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Short Communication

A mafic and partially metamorphic lower crust of Mars revealed by geophysical integration

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The composition of the Martian crust is fundamental for understanding planetary differentiation, tectonic regimes, and habitability. Both China and the United States are planning Mars Sample Return missions around 2030, which will provide unprecedented opportunities to study Martian materials directly. In the mean time, current constraints on crustal composition come largely from orbital and rover-based analyses of surface rocks [1], leaving the deep crust—critical for planetary evolution—virtually unconstrained, despite recent orbital remote sensing detections of feldspar-rich, possibly anorthositic, rocks that may represent part of the lower crust exposed by the impact that formed the Argyre Basin [2].

Seismic velocity and bulk density of medium are key parameters derived from geophysical observations and act as primary proxies for subsurface rock composition. On Earth, laboratory studies have established robust empirical links between lithology and velocity-density pair, most notably Birch's Law [3]. The law represents an empirical linear relationship between compressional-wave velocity (V_P) and density observed in most terrestrial crustal and mantle rocks. For Mars, seismic data provide velocity and density constraints at depth, but these parameters alone cannot uniquely resolve lithology. Laboratory rock physics, in contrast, directly links velocity–density to lithology [4]. Integrating the two approaches bridges this gap, enabling more robust identification of the Martian lower crust (Texts S1–S3 online).

We validate this integration using the Australian Seismological Reference Model (AuSREM), which integrates diverse geophysical constraints across Australia (Text S4 online) [5]. The nearly identical slopes (3.05 for Birch's Law versus 2.91 for AuSREM) in Fig. 1 show that seismically inferred trends closely follow laboratory measurements across a wide range of rock types. This confirms that seismic observations can reliably serve as proxies for crustal lithology, providing a basis for their direct application to the Martian lower crust. Having established the method's robustness on Earth, we next apply it to Mars using seismic data from the InSight mission.

The InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission deployed the first seismometer on Mars and has provided critical constraints on seismicity and crustal velocities and bulk densities [6], which are not available for the Moon due to the lower precision of the Apollo-based lunar models (Text S5 online). The InSight-based seismic models [7] incorporate many more high-quality body-wave phase picks, providing improved constraints on Mars's internal structure (Fig. S1 online). The derived P-wave velocities and densities align with phase equilibria calculations in the CFMASNa ($CaO–FeO–MgO–Al_2O_3–SiO_2–Na_2O$) system.

To interpret these velocity–density values in terms of crustal lithology of Mars, we draw on a global rock physics database spanning over 40 years of laboratory measurements [4]. This dataset covers P-wave velocities and densities of most major terrestrial rock and mineral types across igneous, metamorphic, and sedimentary lithologies. Given that the crust of Mars is relatively cold (−10–45 °C at a depth range of 30–60 km) [8], with lower-crustal pressure of 300–500 MPa, we adopt measurements at 25 °C and 400 MPa as compiled in Tables 2.3 and 2.4 of Ref. [4]. At lower crustal depths, elevated confining pressures likely result in minimal porosity, so their influence on seismic velocity can be neglected [9].

Using seismic constraints on Mars and the terrestrial rock database, we identify candidate lithologies for its lower crust by

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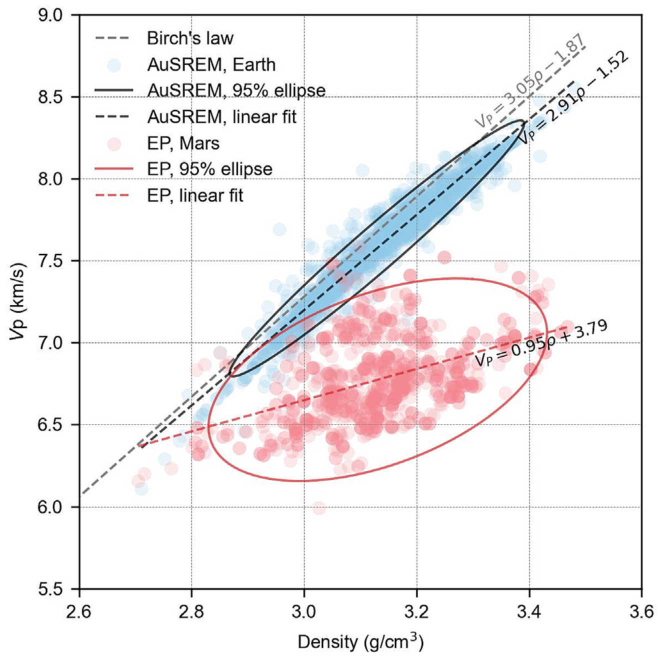

Fig. 1. P-wave velocity–density distributions for Mars and Earth. Red dots represent the velocity–density pairs from models of Mars's interior derived from InSight data, with a red 95% confidence ellipse and a red dashed best-fit line. Blue dots show AuSREM Earth lower-crust data with a black ellipse and dashed fit.

statistically matching P-wave velocities and densities (Fig. S2 online). P-wave velocity and density pairs from the inverted models are used to construct a 95% confidence ellipse in $V_P - \rho$ space, defining the plausible range for the lower crust of Mars. We then screen the global terrestrial rock physics database for samples within this envelope, yielding terrestrial rocks with compatible properties. Based on lithologies in this subset, we infer the most probable rock types that comprise the lower crust of Mars.

With the candidate lithologies identified, we then examine the velocity–density trend of the lower crust of Mars. The 1000 P-wave velocity–density pairs (red symbols in Fig. 1) yield a best-fitting linear slope of 0.95, nearly three times lower than the Earth-based values, indicating the crustal properties of Mars fundamentally differ from Earth's.

We then apply the 95% confidence ellipse (red in Fig. 1) to filter plausible lithologies for the lower crust of Mars. Screening 6672 laboratory-measured terrestrial rock samples against this envelope yields 1628 matches. The top 21 rock types account for ~70% of these samples, with the top five—basalt, amphibolite, diabase, metagabbro, and gabbro—collectively comprising ~37% (Fig. 2a). Focusing on these five rock types highlights the strongest matches while avoiding overinterpretation.

Examining the velocity–density distributions of these five rock types (Fig. 2b–f), basalt yields the largest number of matches (218 samples), though coverage across the Martian envelope is uneven. Diabase, a shallow-intrusive mafic rock, also matches well but is not uniformly distributed in the ellipse. Amphibolite, metagabbro, and gabbro align closely with the confidence ellipse, collectively spanning much of the Martian velocity–density space.

The closest matches are gabbro, metagabbro, and amphibolite—rocks produced by magmatic underplating and fluid-assisted metamorphism of mafic intrusions (Fig. 2). Their predominance indicates that the lower crust of Mars is chiefly mafic, mainly formed through magmatic accretion at depth [9]. The potential presence of metamorphic lithologies is consistent with the penetration of primitive water into the Martian crust suggested by seismic investigations [10], and with the high geothermal gradients of the Noachian [11], which could have favored water–rock interactions at depth. Amphibolite-facies metamorphism of intrusive rocks under such conditions would have yielded a lower crust that is mafic yet partially metamorphosed. The absence of felsic lithologies among the best-fitting candidates suggests limited crustal recycling and differentiation, underscoring a fundamental difference in the tectonic evolution of Mars and Earth.

Mars exhibits a distinct velocity–density slope compared with Earth, reflecting fundamental differences in tectonic regime. This difference is not due to pressure variations: although higher pressures increase both seismic velocity and density, they do not alter the linear slope of the velocity–density relationship. On Earth, active plate tectonics drives extensive crustal differentiation and

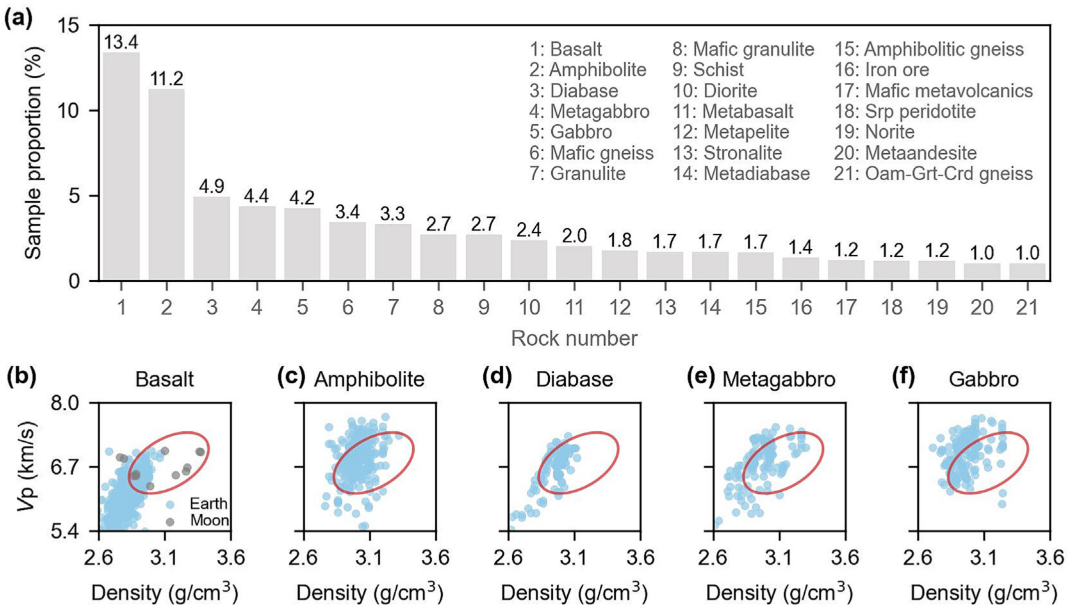

Fig. 2. Candidate lithologies of the lower crust of Mars. (a) The top 21 rock types whose experimental P-wave velocity and density pairs fall within the 95% confidence ellipse derived from Martian seismic models. (b–f) Velocity–density distributions for the five most abundant lithologies: basalt, amphibolite, diabase, metagabbro, and gabbro. Blue dots represent experimental data from Earth samples; the red ellipse indicates the 95% confidence range for the lower crust of Mars. Lunar basalt data (grey dots) are included in panel (b).

recycling, producing a steep slope (~3.0). In contrast, the absence of plate tectonics on Mars results in a mild slope (~0.95), indicating limited crustal differentiation. This contrast suggests that velocity–density scaling can serve as a proxy for tectonic regimes on rocky planets.

By analogy, the mild velocity–density slope of Mars's crust may provide insights into the composition of Earth's earliest lower crust, which remains largely unknown. While the modern lower crust is debated, with models ranging from mafic primitive basalts [12] to more evolved intermediate to felsic andesitic-dacitic compositions, virtually no direct record exists for Earth's first 500 million years [13]. Understanding this early crust is critical because the Hadean marks a period of profound planetary transformations. The pronounced difference in velocity–density scaling between Mars and Earth (~0.95 vs. ~3.0) likely reflects fundamental differences in tectonic regime, highlighting Birch's law slope as a geophysical proxy for identifying tectonic states on rocky planets. By analogy, Earth's primordial crust was probably mafic and weakly differentiated, forming above a convecting magma ocean in a pre-plate tectonics state, broadly resembling other inner planets [14]. Subsequent crustal recycling and differentiation under plate tectonics produced the more evolved structure observed today.

This framework elevates Birch's law slope from an empirical relation to a diagnostic of tectonic regime, reshaping the interpretation of geophysical observations across the Solar System and providing a new perspective on the evolution and potential habitability of rocky exoplanets driven by internal geological processes.

In conclusion, combining seismic constraints from Mars with a global rock physics database reveals a velocity–density scaling of ~0.95, with a far milder slope than that of modern Earth, defined by Birch's Law (~3.0). This trend for Mars reflects a mafic, partially differentiated lower crust composed of gabbro and subordinate metamorphic rocks, preserved in the absence of plate tectonics and offering an analogue for Earth's primordial crust. By contrast, Earth's steep modern slope records extensive crustal recycling and differentiation under active plate tectonics. The apparent difference in velocity–density scaling between Mars and Earth highlights Birch's law slope as a diagnostic proxy for tectonic regime on rocky planets, providing a framework to interpret planetary evolution and generating testable hypotheses for forthcoming Mars Sample Return missions.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Weijia Sun collected and refined the seismic models and compiled the global rock physics database. Weijia Sun, Hrvoje Tkalčić, and Liang Zhao extended the terrestrial velocity–density–lithology relationship to Mars. Marco G. Malusà and Shun Guo interpreted the crustal compositions. Yongxin Pan conceptualized and supervised the study. All authors discussed the results and contributed to the writing and revision of the manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2026.02.007.

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