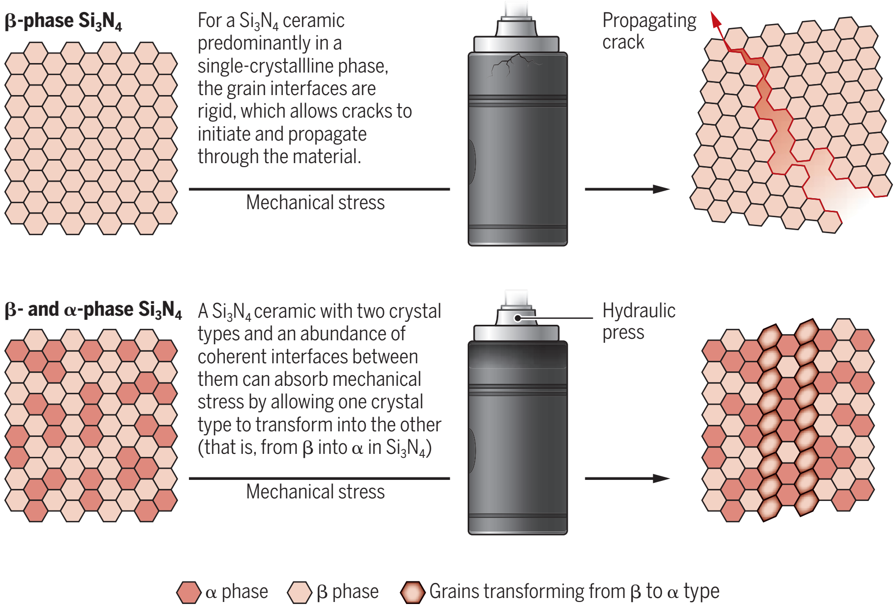
The stress-strain behavior of Si_3N_4 ceramics

The ceramic material silicon nitride (Si_3N_4) can be engineered to possess plasticity and strength comparable to that of high-strength steel. This surprising property can be attributed to how its two main types of crystals interact when the material is under mechanical stress.



crystals only happens one way and not the other way around. These transformations allow changes to the macroscopic shape of the material without fracture.

Synthetic Si_3N_4 has been used in industrial and commercial applications for almost a century (*9*), for example, in cutting tools, bearings, and combustion engine components (*10*, *11*). One specific application of Si_3N_4 is the microshutters used by the near-infrared spectrometer instrument on board the James Webb Space Telescope (*12*). For these applications, Si_3N_4 is used primarily because of its balance of properties: It is lightweight, durable, and resistant to high temperatures. A ductile version of this already versatile material will usher in a host of new applications. However, it is worth noting that the samples tested by Zhang *et al.* are at the nanoscale and thus free of any macroscopic flaws. However, if the synthesis process is scaled up, the material may form pores and cracks that would make the material more susceptible to fracture initiation.

There is a long road ahead before the full potential of ductile ceramics is realized. However, considering the apparent scarcity of plastic ceramics at room temperature, each discovery of a plasticity mechanism should be regarded highly. A scaled-up, ductile ceramic material would offer a versatile and economically attractive alternative to metals in many applications, for example, by reducing the weight of machine components; increasing machinery uptime with higher wear, fatigue, and corrosion tolerance; and increasing the energy efficiency of thermal power engines by allowing them to run at higher temperatures. Future studies should investigate whether bulk Si_3N_4 gains similar benefits from the stress-induced microstructural transformations as ZrO_2 and whether the required coherent interfaces remain stable at temperatures and process conditions that are relevant for practical applications. How to control the number of coherent interfaces and process flaws in a bulkier material will also need to be clarified. Although ceramics are already a tremendously important group of functional materials, without plasticity, their full potential remains untapped. ■

REFERENCES AND NOTES

1. P. W. Bridgman, *Studies in Large Plastic Flow and Fracture* (Harvard Univ. Press, 1964).
2. J. Zhang *et al.*, *Science* **378**, 371 (2022).
3. M. Soleimani, A. Kalhor, H. Mirzadeh, *Mater. Sci. Eng. A* **795**, 140023 (2020).
4. B. D. Flinn, A. J. Raigrodski, L. A. Mancl, R. Toivola, T. Kuykendall, *J. Prosthet. Dent.* **117**, 303 (2017).
5. R. C. Garvie, R. H. J. Hannink, R. T. Pascoe, *Nature* **258**, 703 (1975).
6. G. A. Gogotsi, V. P. Zavada, M. V. Swain, *J. Eur. Ceram. Soc.* **15**, 1185 (1995).
7. A. Liens *et al.*, *Acta Mater.* **183**, 261 (2020).
8. J. Chevalier, L. Gremillard, A. V. Virkar, D. R. Clarke, *J. Am. Ceram. Soc.* **92**, 1901 (2009).
9. F. L. Riley, *J. Am. Ceram. Soc.* **83**, 245 (2000).
10. H. Klemm, *J. Am. Ceram. Soc.* **93**, 1501 (2010).
11. N. R. Katz, *Ceram. Ind.* **149**, 33 (1999).
12. M. J. Li *et al.*, in *Proceedings SPIE*, vol. 6687, H. A. MacEwen, J. B. Breckinridge, Eds. (Paper 668709, Society of Photo-Optical Instrumentation Engineers, 2007).

10.1126/science.ade7637

PLANETARY SCIENCE

A seismic meteor strike on Mars

A meteor impact and its subsequent seismic waves reveal the crustal structure of Mars

By **Yingjie Yang** *and* **Xiaofei Chen**

The crustal and mantle structures of a planet bear important information about its origin and evolution. Seismic waves propagating along the shallow surface of a planet, known as surface waves, can be used to map its crustal and upper mantle structures. However, no such waves have ever been detected on any planet besides Earth. On pages 412 and 417 of this issue, Posiolova *et al.* (*1*) and Kim *et al.* (*2*), respectively, report a large meteorite impact on Mars, as recorded by the National Aeronautics and Space Administration's (NASA's) InSight Mars lander and the Mars Reconnaissance Orbiter, and present analysis of the detected surface waves produced by the meteorite impact. Kim *et al.* also present an updated crustal model of Mars that provides a better understanding of the formation and composition of the martian crust and extends the current knowledge of the geodynamic evolution of Mars.

There are two types of seismic waves generated by quakes. Body waves travel into the deep interior of a planet and are useful for extracting information about the core and deep mantle. Then there are surface waves, which are most useful for mapping the shallower structures of a planet. The main task of the InSight lander (which stands for Interior Exploration using Seismic Investigation, Geodesy and Heat Transport) is to detect marsquakes and capture seismic data for studying the internal structure of Mars. Since February 2019, the seismometer deployed by InSight has recorded more than 1300 marsquakes, proving that Mars is a seismically active planet (*3*). The collected body wave data suggest that Mars has a layering structure similar to that of Earth, having a

Department of Earth and Space Sciences, Southern University of Science and Technology, Shenzhen, Guangdong, China. Email: yangyj@sustech.edu.cn

GRAPHIC: A. FISHER/SCIENCE

core radius of ~1830 km (*4*), a mantle thickness of ~1500 km (*5*), and a crust thickness of ~20 to 70 km (*6*).

Mars has a notable diversity of topographical features and crustal thicknesses (*7*). Better measuring of these variations is crucial to unravel the mysteries about the evolution of the martian crust and mantle. Because the InSight lander is the only seismometer on Mars, imaging the variations of the planet's internal structures based on body waves is limited. Because body waves from distant sources travel through paths deep inside the planet and arrive nearly vertically beneath the seismometer, it is difficult to infer the spatial variations of martian internal structure. By contrast, surface waves that travel through the planet's crust and upper mantle arrive at the seismometer horizontally, which makes it much easier to map the lateral variations of the martian crust and upper mantle.

Meteorite impacts on Mars are common, with ~200 impacts each year. On 24 December 2021, the InSight lander recorded a seismic event. By examining images of the martian surface from the Mars Color Imager onboard the Mars Reconnaissance Orbiter, Posiolova *et al.* identified a crater with a diameter of 150 ± 10 m that was created within a 24-hour window of the recorded seismic event (see the figure). They analyzed the data and confirmed that the recorded seismic event can be traced back to the location of this crater, thus concluding that the recorded seismic event was the result of a meteorite impact. This confirmation validates the method used to analyze the data from a single seismometer for locating the sources of marsquakes (*8*, *9*), which is a critical step in mapping the interior structure of Mars.

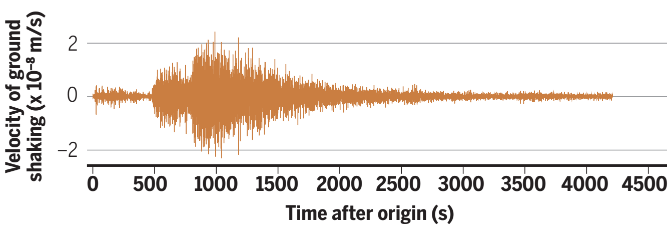
The meteorite impact on the surface of Mars generated both body and surface waves. Kim *et al.* analyzed the waveform features of the recorded body and surface waves on Mars on the basis of what is known about earthquakes. Surface waves generated by large earthquakes are observed at periods ranging from several seconds to minutes. Because of this broad range of surface wave periods, information about crustal and upper mantle structures can be extracted up to a few hundred kilometers deep. By comparison, the surface waves generated by the impact on Mars have a shorter and narrower period range because of the relatively weak force generated by the impact, which meant that the data could only reveal the structure of a shallower portion of the crust. Kim *et al.* measured the surface waves to have a period of 8 to 15 s, which translates to an imaging depth of ~30 km. Their result indicates that surface waves traveled faster between the impact crater and the InSight lander site than at the lander site. The speed difference means that the crust between the crater and the lander site is denser than that at the lander site itself and provides evidence for structural variations in the martian crust. Topography and gravity data of Mars are currently used to infer the large-scale crustal thickness of Mars. However, such an inference depends heavily on the presumption of a uniform crustal density (*10*). The seismic model reported by Kim *et al.* offers a more sophisticated way to understand the crustal structures of Mars, which should be considered in future topographical and gravitational analyses.

The north-south difference in the topography and morphology of Mars, with lowlands in the north and highly dense cratered highlands in the south, is the most pronounced geologic feature of the Red Planet. The reason behind this dichotomy is still under debate, with competing hypotheses including giant impact–related exogenic processes (*11*) and mantle convection–related endogenic models (*12*, *13*). A more granular understanding of deep crust and upper mantle structures would help discern the competing hypotheses on the geodynamic evolution of Mars. Recent development in seismic data processing suggests that long-period surface waves can be retrieved from single-station autocorrelation of seismic ambient noises (*14*, *15*), which are tiny ground vibrations excited by sources such as wind vortices and ocean waves on Earth. On Mars, seismic ambient noise excited by wind vortices may contain weak signals of long-period surface waves. The 3+ years of single-station seismic ambient noise data recorded by the Insight lander may be used to extract information about long-period surface waves on Mars. Additionally, surface waves excited by individual marsquakes may be too weak to be meaningfully analyzed, but the stacking of data collected from multiple marsquakes may enhance their statistics.

The InSight lander is expected to end its operation by December 2022 because of dust accumulation on its solar panels. However, continuing work on the already recorded seismic data should continue to deliver discoveries about the structure of Mars. Future exploration missions to Mars, such as ExoMars headed by the European Space Agency and Tianwen headed by the China National Space Administration, are expected to be launched with more advanced seismometers. With additional data from these missions, a more detailed map of crustal and upper mantle structure can be produced to paint a clearer picture of the crustal and mantle evolution of Mars. ■

Seismic waves on Mars

On 24 December 2021, the InSight Mars lander recorded, for the first time ever, a seismic surface wave on Mars generated by a meteor strike. The data revealed previously unknown structural details of the martian crust.



A Mars-shaking impact

A satellite image of the meteor impact site was captured by the Mars Reconnaissance Orbiter. The dark streaks radiating away from the crater were caused by the supersonic speed of the impact.

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REFERENCES AND NOTES

1. L. V. Posiolova *et al.*, *Science* **378**, 412 (2022).
2. D. Kim *et al.*, *Science* **378**, 417 (2022).
3. D. Giardini *et al.*, *Nat. Geosci.* **13**, 205 (2020).
4. S. C. Stähler *et al.*, *Science* **373**, 443 (2021).
5. A. Khan *et al.*, *Science* **373**, 434 (2021).
6. B. Knapmeyer-Endrun *et al.*, *Science* **373**, 438 (2021).
7. M. T. Zuber, *Nature* **412**, 220 (2001).
8. M. Böse *et al.*, *Phys. Earth Planet. Inter.* **262**, 48 (2017).
9. J. F. Clinton *et al.*, *Phys. Earth Planet. Inter.* **310**, 106595 (2021).
10. M. T. Zuber *et al.*, *Science* **287**, 1788 (2000).
11. M. M. Marinova, O. Aharonson, E. Asphaug, *Nature* **453**, 1216 (2008).
12. S. Zhong, M. T. Zuber, *Earth Planet. Sci. Lett.* **189**, 75 (2001).
13. J. H. Roberts, S. Zhong, *J. Geophys. Res.* **111**, E06013 (2006).
14. M. Schimmel, E. Stutzmann, S. Ventosa, *Seismol. Res. Lett.* **89**, 1488 (2018).
15. J. Xie, S. Ni, *Seismol. Res. Lett.* **90**, 708 (2019).

10.1126/science.add8574

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Yingjie YangXiaofei Chen

Science, 378 (6618), • DOI: 10.1126/science.add8574

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