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Ultraslow-spread lithosphere accreted by episodic magmatism and serpentized mantle exhumation

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Mid-ocean ridges spreading at ultraslow rates of $<20 \text{ mm yr}^{-1}$ can exhume serpentized mantle to the seafloor, or they can produce magmatic crust. However, seismic imaging of ultraslow spreading centres has not been able to resolve the abundance of serpentized mantle exhumation, and instead supports 2-5 km of crust. Most seismic crustal thickness estimates reflect the depth at which the 7.1 km s^{-1} P-wave velocity is exceeded. Yet, the true nature of the oceanic lithosphere is more reliably deduced using the P- to S-wave velocity (V_p/V_s) ratio. Here, we report on seismic data acquired along off-axis profiles of older oceanic lithosphere at the ultraslow spreading Mid-Cayman Spreading Centre. High V_p/V_s ratios of >1.9 and continuously increasing P-wave velocity, changing from 4 km s^{-1} at the seafloor to $>7.4 \text{ km s}^{-1}$ at 2 to 4 km depth, indicate highly serpentized peridotite exhumed to the seafloor. Elsewhere, either magmatic crust or serpentized mantle deformed and uplifted at oceanic core complexes underlies areas of high bathymetry. The Cayman Trough provides therefore a window into mid-ocean ridge dynamics that switch between magma-rich and magma-poor oceanic crustal accretion, including exhumation of serpentized mantle to $\sim 25\%$ of the seafloor.

About 60% of the Earth's surface is oceanic crust and new seafloor is continually created along the $\sim 65,000 \text{ km}$ long mid-ocean ridge (MOR) system¹. Most oceanic crust has a relatively uniform

27 thickness, but for about 25% of MORs that spread at an ultraslow spreading rate of $<20 \text{ mm yr}^{-1}$ melt
28 supply to the ridge is thought to dramatically decrease, implying that crustal thickness should also
29 decrease². The few existing seismic studies of ultraslow spreading MORs undertaken to date reveal
30 that crustal thickness is indeed thin (2-5 km)^{2,3,4} when compared to normal oceanic crust formed at
31 slow to fast spreading rates (6-7 km)⁵. However, crust formed at ultraslow spreading rates is also
32 highly diverse in its thickness, structure, and geological composition. For example, both the Gakkel
33 Ridge and Southwest Indian Ridge (SWIR) have areas of enhanced volcanism and other areas where
34 magma-starved conditions promote exhumation of the mantle^{6, 7, 8}. Yet, seismic data, which could
35 provide a more complete view of the oceanic lithospheric structure and composition, finds little
36 evidence for magma-poor lithospheric accretion at any spreading rate^{3, 4, 5}, except in some large
37 massifs, or oceanic core complexes (OCCs), where large-scale detachment faulting⁹ exposes upper
38 mantle rocks at the seafloor¹⁰. However, many OCCs at both slow- and ultraslow spreading rates
39 comprise thick lower crustal sections^{11, 12}.

40

41 **Seismic Imaging of Oceanic Lithosphere**

42 Seismic surveys of the oceanic lithosphere find that it is generally formed via continuous magmatic
43 accretion resulting in a well-stratified crust with seismic layers 2 and 3 above the seismic Moho^{13, 14}. A
44 widely accepted model¹³ equates these seismic layers with an extrusive basaltic upper crust and
45 sheeted dyke complex (layer 2), a gabbroic lower crust (layer 3), and a well-defined crust-mantle
46 boundary. This layered seismic velocity structure and measure crustal thickness should be greatly
47 affected during magma-poor seafloor spreading as mantle is exposed to seawater and
48 serpentinization occurs. In marine seismic studies, crustal thickness is best defined when wide-angle
49 reflections from the seismic Moho are observed along reversed profiles. Alternatively, estimates may
50 be based on the depth at which the P-wave velocity exceeds $7.1\text{-}7.2 \text{ km s}^{-1}$ (3, 14, 15). Seismically, the
51 upper oceanic crust exhibits a strong velocity gradient with velocities increasing from $<4.0 \text{ km s}^{-1}$ at

the seafloor to $\sim 6.7 \text{ km s}^{-1}$ at 1.5-2.0 km depth, while the lower crust exhibits a moderate gradient and velocities of ~ 6.8 to 7.1 km s^{-1} ^(13, 14, 15). In contrast, exhumed serpentinized mantle will have a P-wave velocity that increases gradually from $\sim 4 \text{ km s}^{-1}$ at the seabed to $\sim 8 \text{ km s}^{-1}$ at depth ^{16, 17, 20}. Thus, most P-wave estimates only discriminate between magmatic oceanic crust and serpentinized mantle exhumed to shallower depths via contrasts in velocity gradients, which is likely insufficient for distinguishing between types of oceanic crust. However, serpentinites are characterized by high P- to S-wave velocity (V_p/V_s) ratios of ≥ 1.9 , compared to 1.75-1.85 in crustal rocks ^{18, 19} and so this ratio may more reliably provide a tool with which to evaluate the degree of serpentinization in the lithosphere as a whole ^{16, 18, 20}. Most seismic imaging efforts along ultraslow spreading centres have not, in general, favoured the recording of S-waves for a variety of reasons, not least of which is the lack of sediment cover hindering seismic energy conversion, and instrument coupling to the seafloor.

63

64 **Diversity of Ultraslow-Spreading Oceanic Lithosphere in the Cayman Trough**

The Mid-Cayman Spreading Center (MCSC) (Fig. 1), with its end-member ultraslow spreading rate of $\sim 15 \text{ mm yr}^{-1}$ ⁽²¹⁾, not only provides an opportunity to investigate the change from magmatic accretion to amagmatic extension over time, it also allows appraisal of the degree of serpentinization associated with the transition between the magmatic and amagmatic end-member styles of spreading.

Magnetic anomalies suggest that the MCSC has been spreading for at least 45 Myr ⁽²²⁾. Its great axial depth (5000-6000 m) and low mantle potential temperature, derived from basalt geochemical signatures, imply that the lithosphere formed from a relatively cold mantle and with a low extent of melting ²³. The bathymetry of the MCSC includes many OCCs (Fig. 1) that differ from those observed on the Mid-Atlantic Ridge ^{9, 21} in their gross morphology, but exhibit many of the same features including mixtures of gabbroic lower crustal and peridotitic mantle rocks exhumed along detachment faults ²¹. The central OCC, Mt. Dent, hosts a hydrothermal vent ²⁴ in exhumed,

77 predominantly crustal material where fluids cycle through a deep, mafic crustal root²⁵. In the deeper
78 parts of the MCSC to the north and south of Mt. Dent, basalt flows overlie zones of thin crust and,
79 potentially, zones of partial melt²⁶ that drive the world's deepest known MOR black smoker system
80 located at the northern end of the ridge²⁴. However, even in the axial region where upper crustal
81 basalts and lower crustal gabbros are found, serpentinized mantle peridotites are common²¹.

82 Off-axis in the Cayman Trough, in water depths up to 4000 m, seafloor younger than ~10 Ma also
83 hosts many bathymetric highs which we interpret to be OCCs that were internally faulted and
84 deformed, best exemplified by the massif imaged in profile P06. However, for crust older than 10
85 Ma, the seafloor is much smoother and deeper (>~4500 m).

86

87 **Seismic Signatures of Serpentinized Mantle and Magmatic Crust**

88 To investigate the extent of exhumed mantle and degree of serpentinization, and determine the true
89 crustal thickness associated with the variation between the different modes of ultraslow seafloor
90 spreading, we report the results of a wide-angle seismic survey that sampled 4-20 Ma crust along a
91 flowline crossing both conjugate MCSC ridge flanks. The profile, comprising two 90 to 110 km long
92 parts encompassing the similarly aged east and west flanks spread from the axis, was instrumented
93 with ocean-bottom seismographs (OBSs) and hydrophones (OBHs) spaced 2-7 km apart. A large
94 tuned seismic source and dense receiver coverage resulted in excellent data quality, recording both
95 P-wave onsets and P-to-S converted arrivals, representing S-waves turning throughout the crust and
96 uppermost mantle. Crustal phases (Pg, Sg) are ubiquitous and, between 10-60 km offset, mantle
97 arrivals (Pn, Sn) are observed with fast apparent Pn velocities of $>7.5 \text{ km s}^{-1}$. Travel-time picks of
98 these phases were tomographically inverted (see Methods) to reveal the detailed crustal structure
99 (Fig. 2).

100 Our modelling shows that the western ridge flank has lateral (temporal) changes in velocity structure
101 that we correlate with lithological variations associated with varying degrees of magmatism and

mantle exhumation (Fig. 3). For lithosphere older than ~10 Ma, both P- and S-wave velocities show a laterally uniform and continuous increase with depth, with the P-wave velocity increasing from 4.0 to ~7.4 km s⁻¹ and a Vp/Vs ratio >1.9. Seafloor younger than ~10 Ma shallows to <4000 m and the velocity-depth structure is more reminiscent of the layer 2-layer 3-type structure of magmatically accreted oceanic crust¹⁵ with corresponding Vp/Vs ratios of <1.9. Using the 7.1 km s⁻¹ P-wave velocity contour as indicative of the crust/mantle boundary, since the inversion approach will not generate a well-defined velocity discontinuity, and defining the mantle as having a velocity of >7.4 km s⁻¹, crustal thickness is estimated to be 3-5 km to the west of the MCSC. Thus, phases of both magmatic accretion and exhumation of serpentinized mantle occurred, each lasting on the order of ~2 Myr. The change from magmatic to amagmatic seismic structure at ~70 km from the MCSC is supported by the gravity anomaly, which has been interpreted²⁷ to reflect a change of crustal thickness at ~10 Ma. Our results suggest that the gravity low reflects exhumed and serpentinized mantle (see Methods). We interpret the 2-3 km domain sub-seabed as exhumed mantle similar to that observed at magma poor margins^{16,17,20}.

About 50 km to the west of the ridge axis a dome-like structure shallows to ~2500 m water depth and exhibits high Vp/Vs ratios along its eastern ridge-dipping flank. We interpret this dome as a fossil OCC with upper mantle material exposed by detachment faulting given the corresponding Vp/Vs ratios. Except for the core complex, the eastern conjugate ridge flank mimics the features of the western flank, although there is a distinct asymmetry in the durations of periods of magmatic vs amagmatic spreading. However, the pattern of high-low Vp/Vs ratio is more chaotic than on the western flank and, based on studies in other regions^{28,29}, is interpreted as resulting from the intrusion of gabbroic melts into the mantle, and thus OCC footwalls tend to spread to the west relative to their hanging walls²¹. The high degree of heterogeneity observed in this off-axis setting is also observed by P-wave seismic data collected along the MCSC and across the Mt. Dent hydrothermal vent field, revealing both domains of volcanic seafloor and un-roofed mantle^{25,26},

though in those instances the lack of Vs arrivals permits alternative interpretations of the abundance of magmatism relative to serpentinization.

A Local and Global Estimate of Serpentinized Mantle Abundance

Using the $V_p/V_s=1.9$ to discriminate between serpentinized mantle (≥ 1.9) and magmatically accreted crust (<1.9) (see Methods), we observe that along our profile 25% of the western flank and 20% of the eastern flank, respectively, have a $V_p/V_s > 1.9$, suggesting that serpentine is abundant and in many places exposed at the seafloor. In contrast, crust and mantle formed at fast¹⁶ and slow³⁰ spreading rates are comparatively uniform and do not support V_p/V_s ratios >1.9 (Fig. 4). Many of the domains of high V_p/V_s ratio occur in the deeper, smoother >10 -Ma-old seafloor. Other domains of high V_p/V_s occur within the rougher seafloor, such as the axial-dipping zone atop the deformed OCC in profile P06, which is otherwise underlain by crustal materials. Thus, mantle exhumation during MCSC seafloor spreading occurs both during OCC formation in association with exhumation of thicker crustal sections²⁵, but also through continuous un-roofing of the mantle. The latter, continuous mode of mantle exhumation is further characterized by seafloor that is well below the depth expected from the plate cooling trend^{22, 27} and, hence, is also marked by a depth anomaly of 500-1000 m.

The diversity of seafloor types, and especially the deep seafloor regions in the Cayman Trough strongly resemble smooth domains of other ultraslow spreading centres, such as the SWIR⁸ where predominantly exhumed, serpentinized mantle is thought to dominate, punctuated by local basalt flows and OCCs of thick lower crustal sections¹². Ultraslow spreading centres themselves reflect a quarter of the global ridge length^{1, 6}, and many of the mantle exhumation and serpentinization processes that occur along them are observed along other plate-boundary systems. There are key geochemical fluxes and biological activity associated with serpentinization³¹, yet scientific drilling and seafloor geologic mapping have not been able to produce robust measures of the amount of serpentinization along slower spreading centres³². Extrapolating from our data from the Cayman

Trough to other localities such as the SWIR and Gakkel Ridge, we estimate that ultraslow spreading centres accrete lithosphere that is up to 25% serpentinized mantle, placing a possible bound on the long-term serpentinization of ultraslow spreading centres worldwide.

Evolution from Magma-Poor to Magma-Rich Seafloor Spreading

Our geophysical observations from the Cayman Trough indicate that there are 2-10 Myr temporal variations in seafloor morphology and abundant Vp/Vs anomalies (Fig. 4). Though limited to a ~15-20 Myr history of seafloor spreading, our data also suggest that there is an evolution along the imaged flow line from relatively deep seafloor dominated by magma poor spreading conditions and serpentinized mantle, to more complexly faulted mixtures of lower crust and serpentinized mantle. The latter, more recent style of seafloor spreading, including OCC formation, typifies the active spreading centre where two areas of basaltic lavas bound regions of exhumed lower crust and serpentinized mantle. A similar structure is observed along the SWIR and much of the slow-spreading Mid-Atlantic Ridge where OCCs are thought to be indicative of mixed amounts of magmatic and tectonic extension³³. One explanation for the abundance of magma-poor ultraslow-spreading mid-ocean ridges is that passive mantle upwelling dominates over buoyant upwelling at rates $<20 \text{ mm yr}^{-1}$ ⁽⁶⁾. The diversity of the Cayman Trough lithosphere indicates that mantle upwelling can occur through either process at rates $<20 \text{ mm yr}^{-1}$ resulting in serpentinized mantle exhumation during some geologic time intervals, and delivering melt to the crust during others.

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Author Contributions

I.G., N.W.H., H.J.A.V.A., C.P. and A.D. planned the survey and obtained the funding. All co-authors contributed in collecting the data at sea and discussed results. C.P.A., I.G., and M.S. processed the data. I.G. and M.S. conducted seismic inversions and errors analysis. C.P. conducted the analysis of the gravity data. I.G. N.W.H. and C.P. wrote the paper within input from H.J.A.V.A. and all authors commented on the manuscript.

Figure 1 | Cayman Trough bathymetry and layout of seismic experiment. Location of seismic lines P05 and P06 (solid lines) and ocean-bottom-seismomographs (white circles) sampling ~4 to up to 20 Ma old seafloor. Seafloor age isochrones are approximated by broken lines and ages are given by numbers. Red ellipses indicate bathymetric highs interpreted as oceanic core complexes.

Figure 2 | Seismic results. a) Bathymetry along P06 on the western flank of the MSCS, b) V_p/V_s ratio of P06, c) P-wave velocity model, d) bathymetry along P05 on the eastern flank, e) V_p/V_s ratio of P06, and f) P-wave velocity model.

Figure 3 | P-wave properties of magmatic and amagmatic domains. a) Velocity-depth functions from magmatic domains with $V_p/V_s < 1.9$ indicating a 1-2 km thick upper crustal formation and a low gradient lower crust, b) areas with $V_p/V_s > 1.9$ show velocities gradually increasing to values too fast

284 to represent gabbroic crust. Light grey indicates young Atlantic crust¹³ and dark grey serpentinized
285 mantle found in the Tyrrhenian Sea¹⁶.

286

287 **Figure 4 | Vp/Vs ratio as a proxy for rock types and mantle serpentinization.** a) Constraints from
288 laboratory studies on P-wave and S-wave velocity of different rocks from mid-ocean ridges (see
289 Methods for data sources), b) field definition to distinguish rocks types, c) results from P06 on the
290 western ridge flank of MCSC, d) results from P05 on the eastern ridge flank of MCSC, e) P-wave and
291 S-wave velocity data from the Mid-Atlantic Ridge³⁰, and f) from crust formed at the East Pacific Rise¹⁴.

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295 **Methods**

296 *Data acquisition:* Seismic data were acquired in April 2015 in the Cayman Trough aboard the German
297 research vessel METEOR. Two profiles were shot surveying mature lithosphere across both ridge
298 flanks of the Mid-Cayman Spreading Centre. Profile P05, 105 km long, sampled the eastern ridge
299 flank, covering 4 to 20 Myr old seafloor^{21, 34}. In total, 26 ocean-bottom seismographs from GEOMAR,
300 UTIG, and the UK Ocean-Bottom Instrumentation Facility³⁵ were deployed at 2 to 5 km spacing. P06,
301 90 km long, investigated 4 to 14 Myr old lithosphere^{21, 34} of the conjugated western flank. Due to
302 limited time at the end of the survey, the profile had a larger instrument spacing of 7.5 km between
303 nine OBS. As seismic source we used a tuned airgun array with a total volume of 86 litres fired at a
304 pressure of 210 bars. All OBS recorded both P-wave and S-wave arrivals (SI Figs 1 and 2) and neither
305 P-waves nor S-waves provided any evidence for a well-defined crust/mantle boundary. However,
306 large offsets of up to 80 km and apparent velocities of 7.8 to 8.0 kms⁻¹ suggest that most OBSs
307 recorded energy turning in crust (Pg, Sg) and mantle (Pn, Sn).

308 *Seismic data analysis and inversion:* Travel times of first arrival P-waves and secondary arriving S-
309 waves have been hand-picked. In general, picking uncertainties were 20-30 ms for short-offset P-
310 waves (Pg) and reach 40 ms for far-offset P-waves (Pn) and secondary short-offset S-waves (Sg). The
311 largest uncertainties of 60 ms were assigned to far-offset S-wave mantle arrivals (Sn). For profile P05,
312 picking resulted in 14652 P-wave arrival and 5420 S-waves arrival travel times. Profile P06 provided
313 3698 P-wave and 1395 S-wave travel time picks.

314 Seismic refraction travel time data were used to derive 2-D velocity models using a seismic
315 tomography approach³⁶. The method employs a hybrid ray-tracing scheme combining the graph
316 method with further refinements utilizing ray bending with the conjugate gradients method.
317 Smoothing and damping constraints regularize the iterative inversion. A detailed description of this
318 method is given elsewhere³⁶. Picking errors and starting velocity models may control inversion
319 results. We therefore chose a nonlinear Monte Carlo-type error analysis to derive model

uncertainties (SI Figs 3 and 4). The approach consists of randomly perturbing the velocity values of an initial average 1-D model to create a set of 100 2-D reference models³⁷ for both P- and S-waves. Profile P05 provided an rms misfit of 36-48 ms for the P-wave and 49-73 ms for the S-wave inversions. Profile P06 had slightly larger rms misfits of 65-78 ms for the P-wave and 59-120 ms for the S-wave models. For each model, we applied a top-to-bottom layer stripping approach and only five iterations were required to exceed a χ^2 threshold of 1. The mean deviation of all the solutions was then used as a measure of the model parameters uncertainty³⁸. The ray coverage of the models is represented by the derivative weight sum (DWS), which is a measure of the linear sensitivity of the inversion³⁹. To obtain the uncertainty in the Vp/Vs ratio, we randomly combined the 100 different P-waves and S-waves, obtained Vp/Vs ratios, and calculated the rms error.

Vp/Vs ratio: Any interpretation of P-wave velocity with respect to lithology is tenuous. Generally, crustal material is interpreted to have a velocity of $\sim 4 \text{ km s}^{-1}$ at the seafloor^{13, 14} increasing to 7.1 km s^{-1} at the base of the oceanic crust^{14, 19}. However, serpentinized mantle may have a seismic velocity of 4.5 km s^{-1} for highly serpentinized mantle decreasing to $\sim 8 \text{ km s}^{-1}$ for dry mantle^{18, 19} a range overlapping with crustal-type velocities. S-wave velocity and hence Vp/Vs ratio can be used to discriminate between different rock types. Both basalts and gabbros generally have Vp/Vs ratios of < 1.9 ^(ref 40-46) while serpentinized mantle generally has much higher Vp/Vs ratios ^(ref 45-49) (Fig. 4a) ranging, for low-temperature alteration and the formation of Lizardite, from ~ 1.8 for very low degrees of alteration to ratios of > 2.1 ^(ref 18). Consequently, the Vp/Vs ratio is a useful tool, or proxy, to distinguish mantle and crustal-derived lithology's, when considered in concert with both the P-wave and S-wave velocity lateral and vertical variation within a model space (Fig. 4a).

Gravity data analysis: Gravity data were recorded along all seismic lines using a Lacoste & Romberg Micro-G sea-air gravimeter. The calculated free-air anomaly (FAA) was tied to absolute gravity reference stations in Jamaica and Guadeloupe. For modelling, the seismic tomography P-wave velocity model was converted to a block density model using velocity contours and matching standard velocity-density relationships suited to the oceanic crust (SI Fig. 5), with the FAA in the

346 127.21 km ridge-axis gap between profiles P05 and P06 derived from satellite altimeter data⁵⁰, to
347 enable crustal structure determination for current spreading conditions. The combined ship and
348 satellite FAA was modelled using a polygon approach⁵¹, and only in areas of little ray coverage at
349 model extremities did any seismic model-derived block geometry require adjustment to achieve a
350 good anomaly fit. Individual block density variations across-axis, distinguishable within seismic model
351 velocities resolution, match interpreted patterns of seabed lithology, with magmatic and magma
352 poor periods clearly correlated.

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403 Data availability.

404 The seismic data used in this study will be made available at the Academic Seismic Portal at UTIG
405 (www-udc.ig.utexas.edu/sdc), the World Data Center PANGAEA (www.pangaea.de), and the British
406 Oceanographic Data Centre (www.bodc.ac.uk) or can be requested from I.G.
407 (igrevemeyer@geomar.de).

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1 **Supplementary Information Figure 1 | Data example from the eastern ridge flank.** Reduced record
2 section of seismic station no. 519 from profile P05.

3

4 **Supplementary Information Figure 2 | Data example from the western ridge flank.** Reduced record
5 section of seismic station no. 608 from profile P06.

6

7 **Supplementary Information Figure 3 | Results and associated errors of P05.** a) Average P-wave
8 velocity model derived from Monte Carlo inversion of 100 input models, b) average S-wave velocity
9 model derived from Monte Carlo inversion of 100 input models, c) rms error associated with the P-
10 wave analysis, d) rms error associated with the S-wave analysis, e) ray coverage of the P-wave model
11 as expressed by the derivative weight sum (DWS)³⁹, f) ray coverage of the S-wave model as expressed
12 by the DWS, g) average of Vp/Vs ratio obtained from 100 random combinations of P-wave and S-
13 wave models, and h) rms error associated with the Vp/Vs ratio.

14

15 **Supplementary Information Figure 4 | Results and associated errors of P06.** a) Average P-wave
16 velocity model derived from Monte Carlo inversion of 100 input models, b) average S-wave velocity
17 model derived from Monte Carlo inversion of 100 input models, c) rms error associated with the P-
18 wave analysis, d) rms error associated with the S-wave analysis, e) ray coverage of the P-wave model
19 as expressed by the derivative weight sum (DWS)³⁹, f) ray coverage of the S-wave model as expressed
20 by the DWS, g) average of Vp/Vs ratio obtained from 100 random combinations of P-wave and S-
21 wave models, and h) rms error associated with the Vp/Vs ratio.

22

23 **Supplementary Information Figure 5 | Results from gravity modelling.** a) Bathymetry, b) satellite-
24 derived gravity field⁵⁰ c) unfiltered shipboard gravity data compared to satellite-derived gravity, d)
25 key iso-velocity contours used to guide gravity modelling, e) seismic velocity models at P06 (left) and
26 P05 (right), f) density model derived from seismic velocity data, and g) fit of the calculated to the
27 recorded gravity field.