



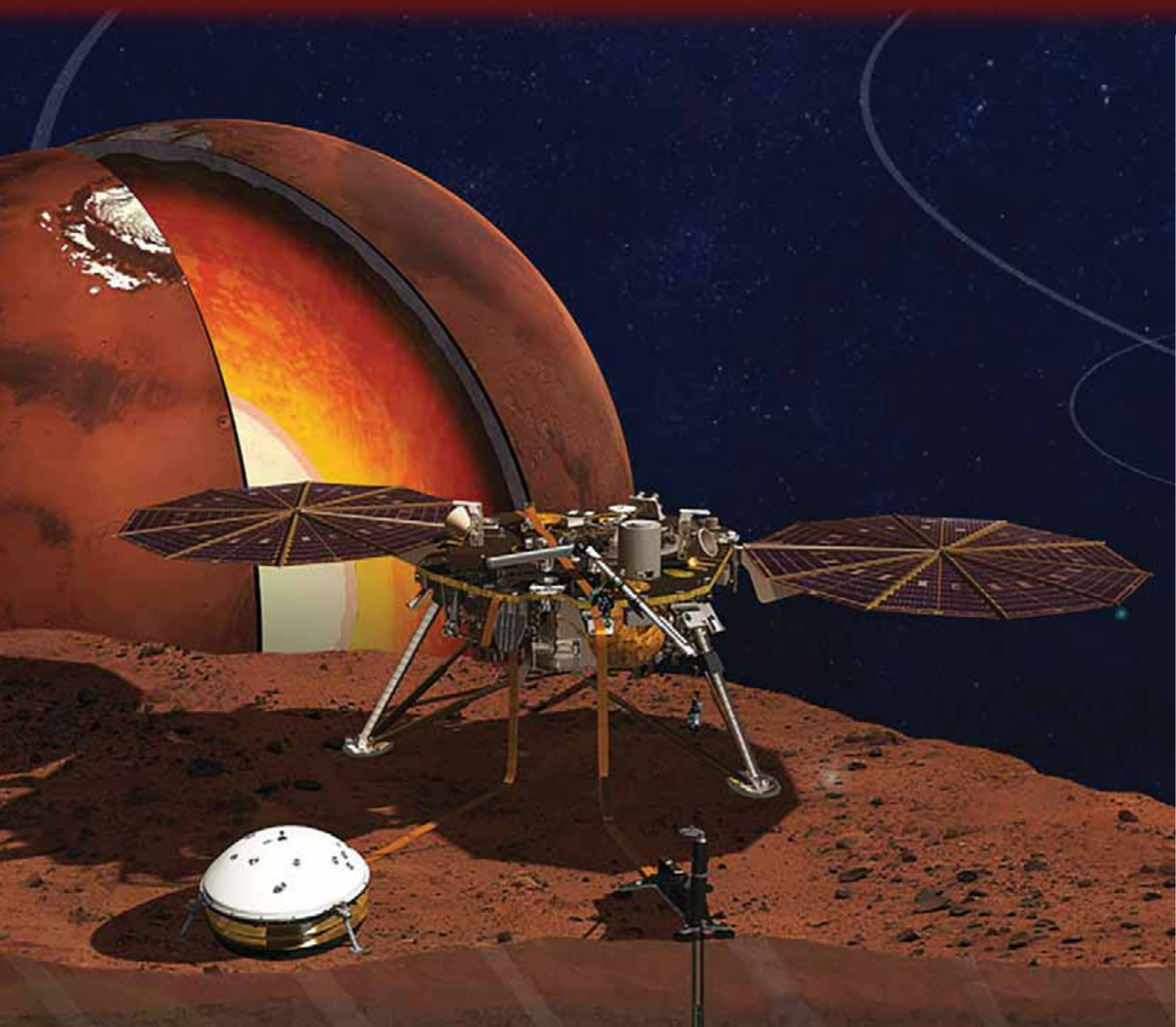
British  
Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL



InSight

# MarsQuake



[www.bgs.ac.uk/marsquake](http://www.bgs.ac.uk/marsquake)

Seismology on another planet





# MarsQuake

Seismology on another planet



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Cover image: NASA

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# Introduction

## Learning about 'marsquakes' and their effects

The MarsQuake project provides a set of teaching resources and classroom activities that can use real data and images sent back from the 2018 NASA InSight mission to Mars.

Aimed at 11–18 year-olds (KS 3, 4 and 5), these activities include modelling and locating meteorite impacts, or marsquakes, which will help us understand more about the internal structure of the 'red planet'.

The InSight lander will deploy two seismometers that will send live data back to Earth. It offers our first chance to look at extra-terrestrial quake data since the Apollo moon missions of the 1960s and 1970s.

Data from InSight's seismometers will be transmitted back to Earth and will be freely accessible online. The mission is expected to last at least a year and should send back a continuous stream of data for scientists, and students, to analyse.

### Practical classroom activities

The activities relating to MarsQuake are online at [www.bgs.ac.uk/marsquake](http://www.bgs.ac.uk/marsquake) and involve a mixture of real data from Mars and simple classroom simulations. The activities include:

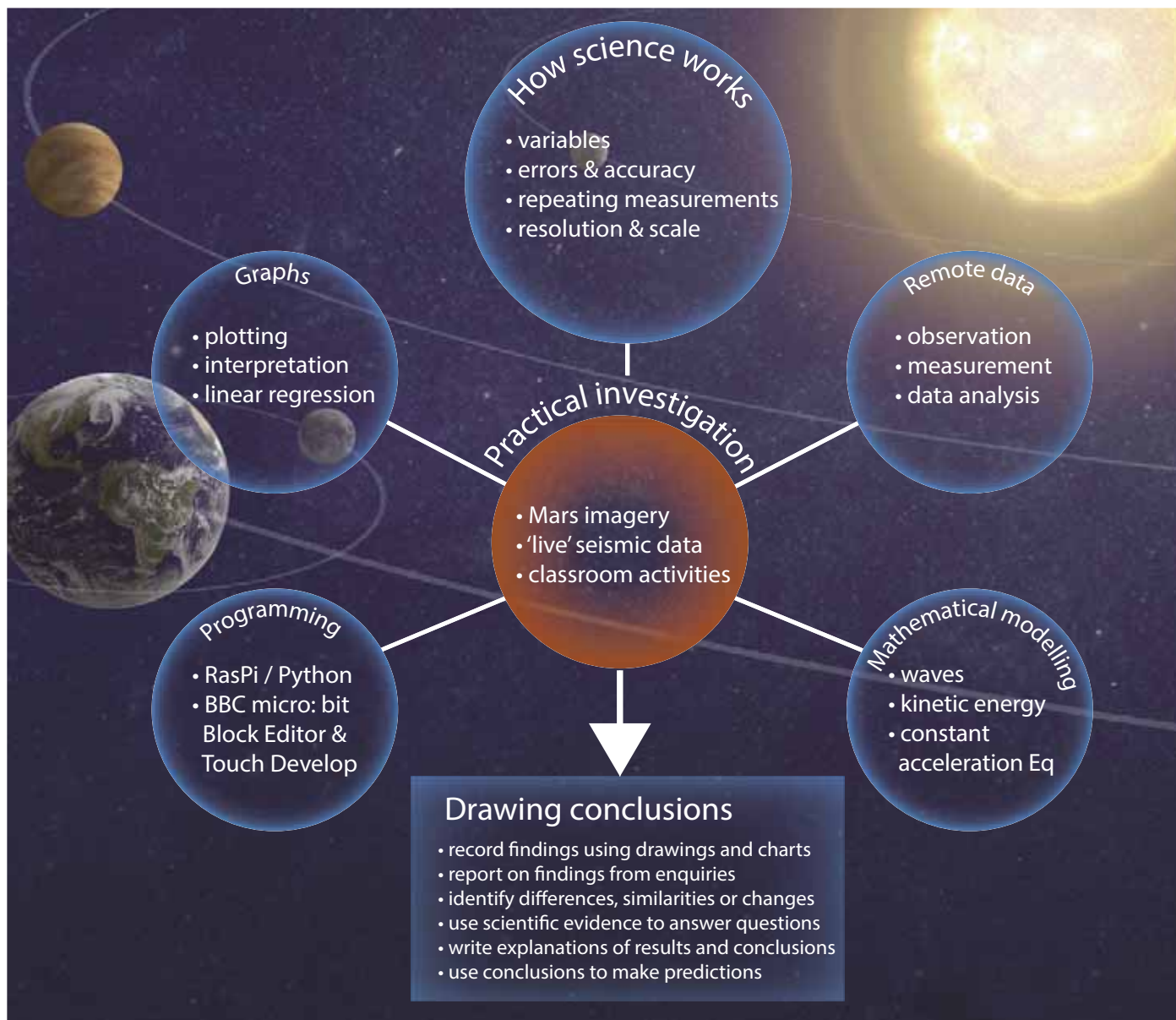
1. finding meteorite impacts on Mars using hi-resolution satellite imagery of Mars from the HiRise Orbiter
2. simulating meteorite impacts in the classroom with ball-drop experiments
3. studying seismic waves in the classroom
4. detecting seismic waves with simple sensors in the classroom, using tablets and smartphones, home-made seismometers and simple accelerometers
5. analysing seismic events from a single station using data from earthquakes, impacts and explosions, 'moonquakes', and eventually data from Mars

Students will be shown how to look at seismic data using simple spreadsheets, semi-professional analysis software and simple computer programs, which they could write themselves.

### Curriculum links

The MarsQuake project covers a broad range of topics primarily within the physics curriculum, including the solar system, waves, energy, distance/speed/time calculations, but the investigations (and its variations) can be used to underpin the teaching within a number of different subjects, such as maths, geology and geography.





### Mars facts

Mars is about half the diameter of Earth, its volume is about 15 per cent and its density about 70 per cent when compared to Earth. Mars' climate is much cooler. The average temperature is about  $-63^{\circ}\text{C}$ , which is in part down its greater distance from the Sun and its thin, carbon-dioxide-rich atmosphere. Martian weather is dominated by dust storms. These storms can grow to encompass the whole planet and raise the temperature.

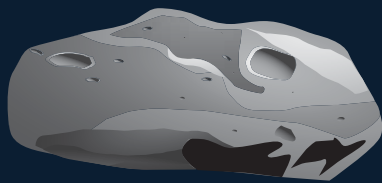
About two-thirds of Earth's surface is covered by oceans, whereas the surface of Mars has no liquid water. However, scientists think that the climate on Mars 3.5 billion years ago was similar to that of early Earth, i.e. warmer and wetter. We can see evidence of a Mars' wetter climate in the form of drainage channels, delta features and former lakes.

Both Earth and Mars have experienced many impacts from meteorites over the years. However, Mars' impact craters are far better preserved due to the slower rates of weathering and erosion, due to the lack of precipitation. Small meteorites burn up in Earth's atmosphere, never making it to the ground, but small meteorites produce craters on Mars because the planet has a much thinner atmosphere.

By studying the seismology of Mars, through 'marsquakes' and meteorite impacts, we can 'see' inside Mars to map its internal structure.



# Space rocks

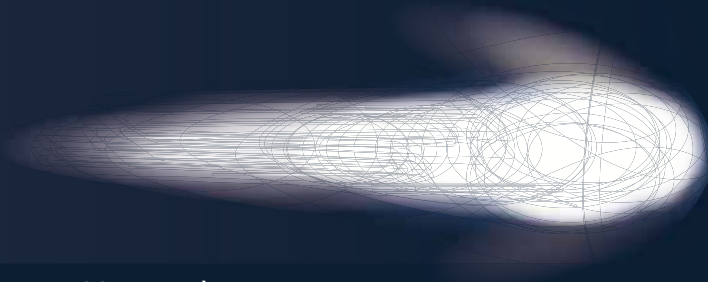


## Asteroid

A relatively small, inactive, rocky body orbiting the sun. Size: from 1m to 1000 km.

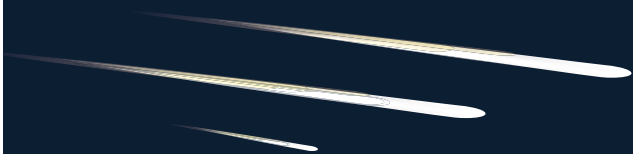
## Comet

A solid body composed of rock, ice and frozen gases. In sunlight, the frozen ice can vaporise forming an atmosphere, or coma, of dust and gas; sometimes, a tail of dust and/or gas.



## Meteor shower

Meteor showers are produced when the dust and other trailing particles of a comet rain down on a planet's atmosphere. When these particles collide with a planet's atmosphere they disintegrate to produce bright streaks in the sky.



## Meteoroid

A small particle from a comet or asteroid orbiting the sun. Size: typically from small grains to 1m.

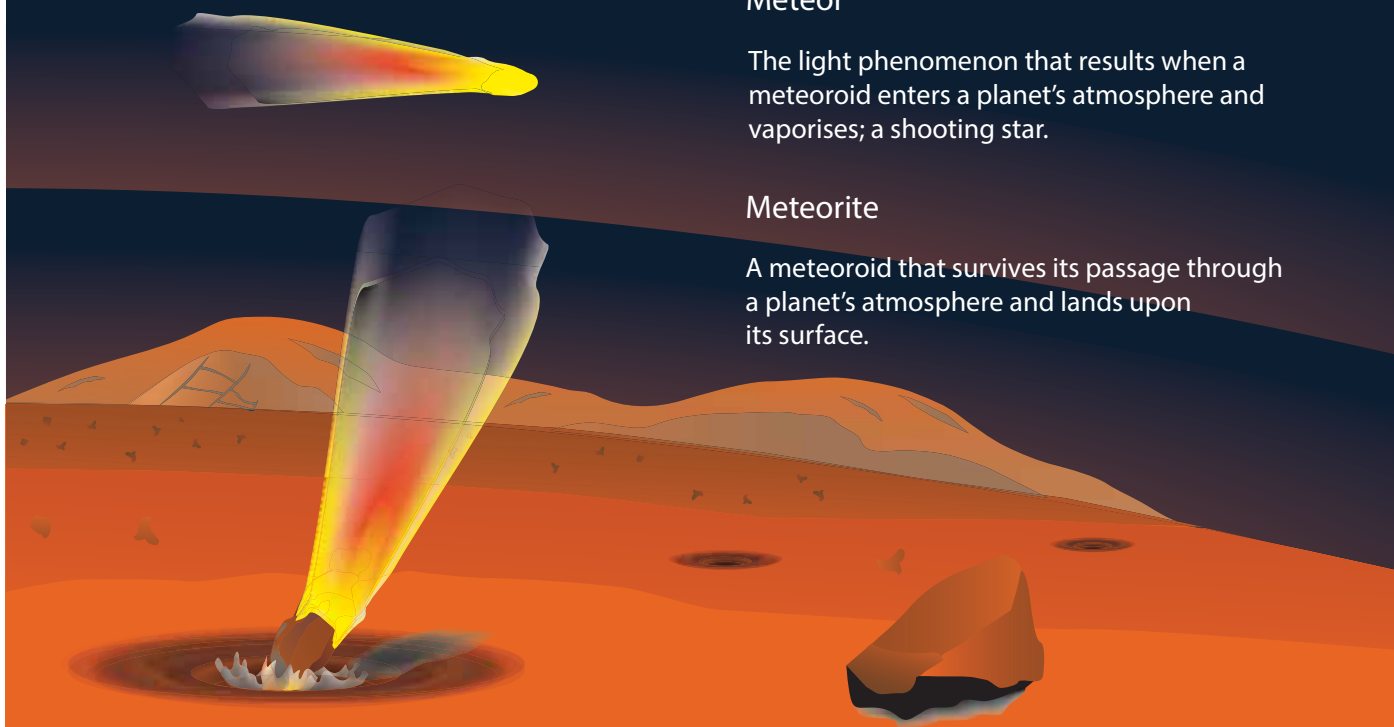


## Meteor

The light phenomenon that results when a meteoroid enters a planet's atmosphere and vaporises; a shooting star.

## Meteorite

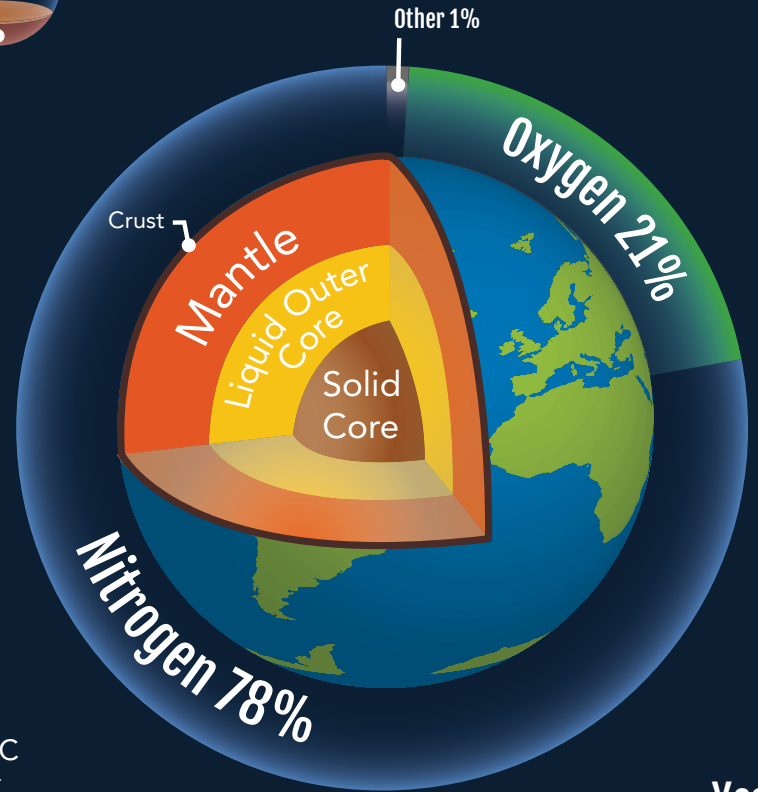
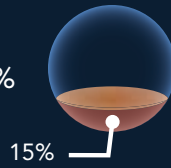
A meteoroid that survives its passage through a planet's atmosphere and lands upon its surface.



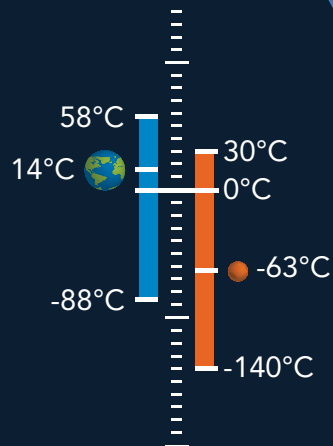
# Earth v

## Volume

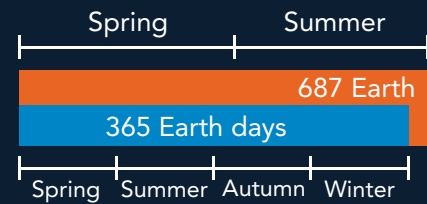
Mars has about 15% of Earth's volume.



## Average surface temperature range



## Year

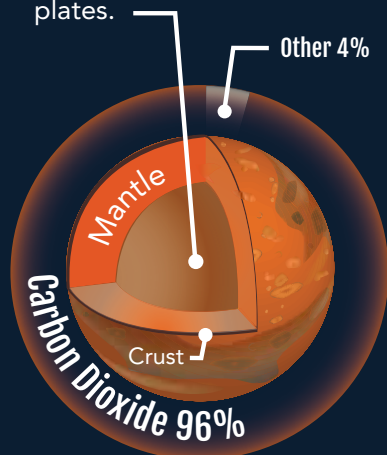


Earth atmosphere is 100 times more dense than Mars'

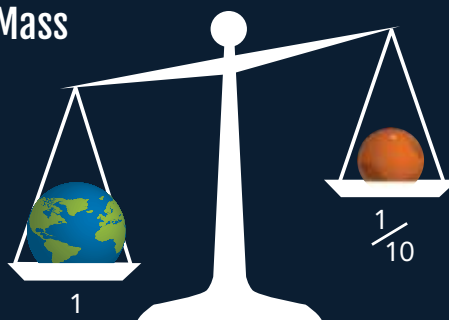


# s Mars

Scientists are not yet certain if the core of Mars is solid, liquid, or in two distinct sublayers, like Earth's. Future measurements will tell us more. Mars shows no evidence of tectonic plates.



## Mass



Mars has about 1/10 of the mass of the Earth.

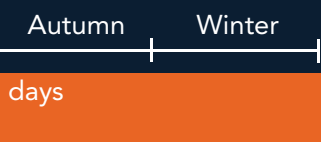
## Density



Mars is about 71% as dense as Earth

## Gravity

62.5 % less gravity on mars



[Northern hemisphere seasons shown]

## Four potential seismic sources on Mars



1. Phobos moon tidal effect?

2. Atmospheric excitation?

3. Meteorite impacts?

4. Faulting



© BGS/NERC (Modified after NASA Mars facts; mars.nasa.gov/allaboutmars/facts)



# The InSight mission overview

InSight (**I**nterior **E**xploration using **S**eismic **I**vestigations, **G**eodesy and **H**eat **T**ransport) is a NASA Discovery Program mission that will place a single geophysical lander on Mars to study its deep interior. InSight's primary objective will be to uncover how a rocky body in space forms and evolves to become a planet.

Generally, a rocky body begins its formation through a process called accretion; dust particles and small meteorites gradually stick together to form larger and larger bodies, eventually reaching planetary size. As the body increases in size, its interior heats up and melts forming a molten sphere. As dust subsequently cools and recrystallizes it evolves into what we know today as a terrestrial planet, containing a core, mantle and crust.

While all of the terrestrial planets share similar structures, and their bulk compositions are roughly the same as the meteoritic material from which they were formed, they are by no means uniform. Each of the terrestrial planets reached their current formation and structure through a process known as differentiation, whereby different elements and minerals crystallize and settle out of the molten 'blob' at different rates.

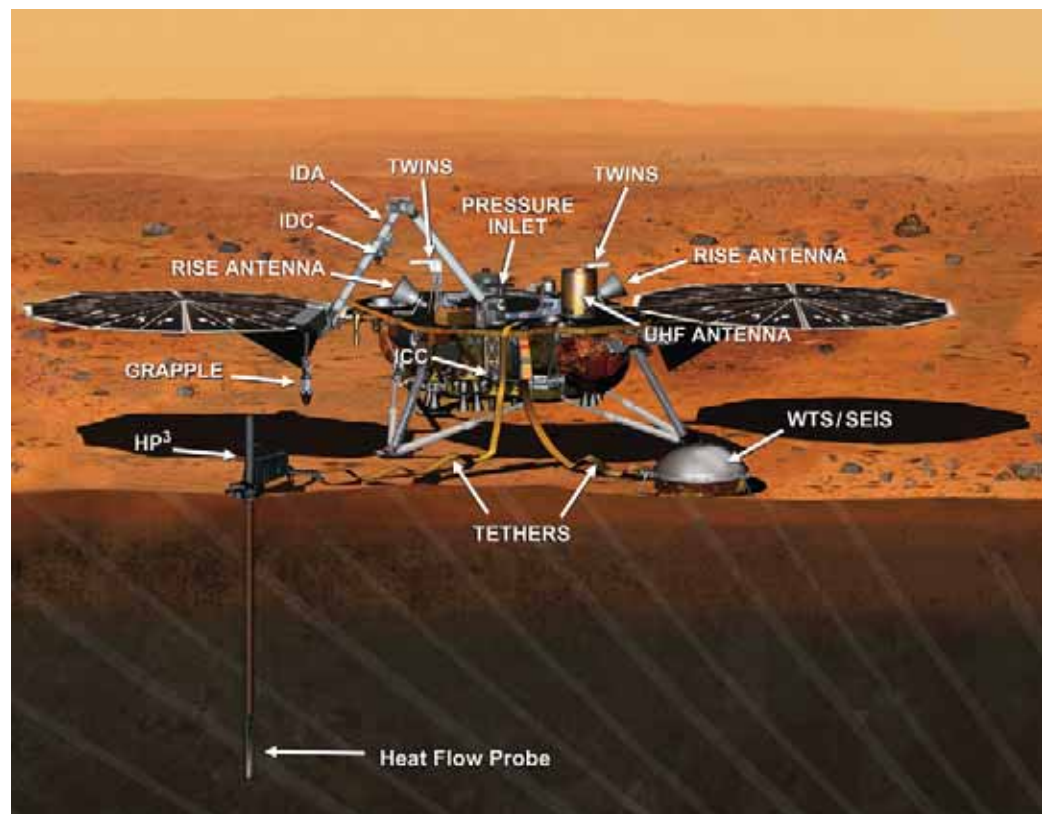
InSight's goal will be to solve the mystery of differentiation in planetary formation — and to bridge the gap of understanding that lies between accretion and the final formation of a terrestrial planet's core, mantle, and crust.

The mission's secondary objective is to conduct an in-depth study of 'marsquake' activity and meteorite impacts on Mars, both of which could provide valuable knowledge about such processes on Earth.

This artist's concept depicts the InSight lander on Mars after the lander's robotic arm has deployed a seismometer (WTS/SEIS) and a heat probe directly onto the ground.

Image: NASA/JPL-Caltech

<http://photojournal.jpl.nasa.gov/catalog/PIA19811>



To achieve each of these objectives, InSight will conduct six investigations at the Martian surface.

### Mission objectives

1. determine the size, composition, physical state (liquid/solid) of the Martian core
2. determine the thickness and structure of the Martian crust
3. determine the composition and structure of the Martian mantle
4. determine the thermal state of Mars' interior
5. measure the magnitude, rate and geographical distribution of Mars' internal seismic activity
6. measure the rate of meteorite impacts on the surface of Mars

The MarsQuake education project will focus on the seismology experiment on InSight and provide resources and tools to help users understand and interpret the results of this seismic experiment.

### The InSight lander

The InSight lander will be a conventional parachute-based static lander based on the tried and tested NASA Phoenix lander technology. The lander will be solar powered with a scientific payload designed by European partners in France (the main long period seismometer instrument), the UK (a simpler and more robust short period seismic sensor), Germany (a temperature heat probe which can burrow up to 5 m underground and measure heat flux from the planet) and Switzerland (providing the on-board electronics and high resolution positional information).

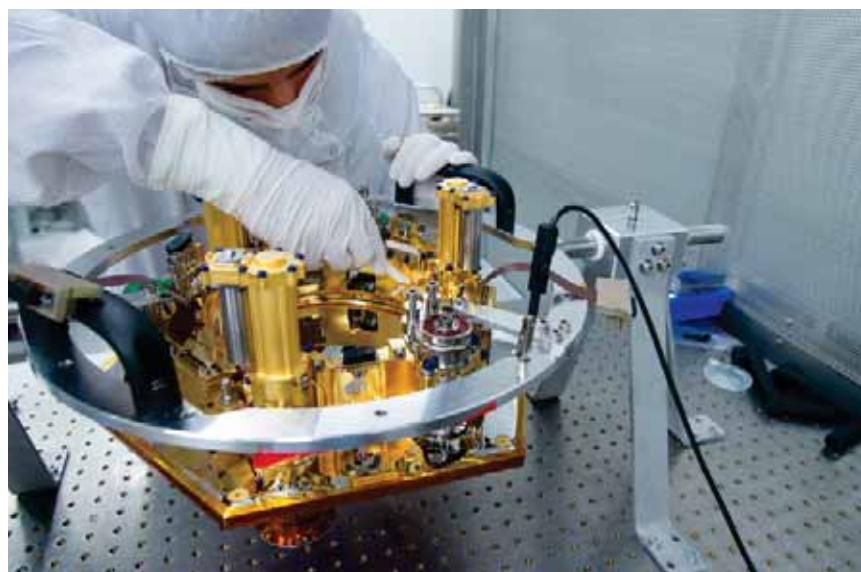
The lander has a robotic arm that will be used to deploy the heat probe sensor (HP3) and to place the seismometer package (SEIS) directly onto the surface. Placing the seismic sensor directly in contact with the ground and adding a windshield cover will greatly reduce the background noise detected and increase the sensitivity of the system to marsquakes.

### SEIS (Seismic Experiment for Interior Structure)

The SEIS Long Period Sphere is a sensitive broadband seismometer designed to detect meteorite impacts, atmospheric excitation and tidal forces from Mars' Phobos moon.

© CNES/GRIMAUULT Emmanuel, 2015

<http://cnes.photonpro.net/cnes/media/browse/1>





The SEIS long period sensor (designed at IPGP in Paris) has a sensitivity and frequency response comparable to the best research seismometers on Earth. The instrument houses three separate detectors in a vacuum enclosure to allow ground motion in three directions to be recorded (up–down, north–south and east–west). An early version of this sensor flew (briefly) on the failed Russian Mars (1996) mission.

The SEIS package also includes a MEMS (micro-electro-mechanical system) accelerometer (designed and built at Imperial College, London) that can record high frequency seismic signals using the same principles as the sensor in your smartphone that tells it which way is up. This sensor is not as sensitive at the lowest frequencies, but is a very robust and lightweight design.

## InSight: A NASA Discovery Program mission spacecraft

- Original launch window: 4–30 March 2016
- Original landing schedule: 28 September, 2016
- Mission budget \$425 million, lander weight 350 kg

The launch in 2016 was cancelled due to a technical failure of the vacuum vessel protecting the SEIS long period sensor. Due to the orbits of Earth and Mars, the next available launch opportunity will be in 2018.

The exact landing ellipse is selected to be relatively flat terrain, without large craters, and with a rock surface soft enough for the heat probe mole to be able to burrow into the surface. In order for the parachutes to work it must be a relatively low elevation and to get enough solar power the landing site should be near the equator.

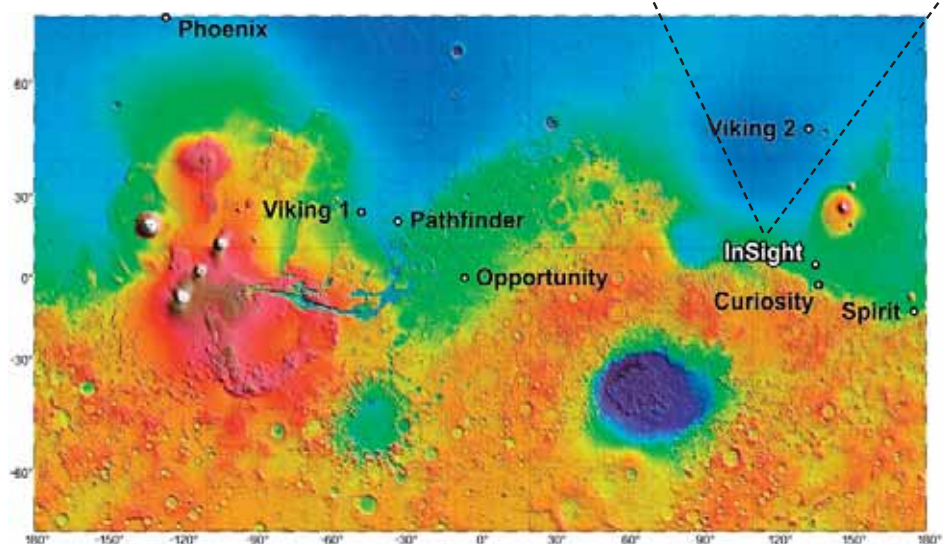


The likely landing site is marked by an ellipse within the northern portion of flat-lying Elysium Planitia. It is centred at about 4.5 degrees north latitude and 136 degrees east longitude.

Images: NASA/JPL-Caltech

Inset Image  
<http://www.jpl.nasa.gov/spaceimages/details.php?id=pia19143>

Main Image  
<http://insight.jpl.nasa.gov/images.cfm?ImageID=8310>





## Structure of Mars

Scientists are still debating the reasons why Mars appears to not experience plate tectonic processes. Is liquid water at the surface an essential component of plate tectonics? Did Mars simply cool too quickly due to its higher surface area–volume ratio?

### Plate tectonics and Mars

Plate tectonics governs the nature and shape of the surface of the Earth, from ocean basins to mountain ranges. It also governs the motions of the surface of Earth, providing a range of natural hazards such as earthquakes and volcanic eruptions. Plate tectonics is the main mechanism through which Earth loses its heat. However, plate tectonics only occurs on Earth. This is puzzling. Why does plate tectonics only occur on Earth? In the absence of plate tectonics, how do other terrestrial planets lose their heat? These are major questions in Earth and planetary sciences research. This section provides a brief introduction to the ways in which terrestrial planets lose their heat, comparing Earth and Mars, and discusses our current understanding of plate tectonics.

### The structure of terrestrial planets

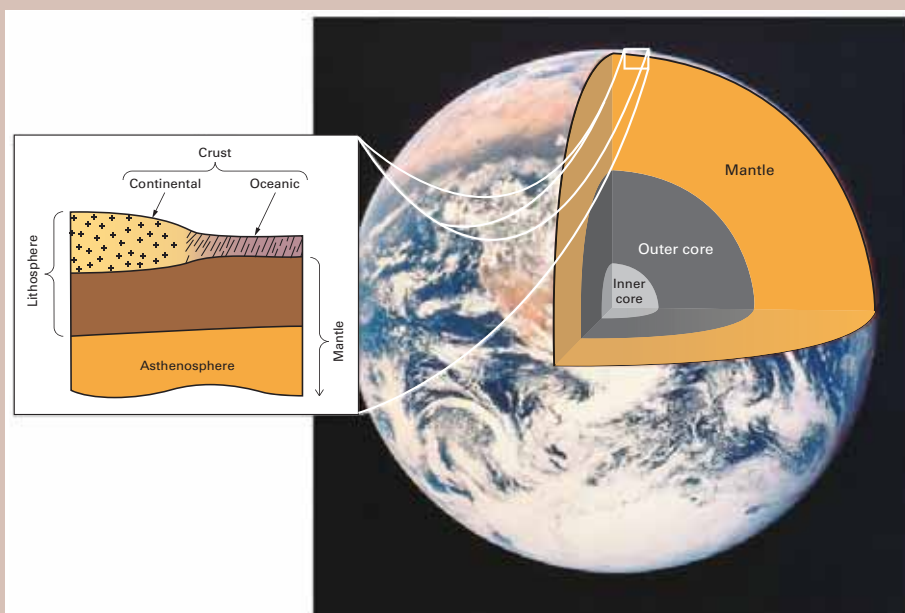
Earth and Mars can both be thought of as a series of approximately spherical layers, defined either chemically or mechanically. For example, starting at the centre and working outwards, Earth is chemically composed of an inner core, outer core, mantle, and crust; it is mechanically composed of an inner core, outer core, lower mantle, upper mantle, asthenosphere and lithosphere. The lithosphere is composed of the crust and the rigid uppermost part of the mantle, and is the 'plate' of plate tectonics. Although it is also solid, in contrast to the rigid lithosphere, the underlying asthenosphere is plastic (i.e. it can flow on geological timescales). We now know that the lithosphere and asthenosphere behave relatively independently, in contrast to the original idea that the motion of the tectonic plates was controlled by motion in the asthenosphere.

The interior structure of Earth. Earth is chemically composed of an inner core, outer core, mantle, and crust; it is mechanically composed of an inner core, outer core, lower mantle, upper mantle, asthenosphere and lithosphere. The lithosphere is composed of the crust and the rigid uppermost part of the mantle, and is the plate of plate tectonics.

© BGS/NERC

Image: Redrawn from NASA/  
JPL-Caltech

Colours modified by the BGS.



### How do terrestrial planets lose their heat?

Terrestrial planets such as Earth and Mars are generally thought to have been initially hot, and gradually cooling, with many planetary processes (e.g. volcanism and tectonism) being driven by this cooling. The sources of heat within these planetary bodies can be categorised as either primordial (i.e. inherited from processes occurring during formation) or the result of radioactive decay. Heat is transferred within planetary bodies and eventually lost to space through a combination of convection, conduction and radiation. Different methods of heat loss dominate in the different layers of planetary bodies, and at the boundaries between these layers. For example, it is estimated that every year Earth loses  $4.2 \times 10^{13}$  W, or 42 TW, of heat: 32 TW conducted through the lithosphere, and up to 10 TW lost by, for example, hydrothermal activity at mid-ocean ridges [1].

There are three main modes of planetary cooling: magma ocean, stagnant lid, and plate tectonics. Regardless of the mode of planetary cooling, all planets lose heat from the surface to some degree via radiation. All terrestrial planets are thought to undergo a short-lived magma ocean stage early in their evolution.



The name 'magma ocean' refers to the stage when a body is so hot that the surface is partially or largely molten, and heat loss from the surface is primarily through small scale convection. This image is an artist's impression of the magma oceans that formed on the moon about 4.5 billion years ago.

Image: NASA/JPL-Caltech

[http://svs.gsfc.nasa.gov/vis/a010000/a010900/a010948/index\\_svs.html](http://svs.gsfc.nasa.gov/vis/a010000/a010900/a010948/index_svs.html)

When a body has cooled sufficiently, the surface solidifies and the common mode of heat loss is stagnant lid behaviour, where heat loss from the surface is primarily through conduction. Alternatively to stagnant lid behaviour, if the conditions are appropriate, a terrestrial planet may begin to lose heat via plate tectonics. It is theoretically possible that a terrestrial planet may alternate between a stagnant lid regime and a plate tectonics regime; this has never been observed, but the lack of observation may simply be a reflection of the long timescales involved. Ultimately, when they have become sufficiently cool, the fate of all terrestrial bodies is to continue to cool by conduction alone; they may then be considered to be inactive or dead (i.e. lacking in any force to drive planetary processes such as volcanism and tectonism).

### What are the conditions necessary for plate tectonics?

This question may be thought of as a Goldilocks problem: everything needs to be just right. Firstly, the planetary body in question must have cooled sufficiently so that it is too cold to sustain a magma ocean. Secondly, there needs to be sufficient heat within the interior of the body to prevent the existence of a stagnant lid, i.e. sufficient heat to maintain convection within the upper

layers of the body. Thirdly, the lithosphere needs to be cool enough, dense enough, strong enough and thin enough to subduct. Finally, probably the most important ingredient for successful plate tectonics is liquid water, which is readily available only on Earth, not on the other terrestrial bodies. This too is a Goldilocks problem: the Earth may be at just the right distance from the Sun to have a surface temperature between 0 and 100°C, and therefore be a stable environment for liquid water. So far, all of the necessary conditions for plate tectonics have only been found together on Earth.

### Is there any evidence for plate tectonics on other planets?

There is no conclusive evidence for plate tectonics on any other planets [2]. Mars is considerably smaller than Earth, but it does have water (mostly in the form of ice). Some surface features on Mars have been interpreted as indicating the possibility of plate tectonics operating there in the past. For example, it has been suggested that magnetic patterns observed by the Mars Global Surveyor spacecraft may indicate that a process similar to plate tectonics may have operated on Mars in the past. However, other surface features have been interpreted as indicating that plate tectonics has not operated on Mars. For example, it has been suggested that the enormous size of volcanoes such as Olympus Mons may indicate that the Martian crust has remained stationary over the magma source for a protracted period of time, whereas on Earth the movement of tectonic plates over magma sources results in linear tracks of relatively small volcanoes on the surface (e.g. the chain of Hawaiian islands). There remains no evidence for coherent planet-wide plate tectonics at any time in the history of Mars.

### Are plate tectonics, continents and life related?

There are many puzzling things about plate tectonics that we are only just beginning to address. For example, Earth is unique in that it has plate tectonics, but also in that it has continents, and in that it has life. Are these issues related? There is no clear consensus on these issues, as we do not yet fully understand how continental crust is formed. We don't know whether it would be possible to have a world with plate tectonics, but no continents, or conversely a world with continents but no plate tectonics. The relation between plate tectonics and life is even more speculative, and this is currently discussed as a chicken and egg problem: do we need plate tectonics in order for there to be life on Earth, or do we need life in order for there to be plate tectonics on Earth? Of course, although our attempts to address this puzzle are more speculative, this puzzle is also very exciting!

How and when did plate tectonics start on Earth? This is the question that we are most likely to be able to answer in the near future. We plan to use data from missions like InSight to understand how Mars loses its heat, and why plate tectonics does not occur on Mars. If we can understand why plate tectonics doesn't occur on Mars, it will help us to figure out how plate tectonics started on Earth.

Will we ever find another planet that does have plate tectonics, or is Earth not just unique within the Solar System, but also within the wider universe? If you want to find out the answers to these kinds of questions, become a geophysicist!

This article is a condensed version of 'Why Does Plate Tectonics Only Occur on Earth?'

Martin, P et al., 2008, which was published in Physics Education. (<http://iopscience.iop.org/article/10.1088/0031-9120/43/2/002/pdf>).

#### References

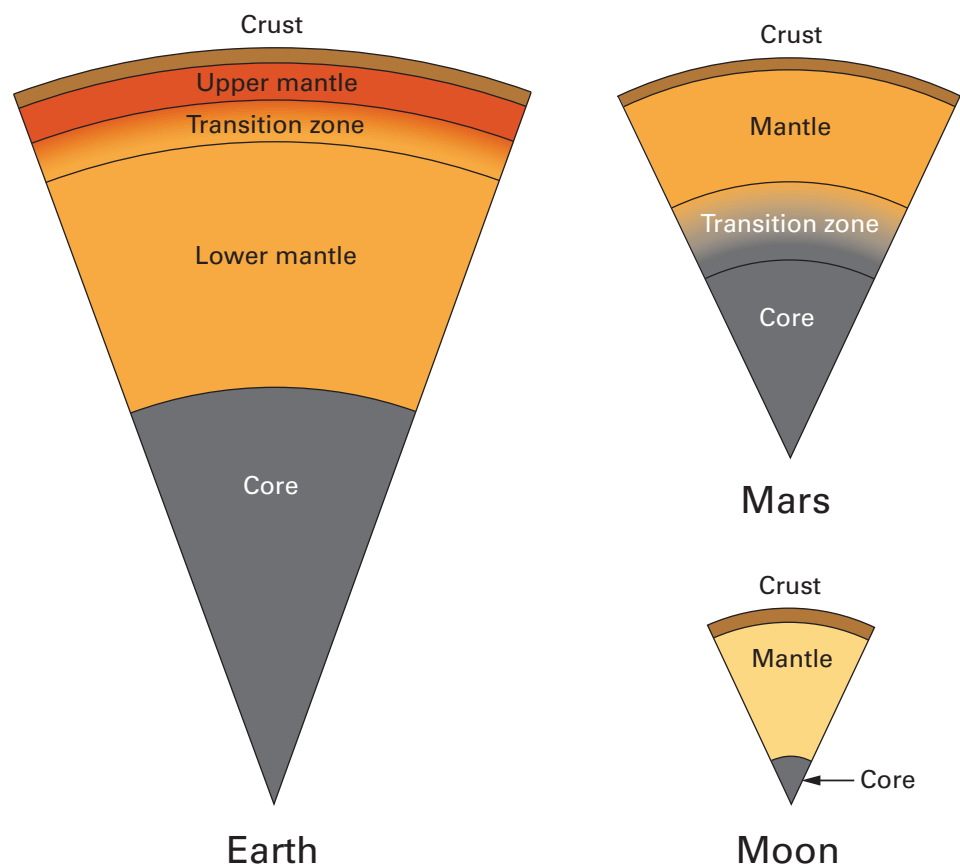
1. Anderson, D. L. (2007) New Theory of the Earth, Cambridge University Press, Cambridge, DOI: 10.2277/0521849594.
2. Beatty, J. K., Petersen, C., and Chaikin, A. (1999) The New Solar System, 4th edition, Cambridge University Press.

### Transition zone and mantle mineral structure

Earth and Mars have similar bulk compositions (the same as primitive meteorites in the solar system). However as they cooled from homogeneous molten spheres they underwent a process called '**differentiation**', whereby different elements settled out at different rates, with the denser metallic components (mostly iron and nickel) forming a core and the lighter silicate components creating a mantle and crust. Within the mantle the composition is mostly made up of minerals containing Oxygen, Magnesium, Silicon, Iron, Calcium and Aluminium. These elements combine to form different minerals and rock types.

However the same mineral can exist as different physical structures depending on how the atoms are packed together. These different structural arrangements of the same mineral are called '**polymorphs**' or '**phases**'. One very well-known material that experiences polymorphism is carbon, which can exist as graphite or diamond. The minerals within the mantle can exist as several different polymorphs depending on the pressures and temperatures at which they are formed. In the Earth, this gives rise to a 'Transition Zone' in the mantle between about 410 km and 1000 km deep where the mineral olivine (forming peridotite) transforms into more closely packed (and denser) minerals with a perovskite-type structure. These phase change boundaries can be detected as changes in seismic velocity. It is expected that on Mars these phase changes in the mantle will occur much closer to the core, being able to detect these with seismic data is one of the mission objectives.

Mars has the same basic internal structure as the Earth and other terrestrial (rocky) planets. It is large enough to have pressures equivalent to those throughout the Earth's upper mantle, and it has a core with a similar fraction of its mass. This diagram shows the depths at which high pressures cause certain minerals to transform to higher-density crystal structures. In contrast, the pressure even near the centre of the Moon barely reach that just below the Earth's crust and it has a tiny, almost negligible core. The size of Mars indicates that it must have undergone many of the same separation and crystallization processes that formed the Earth's crust and core during early planetary formation. (Not to scale).



© BGS/NERC

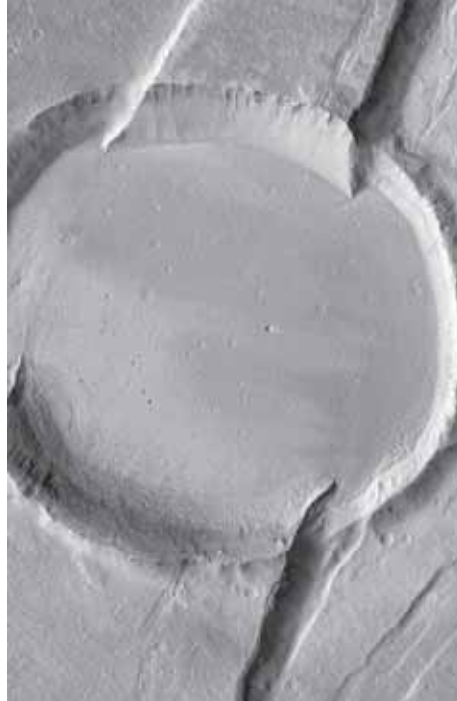
## Sources of seismic signals on Mars

Estimates of potential seismicity rates on Mars have been made, based on observations on satellite imagery of features consistent with surface faulting, estimates of impact cratering rates and an extrapolation from known seismicity rates on the Earth and the Moon.

An impact crater (the large round feature, approximately 6.2 km, or 3.9 miles, across) that intersects a series of faults (the linear features). The faults are seen to cut the circular rim of the impact crater.

Image: NASA/JPL-Caltech

[http://www.uahirise.org/ESP\\_017900\\_2185](http://www.uahirise.org/ESP_017900_2185)



### Faulting

Surface or crustal faulting is visible on images of the Martian surface. The energy for these events could come from residual cooling and shrinking of the planet or from magma motions deep underground.

### Tidal motions

The motion of the moon Phobos around Mars will produce a very low frequency 'tidal' motion on the surface of Mars with a period of about eight hours. The sensitivity of the long period SEIS instrument should be high enough to measure this tidal motion after averaging the data over one or two years.

Phobos, and the second Martian moon, Deimos, are interesting for several reasons. Both objects are small, with average diameters of just 22 and 12 km respectively. At this size, their gravity is insufficient (less than 1/1000th of Earth's) to pull them into spherical shapes, in contrast to the larger moons and planets in the Solar System.

Image: NASA/JPL/University of Arizona

<http://www.uahirise.org/phobos.php>



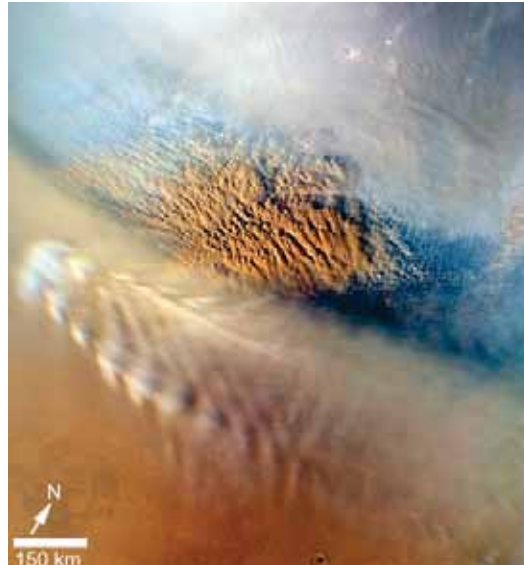
### Atmospheric excitation

Dust storms on Mars will act as energy sources, exciting seismic vibrations in the ground.

This close-up image of a dust storm on Mars was acquired by NASA's Mars Reconnaissance Orbiter.

Image: NASA/JPL-Caltech

<http://photojournal.jpl.nasa.gov/catalog/PIA15959>



The team operating the Context Camera (CTX) aboard NASA's Mars Reconnaissance Orbiter frequently discovers new dark spots on Mars that, upon closer examination, turn out to be brand new impact craters. Sometimes, only a single crater is present, but often there is a cluster of several craters. Depending on the patterns and size, crater clusters are interpreted as indicating that the incoming meteorite broke apart before it hit the surface. In some cases, clusters could be formed by ejecta from other, larger impact craters.

### Meteorite impacts

Visual inspection of cratering on Mars, and knowledge of impact cratering rates on the Moon, enable us to have a reasonable estimate about the number of new meteorite impacts we expect to be able to measure seismically on Mars.

New meteorite craters are being discovered on Mars all the time as orbiting satellites re-image the same piece of ground.



Image: NASA/JPL-Caltech/Malin Space Science Systems

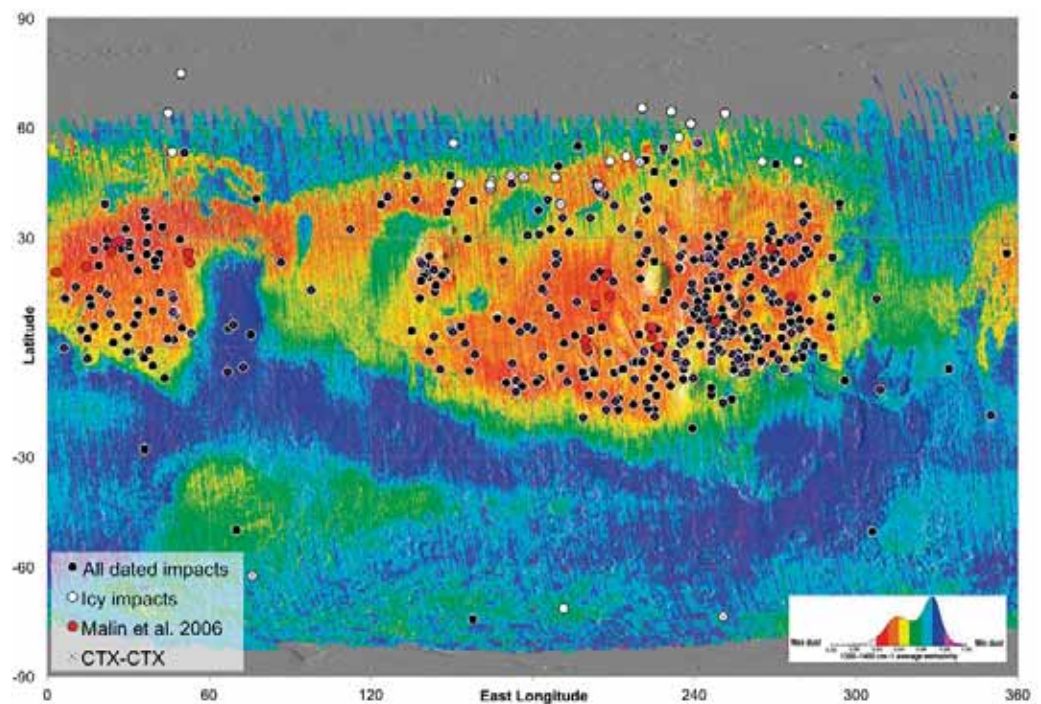
[http://www.nasa.gov/mission\\_pages/MRO/news/mro20090924.html](http://www.nasa.gov/mission_pages/MRO/news/mro20090924.html)



Locations of 248 new dated impact sites on Mars, 2013.

Image: NASA/JPL (Daubar)

[http://www.lpl.arizona.edu/~shane/publications/daubar\\_et\\_al\\_icarus\\_2013.pdf](http://www.lpl.arizona.edu/~shane/publications/daubar_et_al_icarus_2013.pdf)

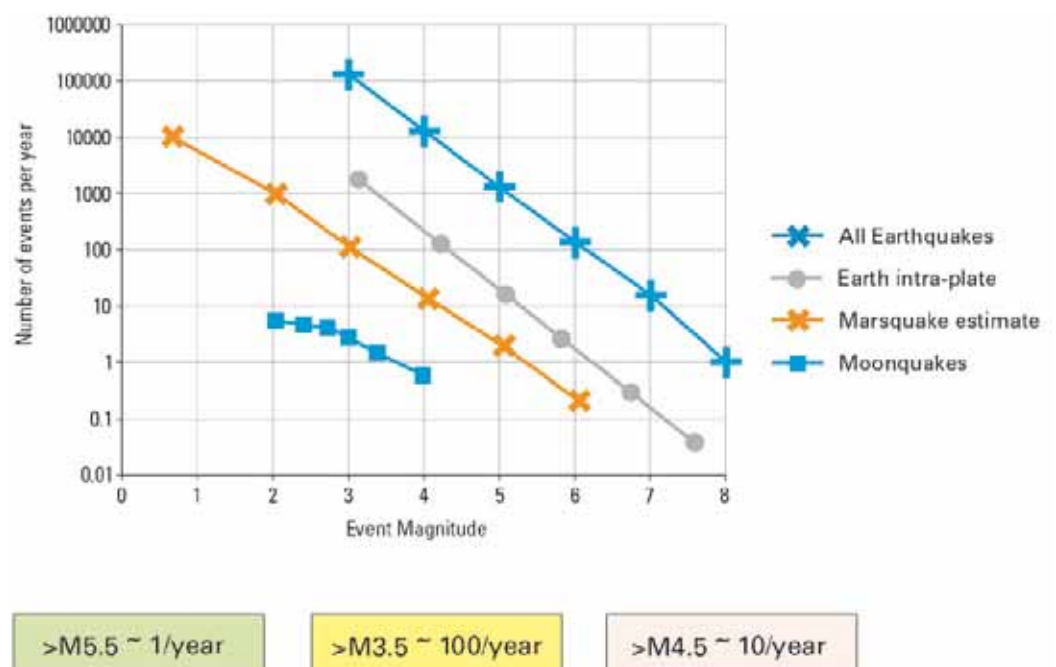


### Marsquakes

Marsquakes caused by faulting (either at the surface or underground) are expected to occur at a rate somewhere between that of shallow moonquakes and intraplate earthquakes on Earth (that is earthquakes occurring a long way from the tectonic plate boundaries where most earthquakes occur).

Average number of 'earthquake' events per year vs event magnitude.

© BGS/NERC





# Impacts and seismic waves: background science

## What is a wave?

In broad terms, a wave is a way of transferring energy without transferring matter. An oscillation or disturbance that travels through a medium from one location to another.

Perhaps the easiest way to think about a wave, and to observe some of the characteristics of a wave is with a slinky spring. If you stretch the spring out along the floor, you can create a wave that travels along the spring by creating a disturbance. If you move one end of the slinky left and then right, the first coil will move, dragging the next coil to follow its motion and this continues throughout the slinky allowing a wave to be transferred along it.

If you look carefully at one coil of the slinky, you will see that it moves up and then down, returning to its equilibrium position. While energy has been transferred through the slinky, no individual bit of matter or coil of the slinky has permanently moved from its starting location. Instead, by oscillating up and down and affecting the next coil along, a wave is able to propagate, or move through the slinky.

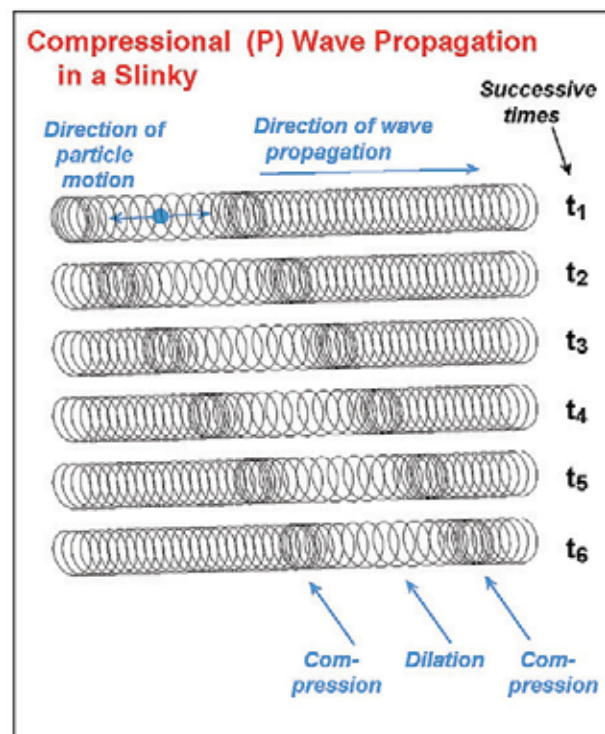
## Types of wave

There are two main types of wave, defined by the way the medium oscillates with regards to the direction of propagation of the wave and the types of medium they can travel through.

### Longitudinal waves

In longitudinal waves, such as sound, the particles oscillate in the same plane as the direction of propagation of the wave. They are compression waves so they need a medium through which they can be transmitted in order to occur.

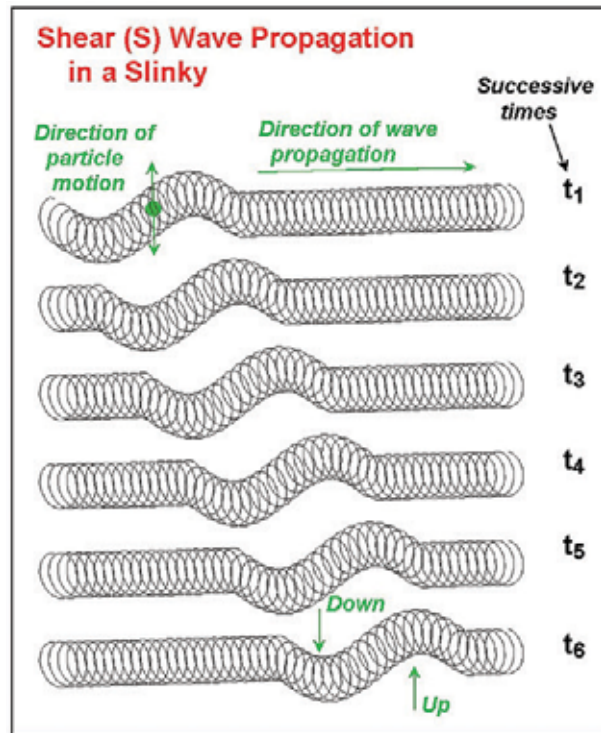
© 2001–2006 L Braile



### Transverse waves

In transverse waves, the particles oscillate in a plane perpendicular to the direction of propagation of the wave. While most transverse waves require a medium to travel through, some such as electromagnetic waves (light waves) do not. In an electromagnetic wave, it is the electric and magnetic fields that are 'oscillating'.

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## Seismic waves

When an earthquake or an impact occurs, huge amounts of energy are released. Some of this energy is transmitted through the ground in the form of seismic waves.

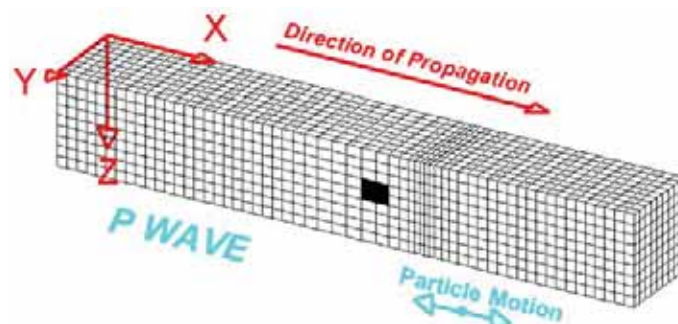
Waves that travel along the surface of the planet are known as **surface waves**, and those that travel through the body of the planet are known as **body waves**.

### Body waves

An earthquake or marsquake rupture will create P- (primary) waves and S- (secondary) waves.

#### P-waves:

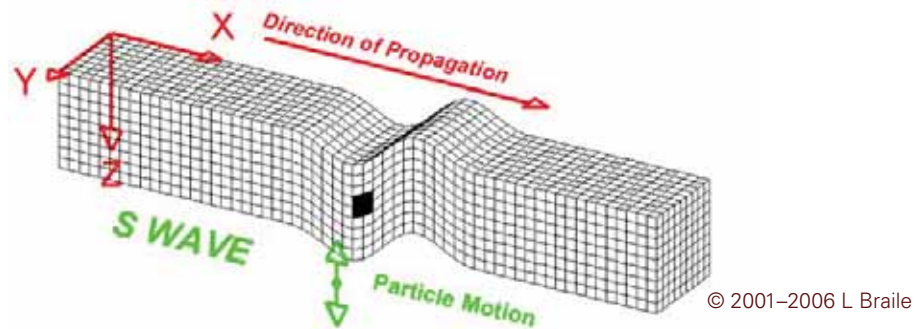
P-waves are **longitudinal waves**, very much like the wave you get if you push a pulse along a stretched slinky spring. P-waves are the fastest seismic waves, and the first to be experienced following an earthquake or impact. You could think of P-waves as sound waves travelling through the ground. P-waves can travel through solid materials like the Earth's crust and mantle and also liquids like the Earth's outer core.



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**S-waves:**

S-waves, also known as shear waves, are **transverse waves**, similar to the wave you get when you send a pulse down a stretched slinky spring by moving your arm from side to side. In S-waves, the particles oscillate in a perpendicular plane to the direction of propagation to the wave, in the vertical plane, horizontal plane or a combination of the two. S-waves can only travel through solids like the Earth's crust and mantle. Liquids do not have sufficient shear strength to allow these transverse waves to pass.



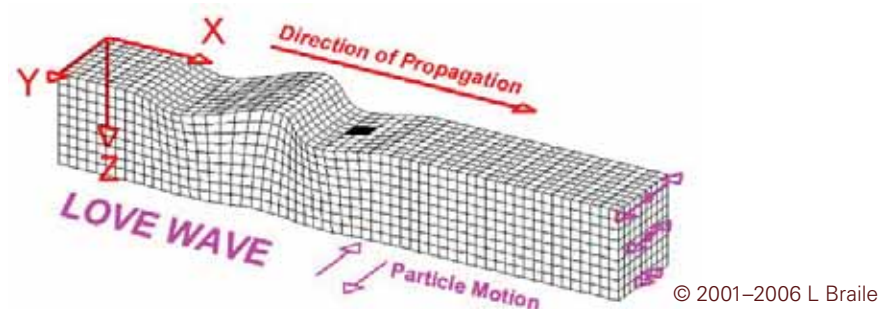
By comparing the amount of energy created as P-waves, and the amount created as S-waves in a seismic event, scientists are able to tell the difference between earthquakes and explosions — explosions generate far more P-waves. On Earth, this is useful for monitoring nuclear bomb tests. On Mars, it will help distinguish marsquakes from meteorite impacts; the latter will be more like surface explosions.

**Surface waves**

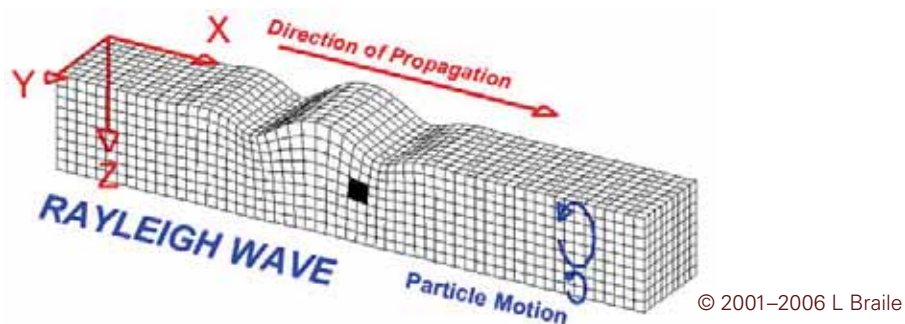
Surface waves are created when P- and S-waves from a deep quake reach the surface and are reflected and refracted by the near surface layers. They fall under two classifications; Love waves and Rayleigh waves.

**Love waves:**

Love waves are transverse waves that travel around the surface of the planet. The particle motion is in a horizontal plane, perpendicular to the direction of propagation of the wave with the amplitude of oscillation decreasing with depth.

**Rayleigh waves:**

The motion of a Rayleigh wave is similar to that of water waves. The particles have a complex motion, in an elliptical pattern. Like Love waves their amplitude also decreases with depth.



Surface waves can have very low frequencies (down to a few millihertz or periods of a few hundred seconds). These very low frequency waves can travel vast distances without being attenuated and are sometimes detected circling the planet several times after a large event.

## What can seismic waves tell us about a planet's structure?

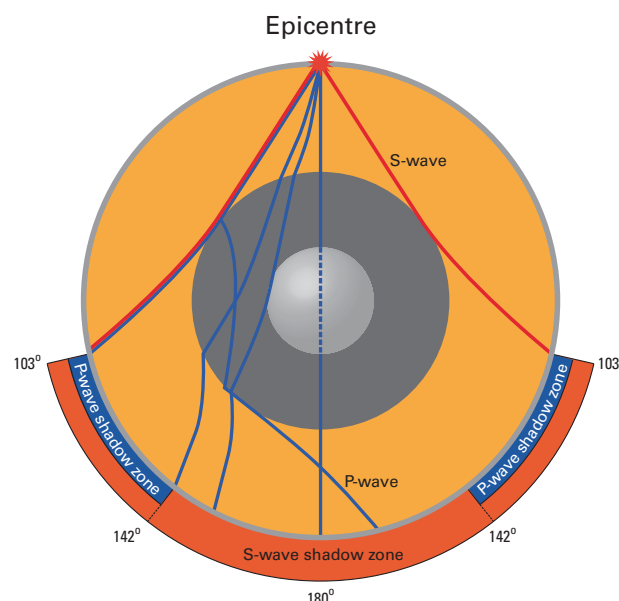
Like all waves, seismic waves can undergo reflection and refraction. The degree to which a seismic wave is refracted, or the position at which one is reflected allows us to build up a picture of the density and structure of material at various points inside a planet. Using the Earth as an example, we can see how this is achieved.

### Refraction of P-waves

P-waves can travel through the Earth's mantle, which acts like a solid for short time periods, and also the liquid core. As pressure increases with depth in the mantle, so the velocity that P-waves travel increases leading to seismic waves being continuously refracted into curved ray paths. At sharp discontinuities like the core mantle boundary, where the velocity of P waves suddenly decreases in the liquid core, P-waves are strongly refracted leading to a region of the Earth's surface which does not see directly arriving P-waves — the P-wave shadow zone running from 103°–142° distance from the event.

Cross-sectional view of the Earth showing ray paths of selected P-waves and S-waves.

© BGS/NERC



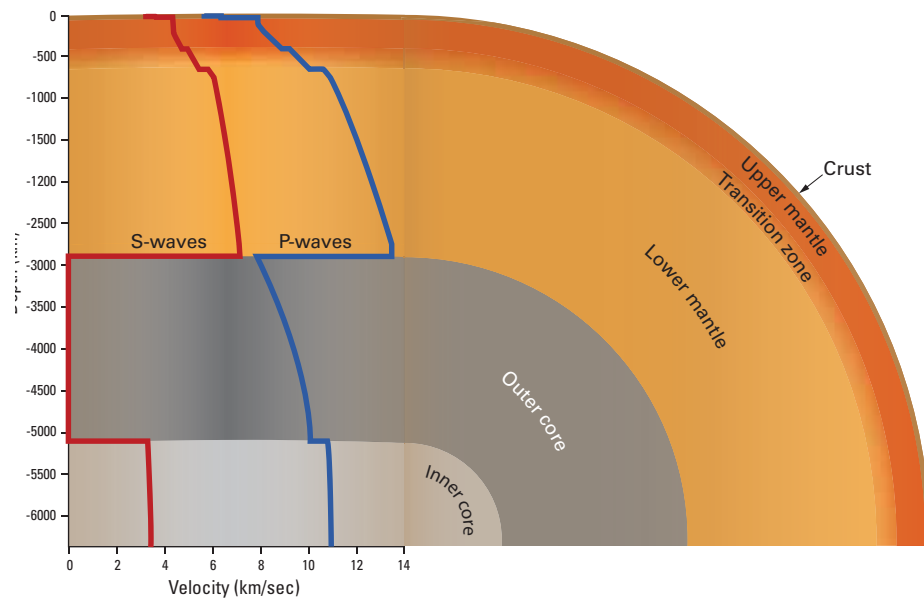
### S-wave shadow zone

S-waves can only travel through solid materials like the Earth's crust and mantle. This leads to a shadow zone at distances greater than 103° from an earthquake where recording sites do not see directly arriving S-waves. In fact, the size and composition of the Earth's liquid core were originally discovered by analysing the location of this shadow zone.

Deep Earth velocity structure shows an increase in seismic velocity with depth in the mantle, a sharp drop in P-wave velocity in the liquid outer core and an absence of S-waves (zero velocity).

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Modified after IASP91 Earth Reference Model.



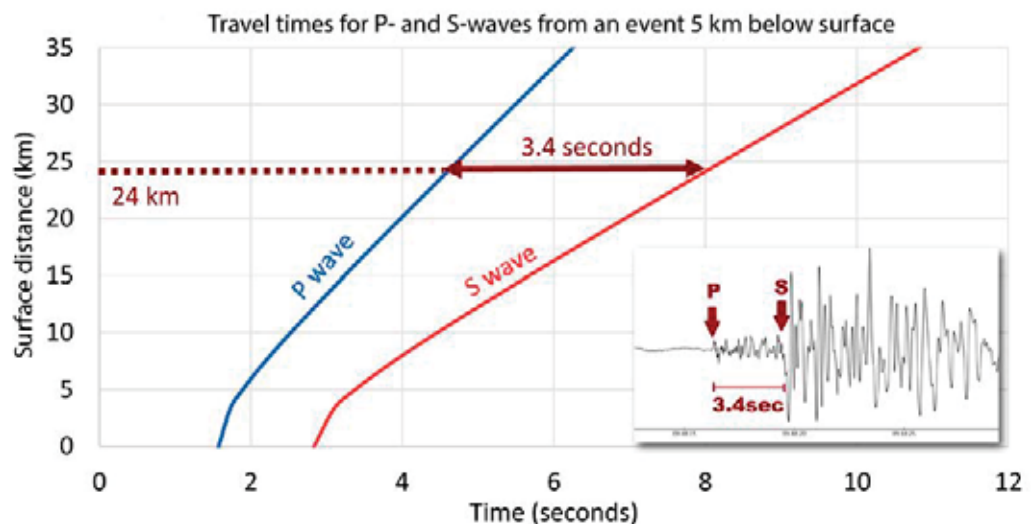
## What will InSight learn from seismic events and how?

It is the seismic waves from events that interest the scientists studying the Mars InSight data. Using seismometers and accelerometers (devices that measure the directionality and amplitude of a seismic wave) and imagery from orbital craft, they will be able to determine the location of an event, and by analysing the wave forms, to begin to gain an understanding of the structure of Mars.

It is the difference in speed between P-waves and S-waves that will allow scientists to do this, in the same way they can on the Earth.

Travel times for P- and S-waves from an event 5 km below the surface.

© BGS/NERC (Paul Denton)



P-waves travel at a speed of 5–7 km/s in the Earth's crust, while S-waves are slower travelling at 3–4 km/s. When an impact happens, a seismometer a distance away from the impact will first detect the faster P-waves which will be recorded as a lower amplitude trace. When the S-waves reach it, a newer, higher amplitude trace will be observed (a combination of the P-waves and S-waves).



As a result, we can use the difference in arrival time to calculate the distance that the impact was from the seismometer. Since a longer distance will yield a longer time interval between the two waves, a graph like the one on page 21 can be used to determine the distance.

### Particle motion

Just like the ripples in a pond, looking at the direction a wave is travelling in, even some distance from an event, can tell you the direction back to the event origin.



© Paul Denton

### Direction of ground movement

Early seismometers, which were just simple pendulums making traces of their motion, used this principle to determine the direction that seismic waves travelled from.

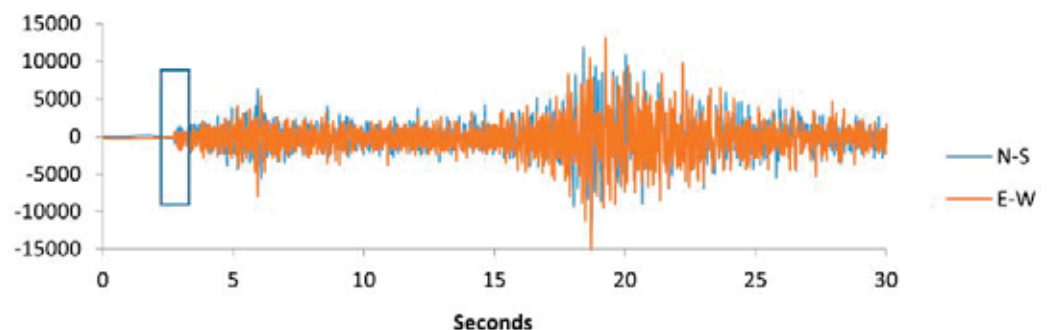
© BGS/NERC (Paul Denton)



5.15 A.M.  
April 18, '06.  
Veterans Home, Cal  
Napa Co.

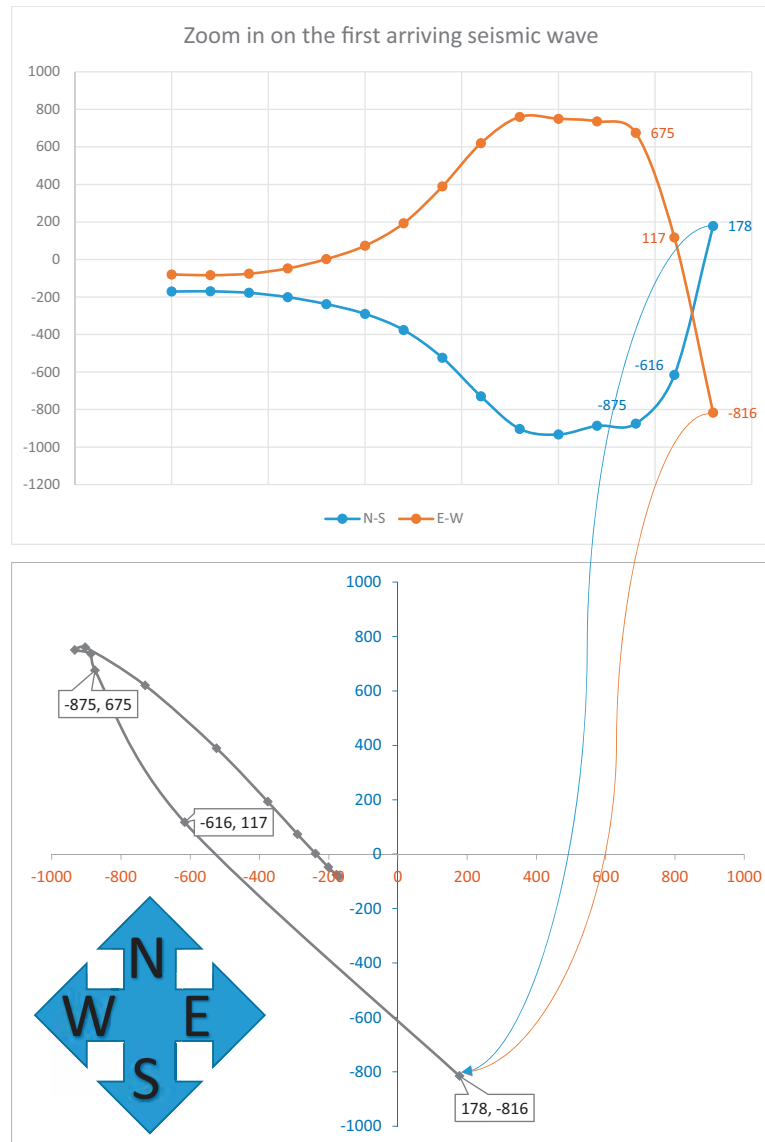
Nowadays, seismometers record the time history of ground movement in three directions, one vertical and two horizontal, usually North–South (N–S) and East–West (E–W).

Seismogram showing small earthquake (M4.2) recorded at a distance of 240 km. Plotted two horizontal components N–S ground motion and E–W ground motion. Detailed analysis of the first arriving seismic waves (inset box) allows us to determine the direction that the waves are travelling in.



Seismogram showing small earthquake (M4.2) recorded at a distance of 240 km. Plotted two horizontal components N–S ground motion and E–W ground motion. Detailed analysis of the first arriving seismic waves (inset box) allows us to determine the direction that the waves are travelling in.

Plotting the N-S and E-W location of each data point on a plan map gives a particle motion plot showing the direction of ground motion.



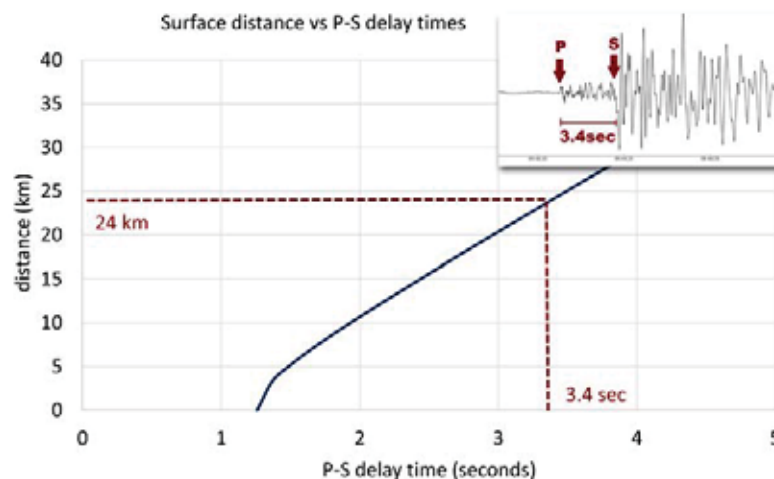
### Locating marquakes using a single station

On Mars, this information will be combined with imagery taken from orbital spacecraft such as NASA's HiRISE craft to look for new craters and pinpoint the impact location using the following approach:

#### Stage 1

Use the S minus P time to determine distance from the seismometer.

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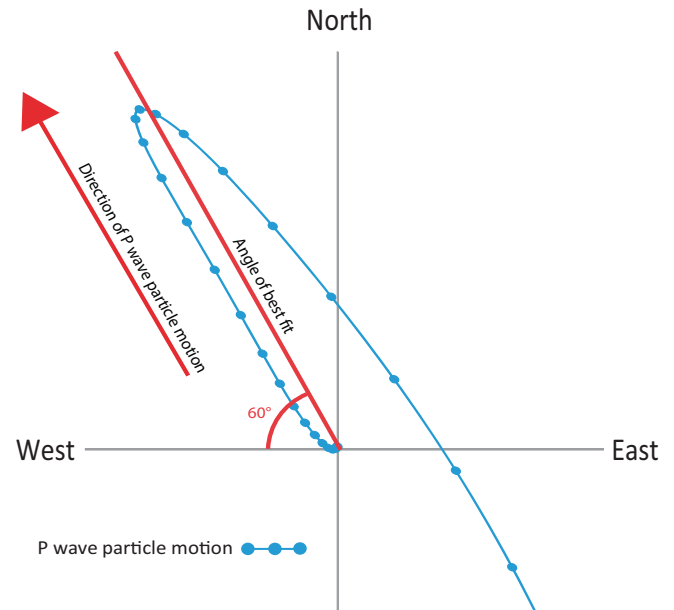


## Stage 2

Find the directionality of the trace from your seismic data.

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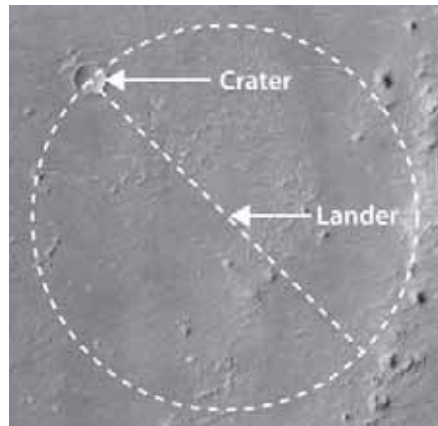
If you know the alignment of your two sensors (for example North–South and East–West) then the trace will give you a relative bearing of the event location.



## Stage 3

Draw a circle of locus around your accelerometer and map your bearing over it. Use this to locate the crater.

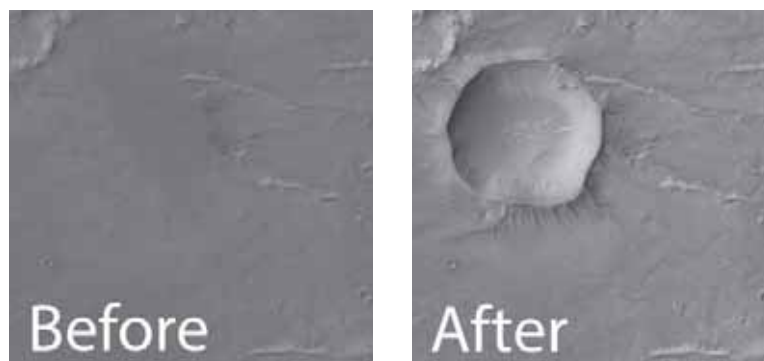
Image: NASA



## Stage 4

Use HiRISE images to compare before and after images of the location to study the crater in more detail.

Image: NASA



Once the crater has been investigated, the information about the impactor, as well as the P-wave and S-wave traces, will allow scientists to begin to determine information about the structure and composition of the interior of Mars.

# Crater formation: background science

## Impact craters

Impact craters are formed on a planet or moon when a smaller object collides with the surface at a very high velocity (typically  $15\,000\text{ ms}^{-1}$ ). An impact crater is identifiable by its approximately circular shape, raised rim, pattern of ejected material and crater floor that is lower than the surrounding surface.

This impact crater was captured by the HiRISE (High Resolution Imaging Experiment) camera on-board NASA's Mars Reconnaissance Orbiter.

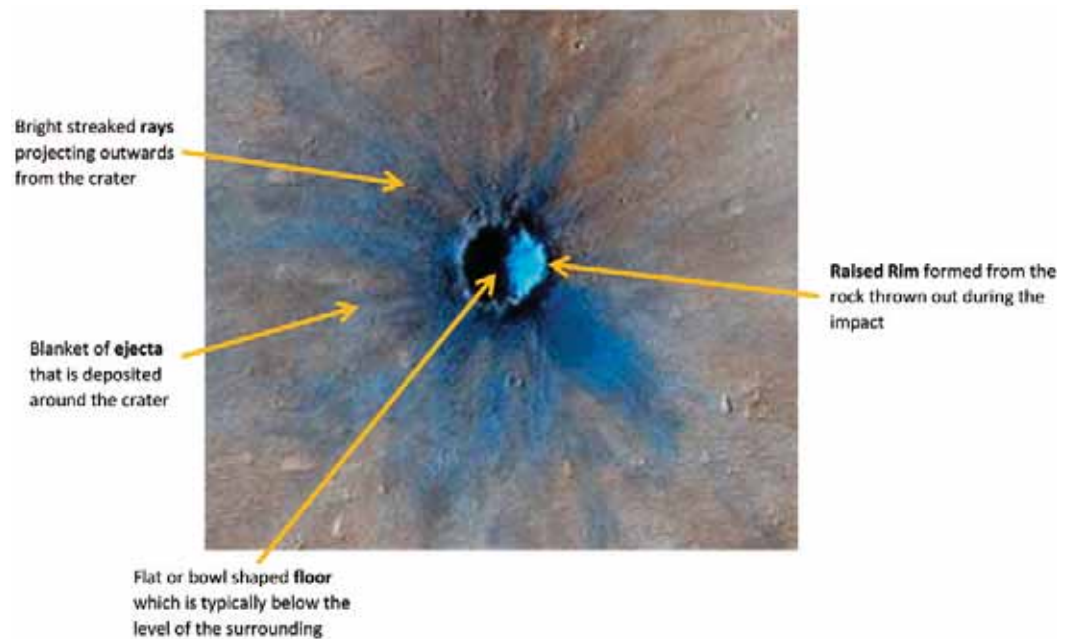


Image: NASA/JPL/University of Arizona

Many objects in the Solar System, for example Mars, Earth's Moon and Mercury, have their surface covered in impact craters. For other objects, including the Earth, visible impact craters are far less common; these objects have active geological processes and the impact craters become weathered over time.

## What happens after an impact?

### Simple crater formation

The smallest impact craters on a planet's surface are called simple craters, because they have simple bowl-like shapes.

These craters are excavated when an impactor, i.e. an asteroid or comet hits the surface creating a shock wave that radiates into the crust of the planet.

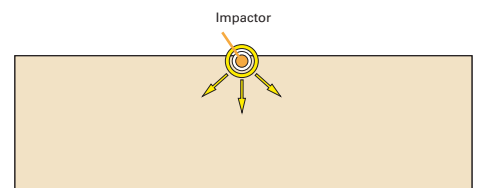
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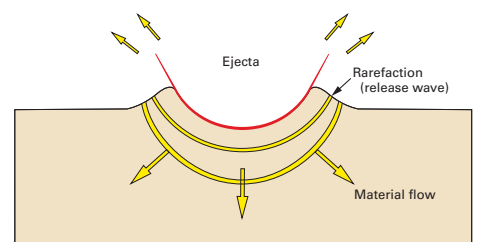
#### Contact and compression stage

This stage begins immediately after the impactor has impacted the target. The projectile travels into the surface of the planet, moving and compressing the material in its way and creating shockwaves. The initial energy of the impactor is transferred into other forms, mainly heat. This leads to the melting and vapourisation of material at the impact site. Following on from this, a release wave, or rarefaction as it is also known, will travel through the projectile, ending the first stage of crater formation. This stage does not take very much time to complete — for the Barringer crater in the Arizona desert, it would have lasted just a few milliseconds.

#### Initial contact and compression stage



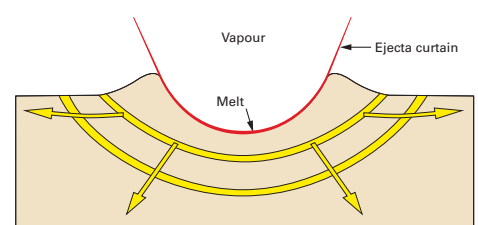
#### End of contact and compression stage



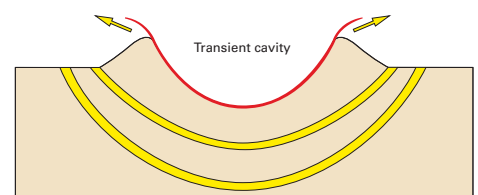
#### Excavation stage

The shockwave continues to travel through the target, followed by the rarefaction wave. Material is pushed downwards and thrown outwards, beginning to form the crater cavity. Some of this material is launched above the surface of the planet in the form of an ejecta curtain. This ejecta curtain is deposited onto the ground surrounding the crater forming a lip. Again, to give an idea of time frames, for the Barringer crater, this stage would have lasted around 10 seconds.

#### Initial excavation stage



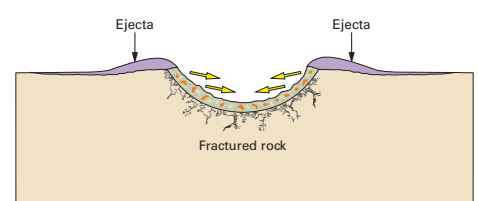
#### End of excavation stage



#### Modification stage

The crater cavity begins to collapse under the influence of gravity with some material falling back into the crater. Portions of the external walls can slump and collapse. If the crater is large enough, central peaks or rings will form.

#### Modification stage



## Complex crater formation

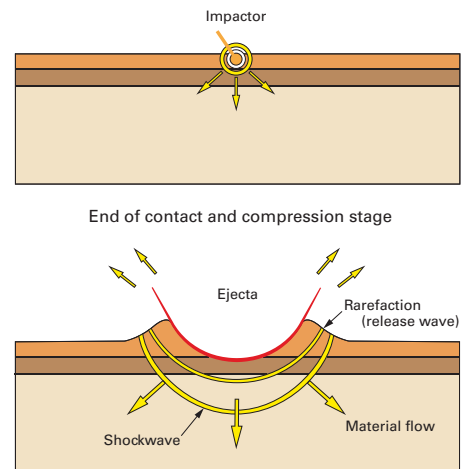
Large impactors, i.e. asteroids and comets, produce complex craters with crater walls that are so steep they are prone to collapse and uplifted rock in the centre that forms high central peaks or central peak rings.

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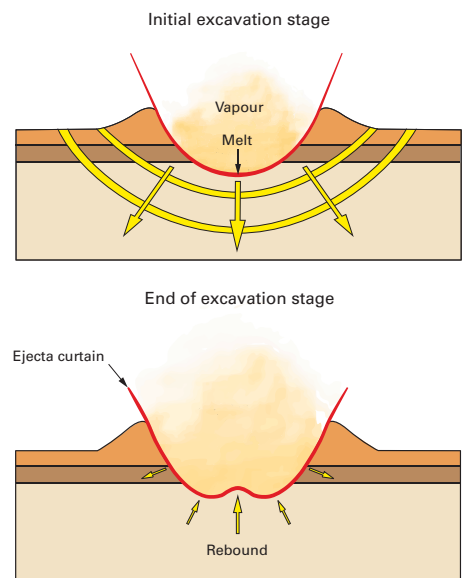
### Contact and compression stage

For complex craters, the initial compression stage is similar to that for simple craters.



### Excavation stage

During the end excavation stage a central peak rises, or rebounds, from the crater floor.

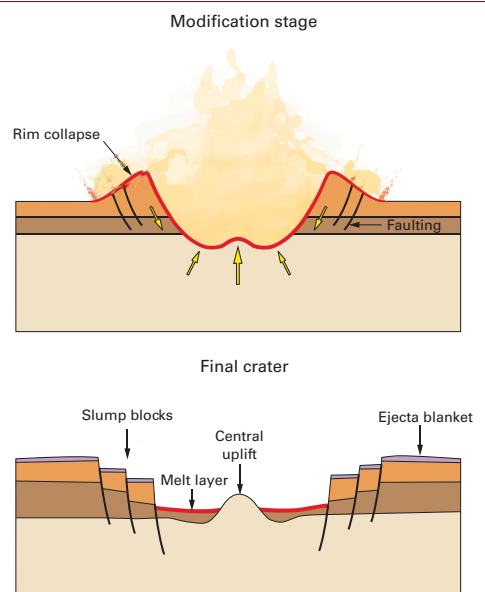


### Modification stage

The walls of the crater collapse to form a modified zone of slumped blocks or rocks near the crater rim. Compared with simple craters, much more melt is produced and can form a thick impact melt sheet within the crater.

In the largest impact events, the uplifted central peak will collapse into a central peak ring (not shown in diagram).

On Earth, the Chicxulub Crater is the best example of a complex peak ring crater with an extensive melt sheet, although it is buried under sediments.



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[www.bgs.ac.uk/marsquake](http://www.bgs.ac.uk/marsquake)