilst it has been suggested that seismogenic stresses on OTFs are highly deterministic[9-11], our result implies that OTF earthquakes, even with long-lived asperity-barrier segmentation, may resemble those of continental strike-slip earthquakes, without requiring orthogonal fault systems.

Our study implies that growing propagation in one direction may not be deterministic of a later emerging larger rupture travelling in the opposite direction. Thus, if back-propagating

193 rupture fronts occur during earthquakes along continental faults[37,38], predictions of ground
194 shaking intensity and duration, such as those made by earthquake early warning systems,
195 could be impacted.

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Author contributions

S.P.H. managed the study, carried out the mainshock and aftershock source analysis, and wrote the manuscript. R.O. computed the teleseismic slip-rate inversion, assisted with the Mach cone analysis and contributed to the manuscript. A.S. and H.S. computed the teleseismic back-projection images and contributed to the manuscript. C.R., N.H. and JMK conceived the experiment, acquired, funding, managed the project, and contributed to the manuscript. R.A carried out a preliminary teleseismic slip inversion and contributed to the manuscript. P.G. and D.S. worked on early estimates of source depth, assisted with aftershock detection and relocation, and commented on the manuscript. J.Z. assisted with the RMT inversions and contributed to the manuscript. Y.Y. and K.S. assisted with the teleseismic slip-rate inversion and commented on the manuscript.

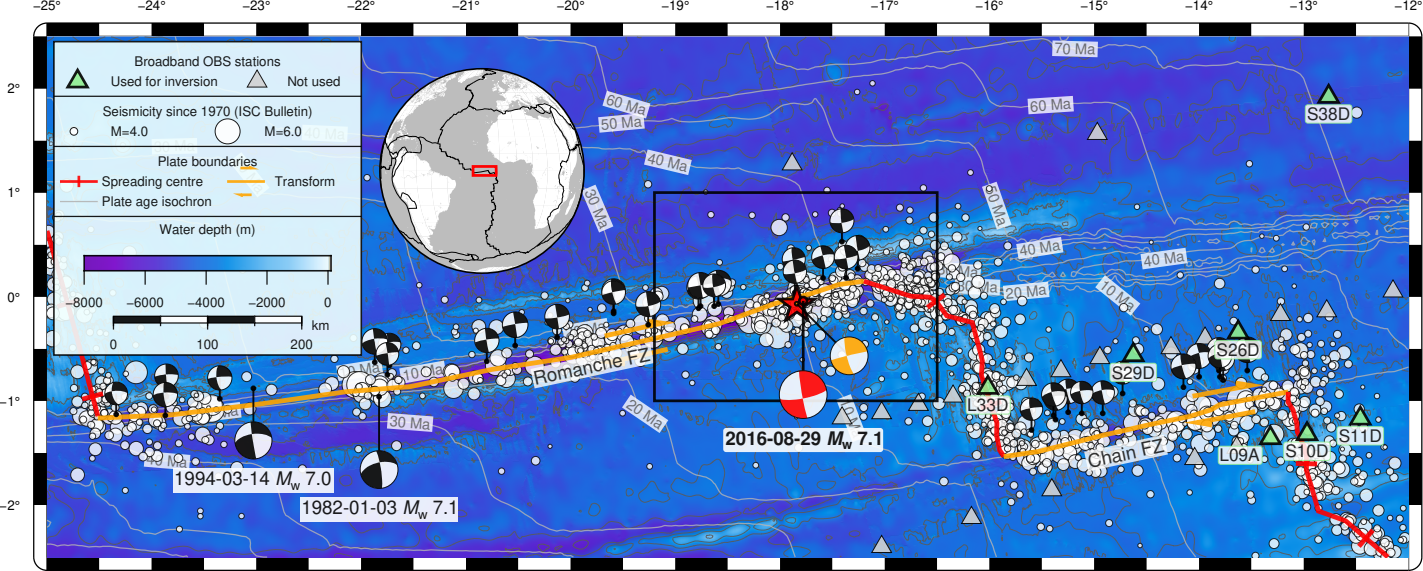
Figure captions

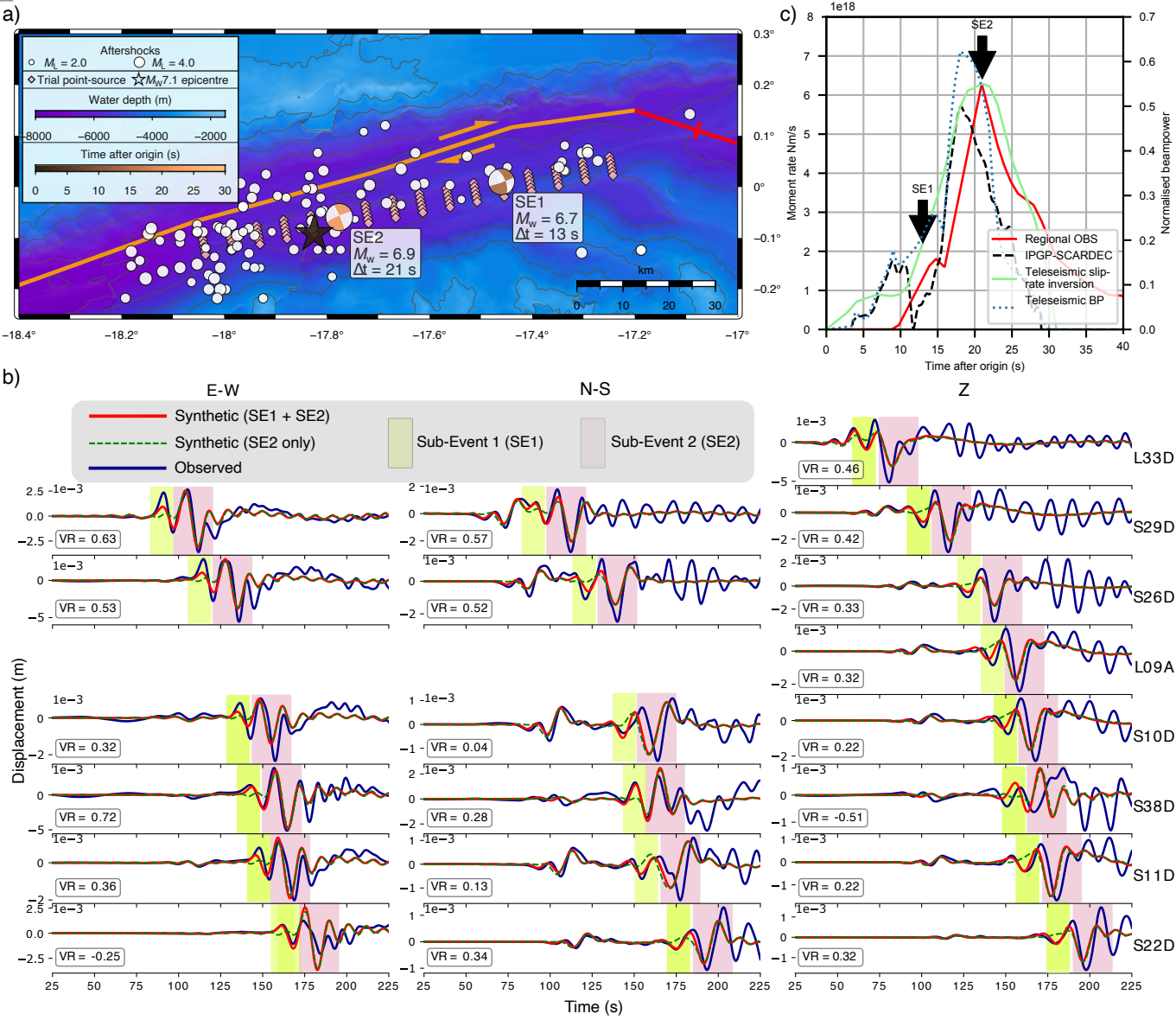
Figure 1: Seismo-tectonic context. Map location is given by the red rectangle on the inset. Focal mechanisms are shown for M_w>6 events[30]. M_w>7.0 events are labelled. Stations of the PI-LAB ocean bottom seismometer network are indicated by triangles. Our relocated hypocentre and low-frequency RMT of the 2016 earthquake are shown by the red star and red beach ball, respectively. The orange beach ball is a co-located M_w 5.8 used for Mach cone analysis. The black rectangle shows the location of map in **Figure 2**.

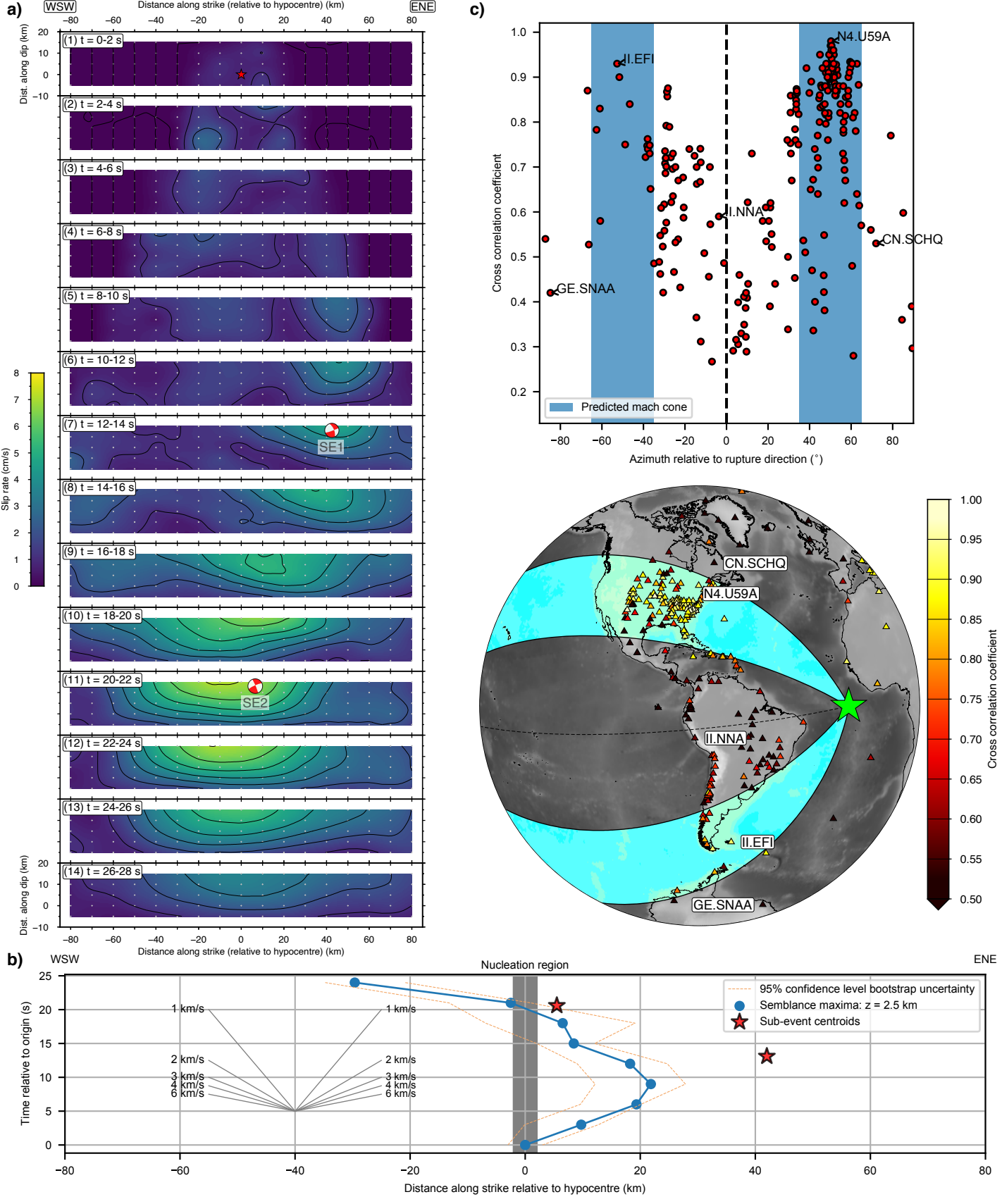
Figure 2: Multiple-point source CMT inversion using OBS waveforms. a) Hypocentral area map of the 2016 Romanche earthquake showing aftershock epicentres and sub-event RMTs coloured by centroid time. b) Waveform fits: displacement waveforms bandpass filtered between 0.01 and 0.1 Hz for multi-point source CMT inversion; shading shows the two sub-event pulses. Synthetics using SE2 are also shown. Waveform variance reduction (VR) is shown in the bottom-left of each panel. Horizontal components for L33D and L09A were removed due to clipping or non-linear tilt effects. c) Total moment-rate functions for different methodologies compared with sub-event centroid times.

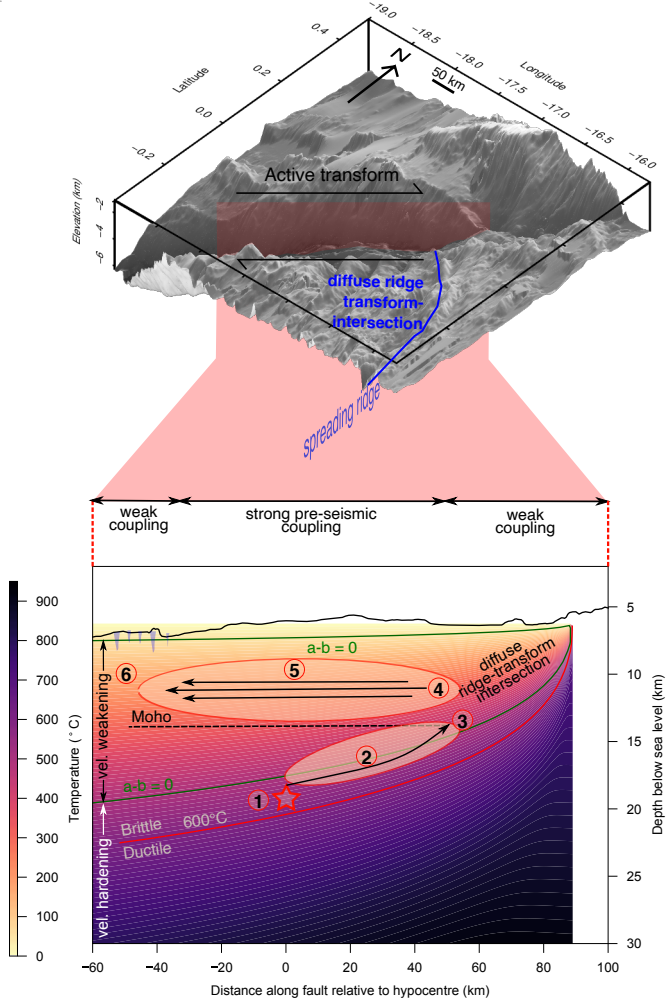
Figure 3: Teleseismic analyses. a) Slip-rate evolution over time along the fault, given in two-second interval steps (labelled in the top-left corner), from teleseismic P-wave inversion. b) Along-strike position (relative to the hypocentre) and timing of high-frequency radiators (blue circles) and estimated uncertainty, sampled at 3 s time-steps. c) Results from Rayleigh wave Mach cone analysis. Cross-correlation coefficient values plotted versus azimuth relative to rupture direction (top) in map view (bottom). The coloured region in the map indicates the estimated Mach cone area. Waveforms from labelled stations are shown in **Extended Data Figure 1**.

366 **Figure 4: Interpretation of rupture dynamics for the 2016 Romanche earthquake**. Top:
367 perspective view of bathymetry along the Romanche FZ. Bottom: interpretive cut-through
368 along the ruptured fault plane. Colours show a thermal profile based on half-space cooling.
369 The green line denotes the predicted transition between velocity-strengthening and velocity-
370 weakening frictional regimes from Gabbro data[35]. Labelled numbers show the key stages of
371 rupture evolution as follows. (1) Rupture initiation (star) in oceanic mantle. (2) Initiation
372 phase has sufficient fracture energy to propagate upwards to the locked section of fault. (3)
373 Weak sub-shear rupture front travels east in the lower crust / upper mantle. (4) Rupture
374 reaches the locked, thinner crustal segment close to the weaker ridge-transform intersection
375 (SE1). (5) Sufficient fracture energy for westwards super-shear rupture in crust along strongly
376 coupled fault segment (SE2). (6) Rupture possibly terminated by serpentinised and
377 hydrothermally-altered fault segment.


Broadband OBS stations
Used for inversion
Not used
Seismicity since 1970 (ISC Bulletin)
M=4.0
M=6.0
Plate boundaries
Spreading centre
Transform
Plate age isochron
Water depth (m)
−8000
−6000
−4000
−2000
0
0
100
200
km
Romanche FZ
Chain FZ
2016-08-29 M_w 7.1
1994-03-14 M_w 7.0
1982-01-03 M_w 7.1
S38D
S26D
S29D
L33D
S11D
S10D
L09A
70 Ma
60 Ma
50 Ma
40 Ma
30 Ma
20 Ma
10 Ma
−25°
−24°
−23°
−22°
−21°
−20°
−19°
−18°
−17°
−16°
−15°
−14°
−13°
−12°
2°
1°
0°
−1°
−2°


a)
Aftershocks
M_L = 2.0
M_L = 4.0
Trial point-source
M_W7.1 epicentre
Water depth (m)
−8000
−6000
−4000
−2000
Time after origin (s)
0
5
10
15
20
25
30
SE2
M_w = 6.9
Δt = 21 s
SE1
M_w = 6.7
Δt = 13 s
km
0
10
20
30
0.3°
0.2°
0.1°
0°
−0.1°
−0.2°
−18.4°
−18.2°
−18°
−17.8°
−17.6°
−17.4°
−17.2°
−17°
c)
1e18
SE2
SE1
Moment rate Nm/s
Normalised beampower
Regional OBS
IPGP-SCARDEC
Teleseismic slip-rate inversion
Teleseismic BP
Time after origin (s)
b)
E-W
N-S
Z
Synthetic (SE1 + SE2)
Synthetic (SE2 only)
Observed
Sub-Event 1 (SE1)
Sub-Event 2 (SE2)
VR = 0.63
VR = 0.57
VR = 0.46
L33D
VR = 0.53
VR = 0.52
VR = 0.42
S29D
VR = 0.33
S26D
VR = 0.32
L09A
VR = 0.32
VR = 0.04
VR = 0.22
S10D
VR = 0.72
VR = 0.28
VR = -0.51
S38D
VR = 0.36
VR = 0.13
VR = 0.22
S11D
VR = -0.25
VR = 0.34
VR = 0.32
S22D
Displacement (m)
Time (s)


a)
WSW
ENE
Distance along strike (relative to hypocentre) (km)
Dist. along dip (km)
(1) t = 0-2 s
(2) t = 2-4 s
(3) t = 4-6 s
(4) t = 6-8 s
(5) t = 8-10 s
(6) t = 10-12 s
(7) t = 12-14 s
SE1
(8) t = 14-16 s
(9) t = 16-18 s
(10) t = 18-20 s
(11) t = 20-22 s
SE2
(12) t = 22-24 s
(13) t = 24-26 s
(14) t = 26-28 s
Slip rate (cm/s)
c)
Cross correlation coefficient
Azimuth relative to rupture direction (°)
Predicted mach cone
N4.U59A
II.EFI
II.NNA
CN.SCHQ
GE.SNAA
Cross correlation coefficient
b)
WSW
ENE
Nucleation region
Time relative to origin (s)
Distance along strike relative to hypocentre (km)
1 km/s
2 km/s
3 km/s
4 km/s
6 km/s
95% confidence level bootstrap uncertainty
Semblance maxima: z = 2.5 km
Sub-event centroids


Latitude
Longitude
Elevation (km)
N
50 km
Active transform
diffuse ridge transform-intersection
spreading ridge
weak coupling
strong pre-seismic coupling
weak coupling
a-b = 0
diffuse ridge-transform intersection
Moho
a-b = 0
Brittle
600°C
Ductile
vel. weakening
vel. hardening
Temperature (°C)
Depth below sea level (km)
Distance along fault relative to hypocentre (km)

Methods

Data: Local OBS network

We deployed 39 broadband OBS stations in March 2016 for twelve months as part of the PI-LAB (Passive Imaging of the Lithosphere-Asthenosphere Boundary) and the EURO-LAB (Experiment to Unearth the Rheological Oceanic Lithosphere-Asthenosphere Boundary) experiments (see **Note S1** & **Data Availability**). The network centred on the Chain Fracture Zone, next to Romanche, provides good coverage of the eastern end of the Romanche OTF (**Figure S1**). Due to instrument issues at some stations, not all sensor components for each station were used in this study.

Mainshock hypocentre and aftershock relocation

For hypocentre relocation, we used a 1-D layered P-wave velocity model for the central Atlantic from CRUST1.0[41], and a constant v_p/v_s ratio of 1.71 (See **Note S2**). We used the NonLinLoc package[42] for hypocentre relocations in which we employed a travel-time dependent error, which effectively gives an epicentral distance weighting. We used true depths below sea level of the OBS stations in the relocation. The epicentre lies NW of the PI-LAB OBS network, with the closest station 130 km away. Our epicentre is located <7 km away from those of other agencies that used teleseismic arrivals alone (**Table S1**), suggesting a robust estimation of the rupture nucleation position (**Figure S2**). Although the PI-LAB OBS network offers sub-optimal coverage of the rupture area, we are confident that the hypocentre locations are sufficiently accurate to probe the seismicity distribution along the fault (**Note S3**), although depths are poorly constrained. Next, we relocated 101 aftershocks and further refined these by performing a multiple-event relocation relative to the mainshock

hypocentre (**Note S3**). We also scanned continuous waveforms at the closest three stations to find any foreshocks in the days leading up to the mainshock, but we found none within this period along the Romanche Fracture Zone. Eleven of these aftershocks are in the USGS-NEIC catalogue. See **Supplementary Data S1** for the full hypocentre and arrival time catalogue.

RMT inversion

For RMT inversion, we computed Green's functions (GF) in our layered velocity model using the discrete wavenumber method[43]. We used the ISOLA software package[23] (see **Code Availability**), which inverts for waveforms in the time domain to compute moment tensors. ISOLA searches across a prescribed grid of trial-point-sources to find the deviatoric centroid moment tensor in space and time that maximises the fit (given as variance reduction, *VR*) between synthetic and observed waveforms. We carefully chose waveforms unaffected by clipping and non-linear tilting due to the Romanche earthquake to stabilise the moment tensor solutions. We also tested the stability of inversion by jack-knifing waveform traces. We used stations located up to 700 km epicentral distance from the hypocentre of the Romanche mainshock. **Figure 1** shows the stations used for regional waveform inversion.

Based on initial CMT inversions, together with the mainshock hypocentre and the geometry of Romanche OTF from bathymetric data, we designed a grid of trial-point sources along a plane striking 75° and dipping 80° to the south-east. The origin of the plane is given as our relocated hypocentre. We placed 16 sources along-strike (spacing of 6 km), and 6 sources in the down-dip direction (spacing of 4 km); (**Figure 2**).

We first inverted for a single-point source moment tensor solution using long-period waveforms (33–100 s period; **Figure S3).** Even with the suboptimal station coverage, the

retrieved moment tensor solution is consistent with the faulting style along the Romanche FZ.

To investigate source complexity, we inverted waveforms at higher frequencies of 0.01 to 0.10 Hz. We used iterative deconvolution, which has been used extensively to probe rupture complexity at regional scales[3,44,45]. For each sub-event, we searched for length of the triangular source-time function that maximised VR. The centroid location of SE1 is better constrained than that of SE2 (**Figure S4**), which may reflect the long, fast rupture of SE2. We do not find any significant waveform pulse closer to the origin time, so we cannot robustly add a third sub-event, indicating comparatively less slip during the nucleation phase. This observation is in line with the 1994 Romanche earthquake[16]. In general, adding more than two subevents for this size of earthquake can be unstable does not improve the fit considerably[3].

To estimate an overall source-time function (STF) for the total rupture (**Figure 2c**), we inverted the waveforms in terms of 10 s long equidistantly-shifted isosceles triangle functions and apply a non-negative least square constraint (NNLS)[46]. We prescribe the CMT parameters for both sub-events as per the result above and fix the total moment.

See **Supplementary Data S2** for the optimum RMT parameters.

Teleseismic slip-rate inversion

We solved the spatio-temporal potency-density tensor distribution[25,47]. We represent slip along the fault with five-basis double-couple components so that we flexibly represent the slip vectors without forcing them to span an arbitrarily assumed model plane, which suppresses modelling errors due to the inappropriate assumption of the fault-plane

geometry[25]. At every 1 s snapshot, the slip-rate function at each source node is represented by linear B-splines. Model parameters are objectively determined by minimising Akaike's Bayesian Information Criterion (ABIC)[48], which is expected to produce solutions similar to fully Bayesian inversions[49], since we do not adopt non-negative constraints for slip vectors (positivity constraint) in our ABIC-based inversion scheme.

Vertical components of teleseismic P waveforms were obtained (see **Data Availability**; **Supplementary Data S3**) and we selected 57 stations (**Figure S5**) that cover all azimuths to capture radiation patterns, and also chose stations with high signal-to-noise ratio so we could reliably pick P-wave first motions. The instrument responses were removed and the records were converted into velocity waveforms, and then we resampled the data to one sample per second. GFs were calculated with the near-source velocity structures adopted from CRUST1.0[41]. GFs were calculated with the near-source velocity structures adopted from CRUST1.0, and the attenuation time constant t* for the P wave was taken to be 1.0 s. We did not apply any filters to both the observed waveforms and the theoretical GFs following the inversion procedure[25]. We used the model plane striking at 79° and dipping at 77° based on the procedure for our regional CMT inversion and the relocated-aftershock distribution. The model plane was discretised into a grid spanning 10 km and 5 km along the strike and dip directions, respectively. Our relocated hypocentre of the mainshock was adopted for the initial rupture point. Guided by the position and timing of the sub-events from RMT inversion, the Mach cone analysis, and the BP imaging results, we set the total rupture duration as 30 s and the maximum rupture speed at 6.0 km/s. **Figure S3** shows the resulting teleseismic P-wave fits.

Synthetic tests and experiments using different fault-plane geometries produced a similar pattern of slip to the optimum solution (**Notes S5 and S6**). The overall source-time function also compares well with that derived from OBS waveforms (**Figure 2c**). We assessed the robustness of the optimum teleseismic slip model by testing different fault geometries (up to ±10° in strike and dip). In all fault geometry configurations, the overall pattern of the slip distribution is very similar to that of the optimum model (**Note S5**). We also forward modelled waveforms from our optimum smooth solution, added Gaussian noise at a level of 1% of the signal variance, and inverted these waveforms. This synthetic test (**Figure S12**) shows that the inversion is able to retrieve the main features of the rupture in space and time.

In raw teleseismic P-waves (**Figure S5**) small pulses following the initial P-wave are visible, with a broad pulse at $\Delta t = 10$ s (SE1) particularly clear at WSW and ESE azimuths. This is followed by a larger pulse at $\Delta t = 20$ s (SE2). **Figure S5** shows the resulting teleseismic P-wave fits for our best-fitting model. The P-wave azimuthal variation of low-frequency teleseismic P-waves confirms that the larger slip patch (SE2) occurred west of the rupture nucleation (**Figure S6**).

Compared to an operational finite fault model for the 2016 Romanche earthquake from USGS-NEIC (https://earthquake.usgs.gov/earthquakes/eventpage/us20006uy6/finite-fault; last accessed June 2020), which requires low rupture velocity during the first 15 s of rupture, we found that a shallower, south-dipping fault substantially increased waveform fits at near-nodal stations.

Teleseismic back-projection imaging

We used the Palantiri software (see **Code Availability**) which clusters stations at teleseismic distances and generates virtual seismic arrays[27,50]. We calculate the travel-times between

grid-points and stations using the ak135 velocity model and stack in 12-second-long moving windows (centred on each timestep) with respect to the expected P-wave onsets using the phase-weighting method[51]. We stack waveforms with respect to normalised semblance, which is a measure of the fraction of the radiated energy released as coherent waves. Semblance has sharper resolution than beampower for low-energy radiation and is less sensitive to amplitude effects due to site terms. The semblance from all virtual arrays is combined at each 3 s timestep for a total duration of 30 s (10 timesteps). To avoid an azimuthal bias, we subdivide all azimuthal directions around the epicentre into twelve sectors. The semblance from each azimuth sector is normalized to one, so that each azimuthal sector has the same influence on the combined semblance.

Bayesian bootstrapping of array weights is used to estimate the significance of the estimated location of the semblance. This means that the semblance is combined 100 times with randomised Bayesian weights for each array and with slightly perturbed velocity models such that arrival times may vary by +/- 4s.

In total, 345 stations (see **Data Availability**; **Supplementary Data S4**) are clustered using the *k*-means algorithm into 27 virtual arrays with a maximum aperture of 5° (**Figure S13**). We use velocity waveform recordings down-sampled to 10 Hz, and to investigate the high-frequency emissions we bandpass filter between 0.2 Hz and 1.5 Hz. Stations for which waveforms have a correlation coefficient <0.6 relative to the centremost station of each virtual array are not used.

Rayleigh wave Mach cone analysis

Past theoretical and observational studies[28,29] have shown that the effect of rupture directivity on surface waves can be used to determine rupture velocity. For earthquakes

512 rupturing at velocities slower than seismic wave speed, waves from the start and end of
513 rupture arrive at a far-field receiver at variable times. However, for super-shear
514 earthquakes, at stations located on the Mach cone, the waves from different parts of the
515 rupture arrive at the same time. These simultaneous arrivals result in surface waves that are
516 highly correlated with those of a smaller, co-located earthquake with identical faulting
517 mechanism that can be viewed as a point-source at the periods considered.

518 The range of azimuths where high waveform correlation can be observed depends on several
519 factors: rupture direction, speed and duration, Rayleigh wave velocity, and frequency band.
520 Given the source duration of SE2 of ~25 s (**Figure 3c**), we can only see a significant azimuthal
521 variation in directivity factor at frequencies above the corner frequency. Therefore, we
522 bandpass filter teleseismic waveforms up to 90° epicentral distance (see **Data Availability**;
523 Source Data Fig 3c) between 10 s and 20 s period. We estimate Rayleigh wave phase velocities
524 from the GDM52 model[52]. GDM52 gives velocities at a minimum period of 25 s – a longer
525 period than that of our filtered waveforms; given the large variation in velocities along the
526 long surface wave paths (typically 40–90° distance; **Figure S14**), we choose a mean surface
527 wave velocity of 3.4 km/s for the shorter periods considered in this study. Taking a short-
528 period cut-off filter corner at 10 s, and assuming a mean along-path Rayleigh wave phase
529 velocity of 3.4 km/s, we predict a high waveform similarity - i.e. a small directivity factor - at
530 azimuths of 35–65° with respect to the rupture direction (**Extended Data Figure 2**).

531 Our Rayleigh wave Mach Cone analysis for the 1994 M_w 7.1 Romanche earthquake[16] also
532 hints at super-shear rupture (**Figure S16**).

Data availability

The facilities of IRIS Data Services, and specifically the IRIS Data Management Center (IRIS-DMC), were used for access to waveforms, related metadata, and/or derived products used in this study. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience (SAGE) Award of the National Science Foundation under Cooperative Support Agreement EAR-1851048. Additional seismic data were obtained from the GEOFON data centre of the GFZ German Research Centre for Geosciences (GFZ-GEOFON), ORFEUS/EIDA, the INGV Seismological Data Centre, and the RESIF Data Center. RESIF is a national Research Infrastructure, recognised as such by the French Ministry of Higher Education and Research. RESIF is managed by the RESIF Consortium, composed of 18 Research Institutions and Universities in France. RESIF additionally supported by a public grant overseen by the French National Research Agency (ANR) as part of the "Investissements d'Avenir" program (reference: ANR-11-EQPX-0040) and the French Ministry of Ecology, Sustainable Development and Energy.

Continuous raw seismic waveform data from the PI-LAB ocean bottom seismometer network[53] can be downloaded from IRIS-DMC (network code XS).

Continuous raw seismic waveform data from various global seismic networks used for the slip-rate inversion[54-61], back-projection[54-81], and Mach cone[54,56-60,67-70,79,82-103] analyses are available to download from the data centres named above.

Code availability

The ISOLA software used for RMT inversion is available from http://geo.mff.cuni.cz/~jz/for_ISOLAnews/ (last accessed June 2020). The Palantiri software used for teleseismic back-projection analysis is available from https://braunfuss.github.io/Palantiri/ (last accessed June 2020). We used the ObsPy package for seismic analysis[104]. Figures were made using GMT[105] and matplotlib[106].

Extended Data Figure Captions

Extended Data Figure 1: Rayleigh wave vertical displacement seismograms. Waveforms are plotted for the M_w 7.1 Romanche mainshock and M_w 5.8 co-located aftershock, for stations shown in **Figure 3b**. The top-left box indicates the network code, station name, epicentral distance, azimuth relative to rupture direction, and cross-correlation value. Stations N4.N59A and II.EFI are located in the predicted Mach cone.

Extended Data Figure 2: Predicted Mach cone. Azimuthal dependence of directivity factor (blue line) for a rupture velocity of 5.7 km/s, period of 10 s, rupture duration of 25 s and Rayleigh wave velocity of 3.4 km/s. The black-dashed line, red dashed lines, and green shaded areas demarcate azimuths where high waveform similarity between the Romanche mainshock and co-located aftershock can be found. These azimuth values correspond well to the locations where high waveform similarity is observed in the data (**Figure 3b**).

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