Draft version March 13, 2023
Typeset using LATEX default style in AASTeX631

PREPRINT OF MANUSCRIPT SUBMITTED TO THE PLANETARY SCIENCE JOURNAL - NOT YET PEER REVIEWED

Two seismic events from InSight confirmed as new impacts on Mars

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ABSTRACT

We report confirmed impact sources for two seismic events on Mars detected by the NASA InSight mission. These events have been positively associated with fresh impact craters identified from orbital images, which match predicted locations and sizes, and have formation time constraints consistent with the seismic event dates. They are both of the Very High Frequency family of seismic events and display impact-acoustic chirps. This brings the total number of confirmed martian impact-related seismic events to eight thus far. All seismic events with chirp signals have now been confirmed as having been caused by impact cratering events. This includes all seismic activity within 100 km of the lander, and two out of the four events with source locations between 100-300 km distance.

Keywords: Craters (2282) — Impact phenomena (779) — Mars (1007) — Planetary interior (1248) — Collisonal Processes (2286)

1. INTRODUCTION

The original scientific goals of NASA's InSight mission (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) required seismic detection of meteoroid impacts on the surface of Mars (Banerdt et al. 2020). InSight's prime mission (sols 1-668; 2018-11-27 through 2020-10-12) saw hundreds of seismic signals recorded, but no impact-generated seismic events were positively identified at the time. This lack of seismic impact detections continued for more than a martian year, despite predicted detection rates ranging from a few to tens per Earth year (Daubar et al. 2018), and despite ongoing orbital monitoring by the Mars reconnaissance Orbiter (MRO). This imaging did result in many new craters identified visually (Daubar et al. 2022), but not seismically.

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One impact that formed a 1.5-m diameter crater close to the InSight lander soon after landing was among those not detected seismically, which allowed the first experimental constraints to be placed on the seismic detectability of small impacts on Mars (Daubar et al. 2020). Two other non-detections of (artificial) impacts also enabled constraints to be placed on martian seismic efficiency: impacts of the NASA Mars 2020 Perseverance ballast mass impacts (Fernando et al. 2021a, 2022), and the Chinese Space Agency Tianwen-1 mission landing (Fernando et al. 2021b).

Later in the second martian year of operations (the first extended mission phase), four events detected by the seismometer were confirmed by orbital images to be impacts. These impacts were the first to be detected seismically on another planet (Garcia et al. 2022), and highlight the importance of extended mission phases to scientific discovery (Daubar et al. 2021). The first of these impact identifications was made based on analyses of an unusual seismic waveform in the coda of the Very High Frequency (VF; for definitions of seismic event types, see Clinton et al. 2021) event S0986c: a ‘chirp’ produced by normal dispersion of acoustic waves that were generated by the impact, propagated through the atmosphere, and then coupled to the ground near InSight (Garcia et al. 2022). These chirps can be modeled as guided infrasound waves (Xu et al. 2022). Hereafter we refer to these as *impact-acoustic chirp signals*.

These impact-acoustic chirp signals are relatively easy to identify in event spectrograms (Fig. 1), and have proved to be pivotal in the detection and location of impact-seismic events and their associated craters. The slow propagation speed of this acoustic wave, compared with the faster P- and S-waves that arrive earlier, allows for calculation of an accurate distance to the source. Moreover, the polarization of the chirp signal provides an estimation of the back azimuth (bearing) to the source (Garcia et al. 2022).

For event S0986c, follow-up imaging by orbital cameras showed a new cluster of craters at the predicted distance and back azimuth, with before and after image constraints bounding the event time that were compatible with the detection date of the seismic phases. Identification and analysis of the same type of impact-acoustic chirp signals in three other VF events provided orbital targeting locations that confirmed the presence of three further impacts (seismic events S0533a, S0793a, and S0981c). Two larger distant impacts, without impact-acoustic chirps, were also detected subsequently (seismic events S1000a and S1094b) (Posiolova et al. 2022; Kim et al. 2022; Dundas et al. 2022). These were larger Broad Band (BB) type events at much greater, teleseismic distances. In this paper, we report two additional verified impacts within 60 km of the lander. This makes for a total of eight impacts seismically recorded by the InSight mission (Table 1).

2. METHODOLOGY

2.1. *Seismology*

Seismic data were recorded on InSight’s SEIS (Seismic Experiment for Interior Structure) VBB (Very Broad Band) and Short Period (SP) seismometers (Lognonné et al. 2019; IPGP et al. 2019), and evaluated by the Marsquake Service (Clinton et al. 2021; Ceylan et al. 2022). Detected seismic events were classified as event types based on frequency content, and where possible, phase picks were made. Distances and back azimuths were estimated, assuming a fixed set of seismic velocities for the crust or the mantle, depending on the time difference between P and S arrivals (Clinton et al. 2021). For events close to the lander, especially when impact-acoustic chirps were also identified, further analysis was activated within the science team to refine the location and initiate orbital searches.

Two seismic events are discussed in this paper: S1034a (2021-10-23) and S1160a (2022-03-02). Both of these were estimated to be located close to the lander (48 and 57 km, respectively). Impact-acoustic chirp signals were identified for both of these VF-type events (Fig. 1). Analysis of the chirps using the technique of Garcia et al. (2022) allowed for estimatation of source locations (Table 1). VBB data were collected for both events, but not SP data.

Although the spacecraft’s pressure sensor was not recording during these impact events, the deformation of the surface due to incident acoustic waves (compliance effects, Garcia et al. 2020) could be measured by SEIS, and thus allowed measurements of the chirp signals.

Orbital searches were then conducted for any associated surface changes. Based on the moment magnitude M_w for each event (3.0 for S1034a and 1.5 for S1160a), the crater diameters were expected to be 25.0 m and 5.4 m, respectively, using the empirical scaling relationship between impactor diameter and seismic moment from Wojcicka et al. (2020). Craters of this size would not be expected to be resolved in medium-resolution orbital imaging. However, surrounding blast zone markings were expected to be observable if the impacts occurred on high albedo, dust-covered surfaces, as those are much larger than the craters themselves (Daubar et al. 2013, 2022).

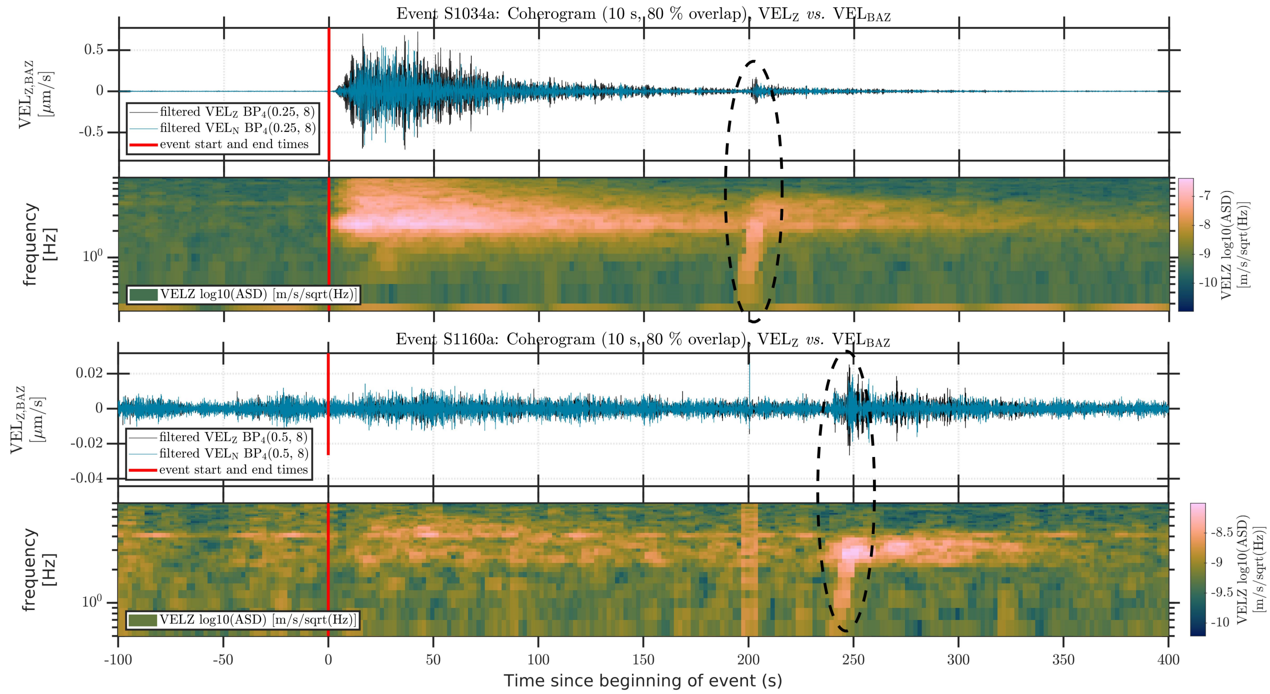

Figure 1. Vertical/north velocity component coherograms (upper panels) and vertical component velocity spectrograms (lower panels) of InSight events S1034a (top) and S1160a (bottom), showing the acoustic chirp signals (dashed black ovals) following the first P wave arrivals (red lines).

2.2. *Imaging*

Imaging campaigns were conducted near the predicted locations by the Context Camera (CTX, Malin et al. 2007) and High Resolution Imaging Science Experiment (HiRISE, McEwen et al. 2007) on the NASA Mars Reconnaissance Orbiter; and by the Colour and Stereo Surface Imaging System (CaSSIS, Thomas et al. 2017) on the European Space Agency Trace Gas Orbiter.

No crater was initially identified at either of the estimated locations using CTX's 6 m/pixel resolution images. The search was then expanded to cover a circle of approximately 100 km radius centered around the lander. This area included the expected locations, as well as additional regions where a crater might have been difficult to identify at first. For example, surfaces with less dust coverage (according to the Thermal Emission Spectrometer Dust Cover Index; Ruff & Christensen 2002) or steep topography could either prevent formation of a clear blast zone, or obscure it in orbital images. Potential locations identified in these searches were used to inform follow-up image targeting.

3. RESULTS

Visual searches were unsuccessful until HiRISE images showed evidence of many small dark splotches near the S1034a estimated location. These were hypothesized to be albedo markings around distant fresh ejecta from a primary crater. The location of the source crater was then estimated using CaSSIS images. Re-examination of CTX images of that location revealed a dark blast zone that had previously been unidentified (Fig. 2A, Top). A subsequent HiRISE image (Fig. 2A, Bottom) verified the crater itself.

Subsequent reanalysis of CTX images also identified changes in the surface albedo near the S1160a estimated source location. Again, the crater itself was resolved when a high-resolution HiRISE image was acquired (Fig. 2B).

Crater diameters and the nature of the impacts were determined from 25 cm/pixel HiRISE Reduced Data Record images. The source for the S1034a event is a single crater, 9.2 m in diameter (Fig. 2A). The source for the S1160a event is a cluster of craters (Fig. 2B), including 5 craters with diameters > 1 m, the largest of which is 2.2 m in diameter. An effective combined diameter of of 3.2 m for this cluster was calculated using $D_{\mathrm{eff}} = \sqrt[3]{\sum_i D_i^3}$, where D_i is the diameter of individual craters in the cluster.

4. DISCUSSION

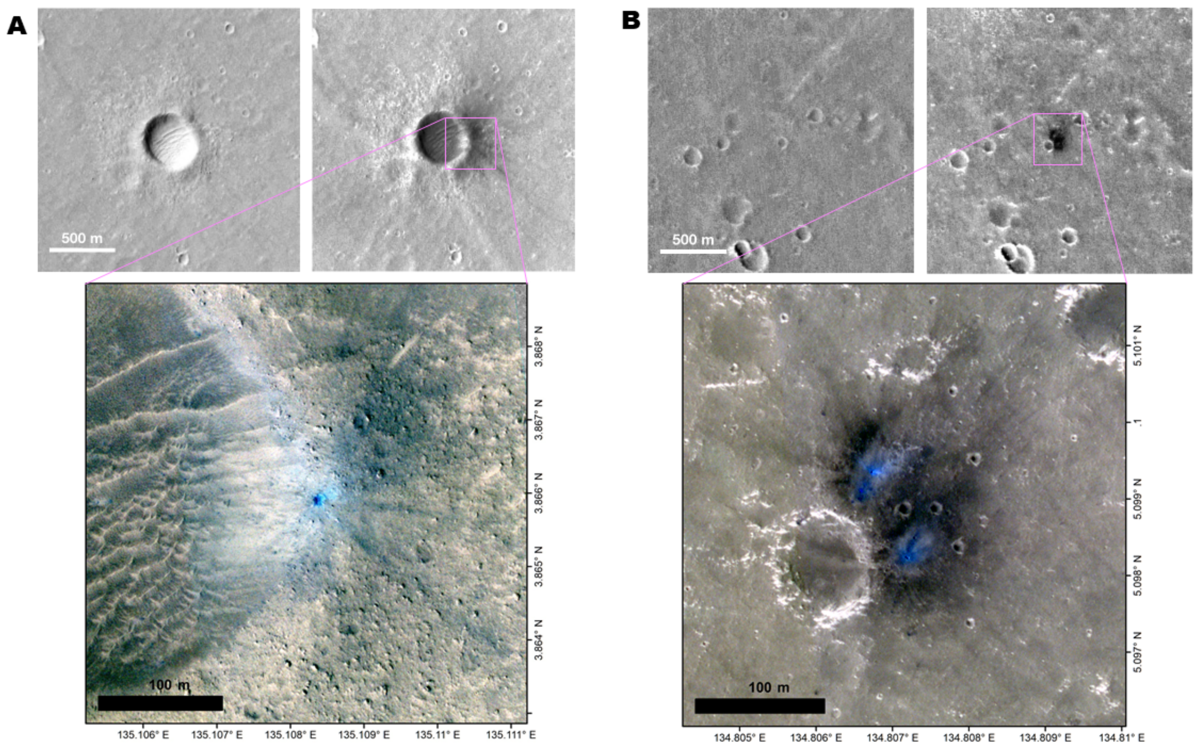

Figure 2. Constraining and confirmation images for InSight seismic events S1034a (A) and S1160 (B). (A, Top) Cutouts of CTX images N22_071075_1861_XN_06N225W (2021-09-24) and U03_072288_1821_XI_02N224W (2021-12-28) constraining the formation of a new darkened area. (A, Bottom) Cutout of HiRISE enhanced color RDR image ESP_075901_1840 of new impact crater corresponding to InSight seismic event S1034a. (B, Top) Cutouts of CTX images U05_073066_1852_XI_05N225W (2022-02-26) and U12_075756_1829_XN_02N225W (2022-09-24) constraining the formation of a new darkened area. (B, Bottom) Cutout of HiRISE enhanced color RDR image ESP_076877_1850 of new impact crater cluster corresponding to InSight seismic event S1160a. Images: NASA/JPL/MSSS/University of Arizona.

The predicted crater diameter, based on the previously established empirical relationship between seismic moment and diameter (Wojcicka et al. 2020), is considerably larger than the observed crater diameter for event S1034a. Likewise, the effective diameter of the impact cluster for the S1160a event is approximately 1.5-2 times smaller than predicted. This could possibly be caused by specific topographic or subsurface properties of the impact locations. More work is needed to fully understand the relationship between magnitude and effective diameter for impact events.

All six of InSight's identified VF type seismic events with impact-acoustic chirps have now been positively associated with fresh impact craters on Mars (Fig. 3 and Table 1). This includes all seismic activity within 100 km (1.7 degrees) of the lander, and two out of the four seismic (VF) events with inferred source locations between 100-300 km (5 degrees) from the lander (Fig. 3). This suggests that detection of a VF-type seismic event with a chirp is diagnostic of a small meteoroid impact on Mars. However, as no VF event without a chirp has so far been associated with an orbitally-detected impact crater, the source mechanisms of other VF events, including those within 300-km of the lander, are unclear. We note that most of InSight's identified seismic events are recorded when the atmosphere is relatively quiet, and thus the seismic data is least noisy. Hence, it remains unclear whether impact-acoustic chirps are always detectable at short distances, or whether they might also be detectable when produced by impacts at farther distances when atmospheric conditions are favourable.

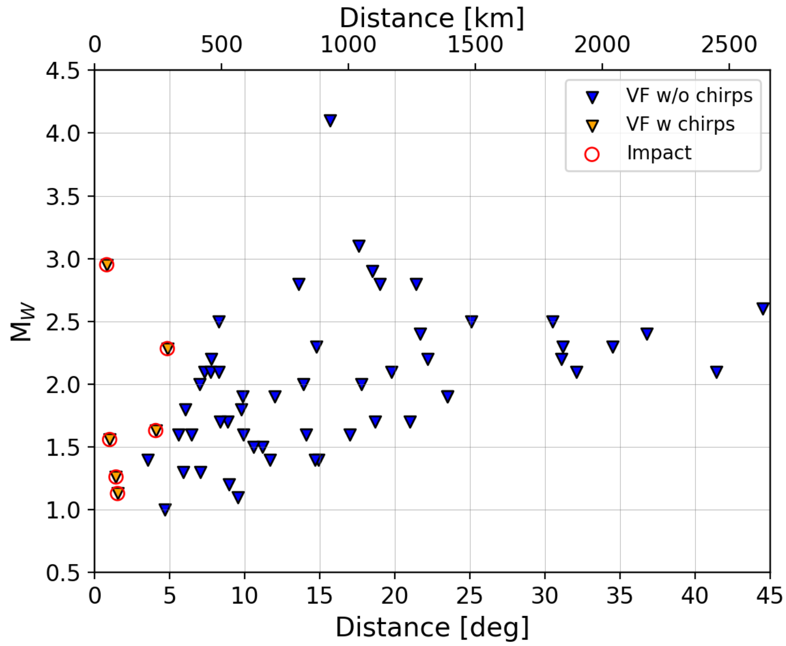

Figure 3. Magnitude-distance distribution of InSight Very High Frequency (VF) seismic events on Mars. Orange and blue triangles mark VF events with and without 'chirps' in their signal, respectively. Confirmed impact events are marked with a red circle. Event distances are taken from the InSight Mars Quake Service (MQS) catalog (Clinton et al. 2023) for non-impacts, while impact events are set to their known respective crater distances from InSight in degrees. Event magnitudes are also from the MQS catalog, but re-calculated for impact events using the correct distances.

Table 1. InSight seismic events known to be impacts and their associated parameters

Event designator	S0533a	S0793a	S0981c	S0986c	S1000a	**S1034a**	S1094b	**S1160a**
Event type	VF	VF	VF	VF	BB	VF	BB	VF
Chirp	Yes	Yes	Yes	Yes	No	Yes	No	Yes
Date	2020-05-27	2021-02-18	2021-08-31	2021-09-05	2021-09-18	2021-10-23	2021-12-24	2022-03-02
Magnitude M_W	2.3	1.4	1.6	1.2	4.1	3.0	4.0	1.5
°N Lat (estimated)	8.63	4.74	-0.04	3.93	26.98	3.92	41.21	5.12
°E Lon (estimated)	135.62	134.22	135.62	136.96	257.86	135.05	188.49	134.88
Date of prior image	2019-04-17	2020-12-03	2018-03-25	2021-04-02	2021-09-17	2021-09-24	2021-12-24	2022-02-26
Date of after image	2021-07-31	2021-06-10	2021-12-28	2021-11-30	2021-09-19	2021-12-28	2021-12-25	2022-09-24
Constraining imager	CTX	CTX	CTX	CTX	MARCI	CTX	MARCI	CTX
°N lat (actual)	9.382	4.606	0.397	3.974	38.107	3.866	35.109	5.099
°E lon (actual)	135.377	134.087	135.689	136.963	280.128	135.107	189.829	134.807
Distance (km)	289	90.8	240	79.1	7460	48.4	3460	59.7
Crater (Eff) Diam (m)	11.9 (cluster)	3.9 (single)	7.24 (single)	6.1 (cluster)	~140 (cluster)	9.2 (single)	~150 (single)	3.2 (cluster)
HiRISE obs ID	ESP_070864_1895	ESP_070073_1845	ESP_072644_1805	ESP_072222_1840	ESP_073522_2185	ESP_074701_1840	ESP_073077_2155	ESP_076877_1850
Reference	Garcia et al. 2022	Garcia et al. 2022	Garcia et al. 2022	Garcia et al. 2022	Posiolova et al. 2022	This work	Posiolova et al. 2022	This work

Note—Highlighted columns show events described in this paper, S1034a and S1160a. Event magnitudes are seismic moment magnitudes taken from the MQS catalog (InSight Marsquake Service 2023) as described in Böse et al. (2021).

5. CONCLUSIONS

The new two impact seismic events described here bring the total number of confirmed seismically-detected impacts on Mars to eight. Of these, four formed single craters and four formed clusters of craters, roughly the proportion expected based on all known orbital detections of new craters on Mars (Daubar et al. 2022).

In the future, additional seismic events of different event types could possibly be associated with impacts. For example, the two large distant impacts that occurred during InSight's mission were of the Broadband (BB) type, with seismic energy over a wide range of frequencies.

Future work currently in progress includes using this catalog to constrain impact rates on Mars and potential enhancements (G. Zenhausern et al, 2023, in prep; Daubar, I.J. et al, 2023, in prep); to study chirp dynamics (Garcia et al, 2023, in prep.; Xu et al, 2023, in prep; Froment et al, 2023, in prep), and atmospheric fragmentation (Collins et al. (2022); Neidhardt et al, 2023, in review:)

We acknowledge NASA, CNES, their partner agencies and Institutions (UKSA, SSO, DLR, JPL, IPGP-CNRS, ETHZ, IC, MPS-MPG) and the flight operations team at JPL, SISMOC, MSDS, IRIS-DMC and PDS for providing SEED SEIS data. Thanks to the HiRISE, CaSSIS, and CTX operations teams who acquired the images used to discover and analyze these new craters.

Data availability: SEIS data are available from the SEIS data service (IPGP et al. 2019). HiRISE data are available from https://www.uahirise.org/catalog/, CaSSIS data are available from the ESA Planetary Science Archive (https://archives.esac.esa.int/psa/#!Home%20View), CTX data are available on the NASA Planetary Data System (https://pds.nasa.gov). Image IDs are included in the main body of the text.

CaSSIS is a project of the University of Bern and funded through the Swiss Space Office via ESA's PRODEX programme. The instrument hardware development was also supported by the Italian Space Agency (ASI) via the ASI-INAF agreement no. 2020-17-HH.0, the INAF/Astronomical Observatory of Padova, and the Space Research Center (CBK) in Warsaw. Support from SGF (Budapest), the University of Arizona (Lunar and Planetary Lab.) and NASA are also gratefully acknowledged. Operations support from Charlotte Marriner, funded by the UK Space Agency (grants ST/R003025/1, ST/V002295/1) is also recognized.

IJD was funded by NASA InSight PSP grant 80NSSC20K0971. PMG was funded by the UK Space Agency grants ST/R002355/1 and ST/V002678/1. GSC and NW were supported by UK Space Agency grants ST/S001514/1 and ST/T002026/1. NAT and ACH were supported by UK Space Agency grant ST/W002523/1.

This manuscript constitutes InSight Contribution Number (ICN) 316.

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