# A tectonic origin for the largest marsquake observed by InSight

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**Key Points:**

- The S1222a marsquake detected by InSight on May 4, 2022 somewhat resembled previous impact-generated events
- We performed an image search in the estimated source region, using data from multiple Mars orbiter missions
- No new impact crater has been discovered in this area, pointing to a tectonic origin for the quake.

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## Abstract

The S1222a marsquake detected by InSight on 2022-05-04 was the largest of the mission, at $M_w^{Ma}$ 4.7. Given its resemblance to two other large seismic events (S1000a and S1094b), which were associated with the formation of fresh craters, we undertook a search for a fresh crater associated with S1222a. Such a crater would be expected to be ∼300 m in diameter and have a blast zone on the order of 180 km across. Orbital images were targeted and searched as part of an international, multi-mission effort. Comprehensive analysis of the area using low- and medium-resolution images reveals no relevant transient atmospheric phenomena and no fresh blast zone. High-resolution coverage of the epicentral area from most spacecraft are more limited, but no fresh crater or other evidence of a new impact have been identified in those images either. We thus conclude that the S1222a event was highly likely of tectonic origin.

## Plain Language Summary

During its time on Mars, NASA's InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission recorded over 1,300 seismic events, known as 'marsquakes'. Of these, a number were identified as coming from meteoroid impact cratering events on the surface. The largest event identified by InSight, labelled S1222a, bore some similarities to two large impact events recorded earlier in the mission. In order to investigate whether the S1222a event might also have been caused by an impact event, we undertook a comprehensive search of the region in which the marsquake occurred. We did not identify any fresh craters in the area, implying that the marsquake was likely caused by geological processes.


## 1 Introduction

On May 4, 2022, NASA's InSight mission recorded the seismic waves from an event on Mars of magnitude $M_w^{Ma}$ 4.7 ± 0.2. This event, labelled S1222a in the catalogue, was the largest of the mission and displayed characteristics spanning all previously identified marsquake families (?, ?). It also displayed clear evidence of surface waves (?, ?).

Seismic data were recorded on the InSight's Very Broad Band (VBB) Seismometer (?, ?, ?). Based upon travel time differentials and signal polarisation, this event was located within a near-ellipse with an epicentre near 3.0°S, 171.9°E; 37° from InSight (?, ?). This region is just north of the dichotomy boundary. Orbital images indicate the presence of wrinkle ridges in the region, which could indicate past tectonic activity nearby (?, ?).

Surface waves had only been identified previously for two other events, both in 2021: S1000a (126.7° away) and S1094b (58.5° away) (?, ?), at magnitudes $M_w^{Ma}$ 4.1 ± 0.2 and $M_w^{Ma}$ 4.0 ± 0.2, respectively (?, ?). In the case of both S1000a and S1094b, orbital image searches confirmed the presence of large, fresh craters at the expected seismic epicentres. The formation times of these craters matched the occurrence times of the events, indicating that they were of meteoroid impact origin (?, ?). Both craters were in the 100 - 200 m diameter range, significantly larger than both the average size of new martian craters in the present era (?, ?) and the other impact events detected seismically by InSight (?, ?, ?).

Owing to their frequency content, all three events, S1222a, S1094b and S1000a have been classified as broadband (BB) by the MarsQuake Service (MQS) (?, ?, ?). Fig. 1 shows filtered time-domain seismograms of S1222a compared to the two confirmed impacts, arranged by increasing epicentral distance. The signal is shown filtered into two main frequency bands of 0.05-1 Hz and 1-8 Hz, in order to demonstrate both the comparative low-frequency and high-frequency content of the three events. These bands are chosen

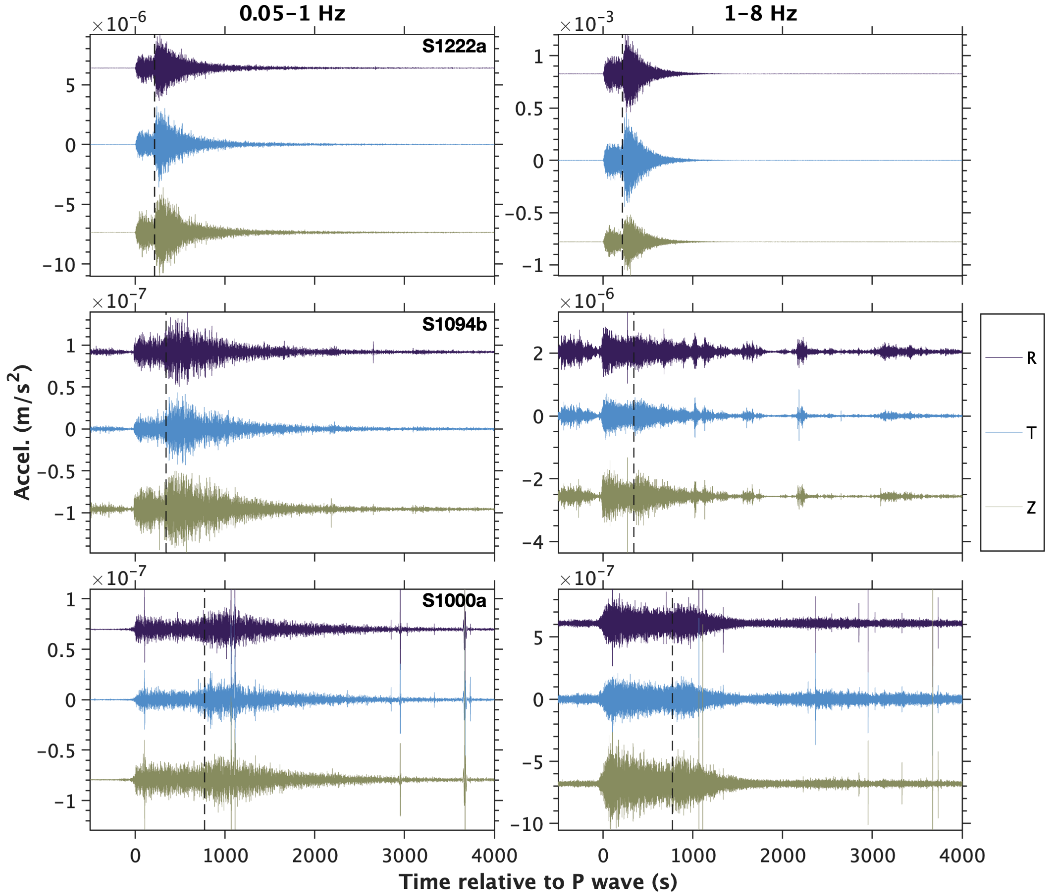


**Figure 1.** Seismograms from the S1222a event and the two confirmed impact-generated events, S1000a and S1094b. Acceleration data are presented from InSight's VBB sensor. Two frequency bands are shown: 0.05 - 1 Hz (left) and 1 - 8 Hz (right). The waveforms have been rotated to radial, transverse and vertical (RTZ) directions using the estimated back azimuth information (for S1222a) (?, ?) and the measured back azimuth from imaged crater locations (for S1094b and S1000a) (?, ?). Seismograms are aligned at zero seconds by the first P-wave arrival (PP for S1000a), while the dashed lines indicate the first S-wave arrival (SS for S1000a)(?, ?).

as they are close to those used by MQS to classify events on Mars (?, ?). Spectrograms of these events are also shown in Fig. 2.

There are numerous similarities between S1222a and the two confirmed impact events. All three events show:

- Long-period surface wave trains; these are also the only three events with identified surface waves.
- Energy spanning a broad range of frequencies, across a broader spectrum than most other events.
- Long-duration codas, with low-frequency energy (< 1 Hz, lasting up to ∼10.5 hours for the larger S1222a event and 1.5-2 hours for both S1000a and S1094b (?, ?)).

However, some differences are also apparent in addition to the much larger magnitude of S1222a:

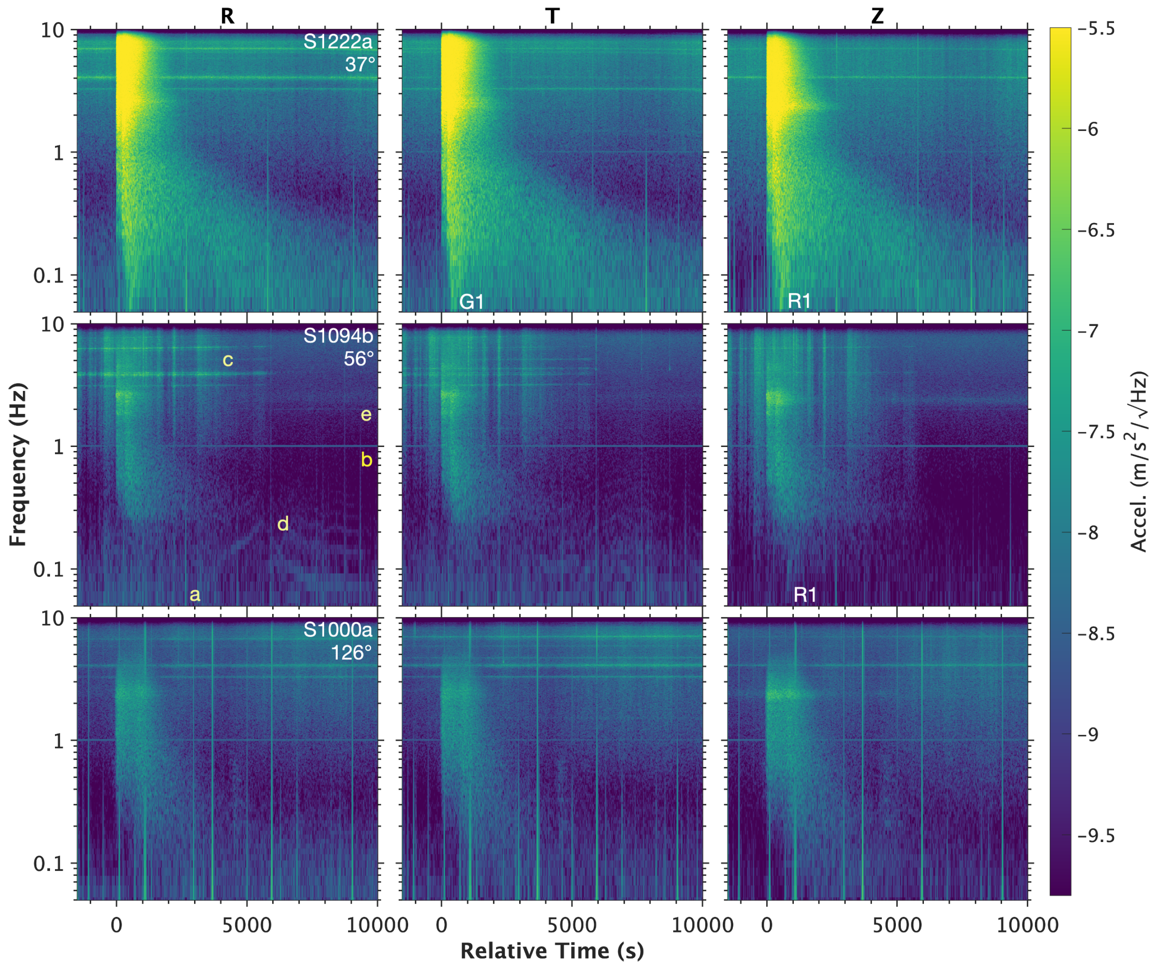


**Figure 2.** Acceleration spectrograms of the S1222a, S1094b and S1000a events rotated into the source-centred coordinate system (RTZ), as in Figure 1. The spectrograms are calculated using 80 s long Hanning windows of the continuous 20 samples/second VBB acceleration. Time is relative to P-wave arrival (PP for S1000a). **Signal**: Surface waves have been observed for all three events; fundamental Love waves (G1) and Rayleigh waves (R1) can be viewed by the naked eye for frequencies below 0.15 Hz at ∼360s in the T component and ∼500s in both R and Z components for S1222a (?, ?), while the R1 for S1094b arrives ∼800s later and is visible in the Z component (?, ?). **Noise**: several noise sources are apparent in all spectrograms: (a) high-amplitude transient spikes which are glitches or donks; (b) the persistent horizontal feature at 1 Hz is tick noise (?, ?). (c) Broadband noise and lander resonances can be seen co-excited by atmospheric injection during windy periods (?, ?), with the modes appearing as horizontal features at several frequency bands, with the most prominent at 4 Hz. (d) Dispersive patterns with overtones emerging during the latter half of S1094b correspond to sunset chirps, a daily feature in late afternoon most visible after the windy period ends (?, ?). (e) The 2.4 Hz resonance is observed consistently during the quiet evening period and excited by all three events.

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- S1222a includes a significantly richer family of surface-wave arrivals, including not only fundamental Rayleigh waves (R1) but also Love waves (G1).
- S1222a also displays overtones and successive multi-orbit major- and minor-arc Rayleigh waves, unlike the two large impact events.
- The S1222a ratio of P-wave energy to S-wave energy is lower than for S1000a or S1094b in the highest frequency bands (Fig. 1b). This may indicate a greater deviatoric component to the source mechanism (?, ?, ?) as may occur from a double-couple fault rather than an isotropic explosive impact source.

Given the extraordinary nature of the S1222a event, and the above similarities to the large confirmed impacts of S1000a and S1094b, it was prudent to consider the possibility of an impact origin. Thus an effort was mounted to search for a fresh crater or other transient signal (e.g. an impact-generated dust cloud) associated with this event that would prove an impact origin.

If S1222a were an impact event, the crater size would likely have been extremely large ($\geq$ 300 m). This estimate is based upon the relationship between seismic moment and crater diameter; where the seismic moment is expected to scale with crater diameter to the power of $\sim$3.3. This estimate is informed by impact modelling results and calibrated against a set of small seismically detected impacts on Mars (?, ?, ?).

It should be noted that the size of this event means that the scaling relationship is extrapolated significantly, and hence the predicted diameter estimates for S1222a come with broad uncertainties. Similarly speculative extrapolation of relationships making assumptions about surface properties (?, ?) suggests that such a crater would have a blast zone in the $\sim$180 km diameter range.

The S1000a and S1094b craters produced blast zones large enough to be visible in low-resolution images from MRO's MARCI (Mars Color Imager) (?, ?, ?). Under similar surface conditions an impact event of this size would also have been expected to produce a large blast zone.

Conversely, a lack of a fresh crater or blast zone, given surface images of sufficient coverage and resolution, would be a strong indication of a non-impact/tectonic origin. This paper describes that search, including excluding the formation of smaller or more irregular crater(s) due to atmospheric breakup or impact into steep topography.

This paper constitutes an international collaboration between all but one of the missions currently operating in orbit at Mars. We hope that it will also prove a useful template for similar collaborations in the future.

## 2 Methodology

### 2.1 Crater-seismic associations

Making the association between a given seismic event and a fresh crater is challenging. This is partly due to the limited number of camera-equipped spacecraft in orbit around the planet. They make infrequent overpassses of any given area, and come with limitations on data volume and operational constraints on imaging. It is also partly due to the fact that most fresh craters of interest are sub-pixel size in images taken with all but the highest resolution instruments. Complex surface topography, e.g. steep slopes, can also further complicate matters by disguising fresh craters to the point that they are difficult to recognise from orbit (?, ?).

## 2.2 Blast zone detection

In dusty areas, fresh craters are surrounded by blast zones (regions where the shockwave from the incoming meteoroid has interacted with the surface). These can be tens or even hundreds of times larger than the crater itself (?, ?), and as such are often the first component of a fresh crater to be identified in orbital images. As blast zones fade on the order of decades (?, ?), they can be used to indicate geologically recent impact phenomena.

Although the larger areal extent of fresh blast zones as compared to fresh craters generally simplifies the search problem, the exact surface conditions and processes involved in their formation remain unclear (?, ?, ?). Blast zones are more prevalent on dusty surfaces (and the S1222a search area is indeed dusty), but they can also be obscured or disguised by local heterogeneities or topography.

As such, low-resolution image searches alone are not sufficient to exclude an impact-generated hypothesis for S1222a's origin; as a blast zone might be missed. Searches for associated transient phenomena and high-resolution sampling of key areas must be used to reinforce our conclusion of a non-detection of a fresh crater of the requisite size.

## 2.3 Image analysis

Images taken as part of our search campaigns can be divided into two categories: repeat images where visual change detection is possible, and those where fresh features are sought without past reference.

In the first category, where 'before' images of a given region exist, post-event 'after' images can also be captured to enable direct change detection. This is generally easier if the same instrument is used for both images in a before-after pair.

However, recent high-resolution coverage of Mars' surface is limited, meaning that in many places only suitable 'after' images exist (the second category). In such cases, searches can only seek to identify fresh craters; which may be identified as 'fresh' through features of their morphology, ejecta, and blast zones.

## 2.4 Potentially observable features

High resolution instruments such as HiRISE (High-Resolution Imaging Science Experiment) on NASA's Mars Reconnaissance Orbiter (MRO) have narrow fields of view (?, ?). Their coverage of the surface is generally limited as compared to wider field instruments such as the context camera (CTX) on MRO (?, ?).

As discussed above, blast zones around fresh craters can be observed more easily than the craters themselves, using medium-resolution (larger field of view/month-to-year cadence) instruments such as MoRIC (the Moderate Resolution Imaging Camera) on CNSA's Tianwen-1 (?, ?), CaSSIS (the Colour and Stereo Surface Imaging Subsystem) on the Trace Gas Orbiter (TGO, (?, ?)), or CTX on MRO. The latter of these has identified the majority of date-constrained impacts (?, ?).

We also explored the possibility that transient atmospheric phenomena (e.g. dust clouds) may have formed following an impact event of this size. Modelling on this topic conducted to date is extremely limited and mostly confined to terrestrial rather than planetary settings (?, ?), but we nonetheless examine high-cadence (hours-to-days), wide field of view images such as those from the ESA Mars Express VMC (Visual Monitoring Camera) instrument as part of a search for these (?, ?).

### 2.5 Instruments involved

Table 1 lists the instruments involved in our search. Of the eight spacecraft in operation around Mars during 2022, seven were involved in this effort.

The pixel scale of the imagers spans 0.25 m (HiRISE) to ∼35 km (VMC). We group them into three categories:

- High-resolution imagers (≤1 m/pixel), providing images of small fractions of the total surface area, selected for particular interest
- Medium-resolution imagers (1-100 m/pixel), providing images of substantial fractions of the search area; in some regions with 'before' images (taken up to several years before S1222a with the same instrument) available as well as new 'after' images
- Low-resolution imagers (≥100 m/pixel, providing images of the entire search area on a regular (hours-to-day cadence) basis

## 3 Imaging strategy

Following the occurence of S1222a on 2022-05-04, new 'before' images of the area to enable change detection could clearly not be gathered *ex post facto*. The low-resolution instruments' regular observations of much of Mars' surface on a daily basis meant that no novel data collection strategy was required for them. However, for some of the medium- and high-resolution instruments, specific imaging strategies could be implemented to optimise the likelihood of finding a fresh crater. The strategy devised was as follows:

- High-resolution instruments: sampling near the estimated epicentre and nearby areas of specific varied topography, to catch any 'hidden' fresh blast zones immersed in shadow or on steep slopes (change detection not possible as limited 'before' images acquired)
- Medium-resolution instruments: Overlapping imaging of the centre of the uncertainty 'ellipse', working outward, with the aim of identifying new blast zones
- Low-resolution instruments: continued regular imaging of the surface and atmosphere, with the aim of identifying new large dark spots in the days after the event, or transient atmospheric phenomena in the hours after it

## 4 Results

### 4.1 Low-resolution images

Overflights of the epicentral region in the hours to days after S1222a by the VMC and EXI instrument data gave no indication of new dark patches (blast zones) or unusual atmospheric phenomena. MARCI data were not publicly available through most of the time of writing, and hence have not been analysed by the authors themselves. However, initial inspections by the MARCI team did not indicate any unusual features.

The absence of a clear blast zone indicates that if a crater did form, it likely did so on unusually complex topography or on a dust-free surface, which might suppress or limit blast zone formation. Although the S1222a source region is quite dusty (?, ?), areas of steep topography do exist in the surrounding area (?, ?).

### 4.2 Medium-resolution images

Near-total coverage of the source region was achieved by multiple medium-resolution instruments (MoRIC, HRSC, and THEMIS in its near-infrared band). Some CTX data

| Spacecraft | Operator | Instrument | Pixel Scale (m/px) | Type | Reference |
|---|---|---|---|---|---|
| Emirates Mars Mission, Hope (EMM) | UAESA | EXI | 2000 | UV/Visible (colour) | (?, ?) |
| ExoMars Trace Gas Orbiter (TGO) | ESA | CaSSIS | 4.6 | Visible (colour) | Thomas et al (2017) |
| Mangalyaan Mars Orbiter Mission (MOM) | ISRO | MCC | $\sim$ 15 | Visible (colour) | (?, ?) |
| Mars Express (MEX) | ESA | VMC | $\sim$ km | Visible (colour) | (?, ?) |
| Mars Express (MEX) | ESA | HRSC | 15 | Visible (colour) | (?, ?) |
| Mars Odyssey (MOY) | NASA | THEMIS | NIR: 100/Vis: 18 | NIR/Visible (colour) | (?, ?) |
| Mars Reconnaissance Orbiter (MRO) | NASA | HiRISE | 0.25 | Visible (colour) | (?, ?) |
| Mars Reconnaissance Orbiter (MRO) | NASA | CTX | (6) | Visible (greyscale) | (?, ?) |
| Tianwen-1 (TIANWEN) | CNSA | HiRIC | 0.5 | Visible (colour) | (?, ?) |
| Tianwen-1 (TIANWEN) | CNSA | MoRIC | 98 | Visible (colour) | (?, ?) |

**Table 1.** The ten imaging systems involved in the search for any crater associated with the S1222a marsquake. Minimum possible instrument pixel scales are also included - note that all images used in this study may not be at exactly this scale. Data for Tianwen-1's HiRIC Camera and MOM's MCC were examined, but did not contain any images of the region of interest after the date of S1222a. MOM has since ceased to be operational so further data are not expected.

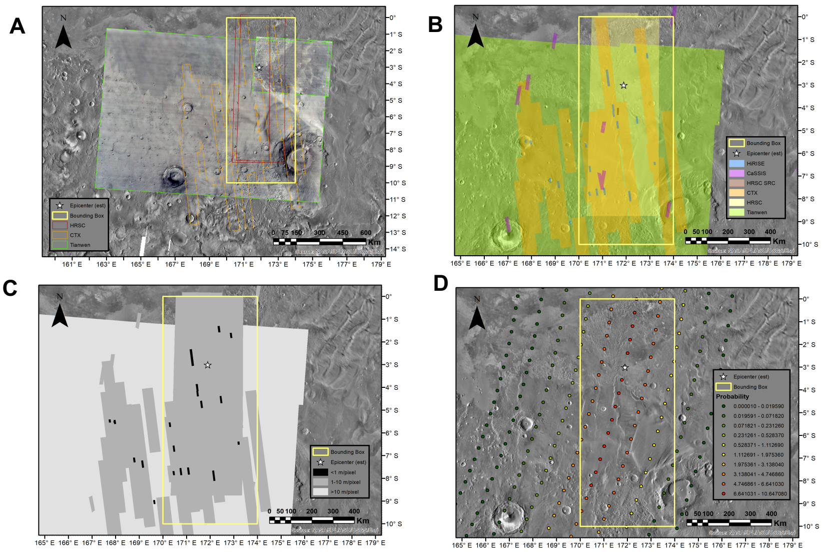


**Figure 3.** The areas imaged as part of this search. In all cases, the yellow rectangle shows the 10○ x 4 ○ primary search box, the white star is the body-wave estimated epicentre of S1222a, and the underlying images are from THEMIS, which mapped the entire area in visible light (∼100 m/pixel). A) shows the regional context of the imaged area, and demonstrates the near-total coverage by medium-resolution instruments (CTX, Tianwen/MoRIC, and HRSC). B) Shows a detail of the search area itself, also including the areas sampled at the highest resolutions. C) shows the variation in pixel scale with area (with ranges given to account for the fact that instrument pixel scales are not constant. D) shows the projections of the probability map for S1222a on area. Each dot represents the probability of the event having epicentre being in the surrounding cell. The colour-coding is the probability of the event epicentre being in that cell, with red being the highest probability and green the lowest. Note that the 'ellipse' formed by the probability map is irregular, accounting for the greater uncertainty in event azimuth than event distance.

in the region of interest was also available. Footprints of these images are all shown in Fig. 3.

No new or unusual features were found in the visible bands, and no thermal anomalies (e.g. those associated with a blast zone due to dust removal and/or surface darkening) were identified in the near-infrared.

In the case of the near-infrared mapping on THEMIS, which would be expected to be particularly sensitive to new thermal anomalies, this is complicated by the terminator-following orbit the spacecraft is currently in.

### 4.3 High-resolution images

A 'sampling' approach was taken with high-resolution instruments, wherein a series of images across the centre of the ellipse and areas of particularly steep topography were gathered. No new crater or indications of surface disturbances other than slope streaks (?, ?) were identified through this search, either.

The images gathered also do not support the hypothesis that the meteoroid disintegrated in the atmosphere prior to impact. The breakup of an impactor of the size required to produce the S1222a would have produced a widely-strewn spread of secondary craters (?, ?), of which there is no evidence in the high-resolution images.

### 4.4 Potential further datasets

Although these data were not explored in this paper, the impacts of a meteoroid atmospheric entry and impact may potentially be noticeable in other Mars spacecraft data. For example, NASA's MAVEN spacecraft (?, ?) has previously recorded the effects of meteor showers on the upper atmosphere in visible and UV light (?, ?). Further studies may wish to consider this line of investigation further.

Similarly, large impact events may generate substantial acoustic waves which may propagate a great distance through the atmosphere under certain conditions (?, ?). Such a signal might theoretically be detectable by the pressure sensors on both the InSight lander and the Mars Rovers (Curiosity/Perserverance); though this has not yet bee explored. due to power constraints all atmospheric sensors on-board InSight were switched off at the time of S1222a.

## 5 Conclusions

Multiple lines of evidence from our search of orbital images point toward S1222a not being an event of impact origin. The lines of evidence are:

- The absence of transient atmospheric phenomena such as dust clouds in low-resolution, global images taken immediately after S1222a (weak constraint - the formation mechanism, duration, composition, and size of any such impact-generated dust cloud on Mars are not well known)
- The absence of any new or fresh dark patches (blast zones) in any of the medium-resolution images covering the search box (strong constraint - the entire area has been mapped at medium resolution, and given the large magnitude of this event, medium resolution imaging should be sufficient to detect an impact of the expected size)
- The absence of suitable fresh craters, blast zones, or fields of secondary craters/secondary blast zones in the limited high-resolution imaging of the source region thus far (intermediate constraint - areas imaged and searched thus far cover a small percentage of the possible source region).

These lines of reasoning lead us to conclude with a high level of confidence that the S1222a event was not associated with a meteoroid impact event. The only explanation which is consistent with current observations is a subsurface tectonic source. Future work will explore in more detail potential seismic discriminators which this event enables, including detailed analysis of the S1222a waveforms and differences between this and large impact events.

The tectonic setting within the epicentral ellipse is very different to that of the Cerberus Fossae region where the strongest other tectonic marsquakes have occurred (?, ?). As such, the proposed source mechanism of S1222a, and its likely tectonic context, remain to be explored and will be a topic for future work.

## 6 Open Research

SEIS data are available from the InSight Mars SEIS Data Service at IPGP, IRIS-DMC and NASA PDS (InSight Mars SEIS Data Service, 2019).

HiRISE data are available from `https://www.uahirise.org/catalog/`, CaSSIS and HRSC data are available from the ESA Planetary Science Archive (`https://archives.esac.esa.int/psa/#!Home\%20View`) VMC data are available from `https://blogs.esa.int/vmc/vmc-data-archive/`, CTX data are available on the NASA Planetary Data System (`https://pds.nasa.gov`). MoRIC and EXI data were sourced directly from the relevant mission teams (personal communication).

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## References

Arya, A., Rajasekhar, R., Singh, R., Sur, K., Chauhan, P., Sarkar, S., … others (2015). Mars color camera onboard mars orbiter mission: Initial observations and results. In *46th annual lunar and planetary science conference* (p. 2123).

Banerdt, W. B., Smrekar, S. E., Banfield, D., Giardini, D., Golombek, M., Johnson, C. L., … others (2020). Initial results from the insight mission on mars. *Nature Geoscience*, *13*(3), 183–189.

Bart, G. D., Daubar, I. J., Ivanov, B. A., Dundas, C. M., & McEwen, A. S. (2019). Dark halos produced by current impact cratering on mars. *Icarus*, *328*, 45-57. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0019103518307206` doi: https://doi.org/10.1016/j.icarus.2019.03.004

Bell, J. F. I., Wolff, M. J., Malin, M. C., Calvin, W. M., Cantor, B. A., Caplinger, M. A., … Thomas, P. C. (2009). Mars reconnaissance orbiter mars color imager (marci): Instrument description, calibration, and performance. *Journal of Geophysical Research: Planets*, *114*(E8). Retrieved from `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008JE003315` doi:

https://doi.org/10.1029/2008JE003315

Ceylan, S., Clinton, J. F., Giardini, D., Böse, M., Charalambous, C., Van Driel, M., ... others (2021). Companion guide to the marsquake catalog from insight, sols 0–478: Data content and non-seismic events. *Physics of the Earth and Planetary Interiors*, *310*, 106597.

Ceylan, S., Clinton, J. F., Giardini, D., Stähler, S. C., Horleston, A., Kawamura, T., ... Banerdt, W. B. (2022). The marsquake catalogue from insight, sols 0–1011. *Physics of the Earth and Planetary Interiors*, *333*, 106943. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0031920122001042` doi: https://doi.org/10.1016/j.pepi.2022.106943

Charalambous, C., Stott, A. E., Pike, W., McClean, J. B., Warren, T., Spiga, A., ... others (2021). A comodulation analysis of atmospheric energy injection into the ground motion at insight, mars. *Journal of Geophysical Research: Planets*, *126*(4), e2020JE006538.

Christensen, P. R., Jakosky, B. M., Kieffer, H. H., Malin, M. C., McSween, H. Y., Nealson, K., ... others (2004). The thermal emission imaging system (themis) for the mars 2001 odyssey mission. *Space Science Reviews*, *110*, 85–130.

Daubar, I., McEwen, A., Byrne, S., Kennedy, M., & Ivanov, B. (2013). The current martian cratering rate. *Icarus*, *225*(1), 506–516.

Daubar, I. J., Dundas, C. M., Byrne, S., Geissler, P., Bart, G., McEwen, A. S., ... Golombek, M. (2016). Changes in blast zone albedo patterns around new martian impact craters. *Icarus*, *267*, 86–105.

Daubar, I. J., Dundas, C. M., McEwen, A. S., Gao, A., Wexler, D., Piqueux, S., ... Werynski, A. (2022). New craters on mars: An updated catalog. *Journal of Geophysical Research: Planets*, *127*. doi: 10.1029/2021je007145

Daubar, I. J., Fernando, B. A., Garcia, R. F., Grindrod, P. M., Zenhäusern, G., Wójcicka, N., ... Banerdt, W. B. (2023). Two seismic events from insight confirmed as new impacts on mars. *The Planetary Science Journal (submitted)*.

Dundas, C. M., Mellon, M. T., Posiolova, L. V., Miljković, K., Collins, G. S., Tornabene, L. L., ... others (2023). A large new crater exposes the limits of water ice on mars. *Geophysical Research Letters*, *50*(2), e2022GL100747.

Garcia, R. F., Brissaud, Q., Rolland, L., Martin, R., Komatitsch, D., Spiga, A., ... Banerdt, B. (2017). Finite-difference modeling of acoustic and gravity wave propagation in mars atmosphere: application to infrasounds emitted by meteor impacts. *Space Science Reviews*, *211*, 547–570.

Garcia, R. F., Daubar, I. J., Beucler, E., Posiolova, L. V., Collins, G. S., Lognonné, P., ... Banerdt, W. B. (2022). Newly formed craters on mars located using seismic and acoustic wave data from insight. *Nature Geoscience*, *15*, 774–780. (Citation Key: Garcia2022) doi: 10.1038/s41561-022-01014-0

InSight Marsquake Service. (2023). *Mars Seismic Catalogue, InSight Mission; V13 2023-01-01.* ETHZ, IPGP, JPL, ICL, Univ. Bristol. Retrieved from `https://www.insight.ethz.ch/seismicity/catalog/v13` doi: 10.12686/a19

Jakosky, B. M., Lin, R. P., Grebowsky, J. M., Luhmann, J. G., Mitchell, D., Beutelschies, G., ... others (2015). The mars atmosphere and volatile evolution (maven) mission. *Space Science Reviews*, *195*, 3–48.

Jaumann, R., Neukum, G., Behnke, T., Duxbury, T. C., Eichentopf, K., Flohrer, J., ... others (2007). The high-resolution stereo camera (hrsc) experiment on mars express: Instrument aspects and experiment conduct from interplanetary cruise through the nominal mission. *Planetary and Space Science*, *55*(7-8), 928–952.

Jones, A., Wolff, M., Alshamsi, M., Osterloo, M., Bay, P., Brennan, N., ... others (2021). The emirates exploration imager (exi) instrument on the emirates mars mission (emm) hope mission. *Space Science Reviews*, *217*, 1–56.

Kawamura, T., Clinton, J. F., Zenhäusern, G., Ceylan, S., Horleston, A. C., Dahmen, N. L., ... Banerdt, W. B. (2022). S1222a - the largest marsquake detected by insight. *Geophysical Research Letters*, *n/a*(n/a), e2022GL101543. doi: https://doi.org/10.1029/2022GL101543

Kim, D., Banerdt, W. B., Ceylan, S., Giardini, D., Lekić, V., Lognonné, P., ... Panning, M. P. (2022, 10 28). Surface waves and crustal structure on mars. *Science*, *378*(6618), 417–421. doi: 10.1126/science.abq7157

Lognonné, P., Banerdt, W. B., Giardini, D., Pike, W. T., Christensen, U., Laudet, P., ... others (2019). Seis: Insight's seismic experiment for internal structure of mars. *Space Science Reviews*, *215*, 1–170.

Lucas, A., Daubar, I. J., Le Teuff, M., Perrin, C., Kawamura, T., Posiolova, L., ... McEwen, A. (under review). Discussion on seismically triggered avalanches on mars after the s1222a marsquake. *Geophys. Res. Letters*.

Malin, M. C., Bell, J. F., Cantor, B. A., Caplinger, a. M., Calvin, W. M., Clancy, R. T., ... Wolff, M. J. (2007, 5 18). Context camera investigation on board the mars reconnaissance orbiter. *Journal of Geophysical Research*, *112*(E5), E05S04. doi: 10.1029/2006JE002808

McEwen, A. S., Eliason, E. M., Bergstrom, J. W., Bridges, N. T., Hansen, C. J., Delamere, W. A., ... Weitz, C. M. (2007). Mars reconnaissance orbiter's high resolution imaging science experiment (hirise). *Journal of Geophysical Research: Planets*, *112*(E5).

Meng, Q., Wang, D., Wang, X., Li, W., Yang, X., Yan, D., ... others (2021). High resolution imaging camera (hiric) on china's first mars exploration tianwen-1 mission. *Space Science Reviews*, *217*, 1–29.

Ormston, T., Denis, M., Scuka, D., & Griebel, H. (2011). An ordinary camera in an extraordinary location: Outreach with the mars webcam. *Acta Astronautica*, *69*(7-8), 703–713.

Posiolova, L. V., Lognonné, P., Banerdt, W. B., Clinton, J., Collins, G. S., Kawamura, T., ... Zenhäusern, G. (2022, 10 28). Largest recent impact craters on mars: Orbital imaging and surface seismic co-investigation. *Science*, *378*(6618), 412–417. doi: 10.1126/science.abq7704

Ruff, S. W., & Christensen, P. R. (2002). Bright and dark regions on mars: Particle size and mineralogical characteristics based on thermal emission spectrometer data. *Journal of Geophysical Research: Planets*, *107*(E12), 2–1.

Schneider, N. M., Deighan, J. I., Stewart, A., McClintock, W., Jain, S., Chaffin, M., ... others (2015). Maven iuvs observations of the aftermath of the comet siding spring meteor shower on mars. *Geophysical Research Letters*, *42*(12), 4755–4761.

Stähler, S. C., Mittelholz, A., Perrin, C., Kawamura, T., Kim, D., Knapmeyer, M., ... others (2022). Tectonics of cerberus fossae unveiled by marsquakes. *Nature Astronomy*, *6*(12), 1376–1386.

Taylor, S. R., Velasco, A. A., Hartse, H. E., Phillips, W. S., Walter, W. R., & Rodgers, A. J. (2002). Amplitude corrections for regional seismic discriminants. *Monitoring the Comprehensive Nuclear-Test-Ban Treaty: Seismic Event Discrimination and Identification*, 623–650.

Thomas, N., Cremonese, G., Ziethe, R., Gerber, M., Brändli, M., Bruno, G., ... others (2017). The colour and stereo surface imaging system (cassis) for the exomars trace gas orbiter. *Space science reviews*, *212*, 1897–1944.

Toon, O. B., Pollack, J. B., Ackerman, T. P., Turco, R. P., McKay, C. P., & Liu, M. (1982). Evolution of an impact-generated dust cloud and its effects on the atmosphere. *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*.

Walter, W. R., Dodge, D. A., Ichinose, G., Myers, S. C., Pasyanos, M. E., & Ford, S. R. (2018). Body-wave methods of distinguishing between explosions, collapses, and earthquakes: Application to recent events in north korea. *Seismological Research Letters*, *89*(6), 2131–2138.

Wojcicka, N., Collins, G. S., Bastow, I. D., Teanby, N. A., Miljković, K., Rajšić, A., … Lognonné, P. (2020). The seismic moment and seismic efficiency of small impacts on mars. *Journal of Geophysical Research: Planets*, *125*(10), e2020JE006540.

Wójcicka, N., Zenhäusern, G., Collins, G. S., Stähler, S. C., Daubar, I. J., Knapmeyer, M., … Ceylan, S. (2023). Impact rate on mars implied by seismic observations. In *54th lunar and planetary science conference 2023 (lpi contrib. no. 2806)*.

Yu, G., Liu, E., Liu, G., Zhou, L., Zeng, J., Chen, Y., … Zhu, S. (2020). Moderate resolution imaging camera (moric) of china's first mars mission tianwen-1. *Earth and Planetary Physics*, *4*(4), 364–370.