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








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# 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 to within a factor of 3, and have formation time constraints consistent with the seismic event dates. They are both of the very high frequency family of seismic events and are present with chirps (dispersed infrasound/acoustic waves). 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 and 300 km distance.

*Unified Astronomy Thesaurus concepts:* [Craters \(2282\)](#); [Impact phenomena \(779\)](#); [Mars \(1007\)](#); [Planetary interior \(1248\)](#); [Collisional processes \(2286\)](#)

## 1. Introduction

The original scientific goals of NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission included attempted detection of meteoroid impacts on the surface of Mars (Banerdt et al. 2020). InSight's prime mission (sols 1–668; 2018 November 27 through 2020 October 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). This was also despite ongoing orbital monitoring by the Mars Reconnaissance Orbiter (MRO), which resulted in many new craters identified visually (Daubar et al. 2022), but not seismically.

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

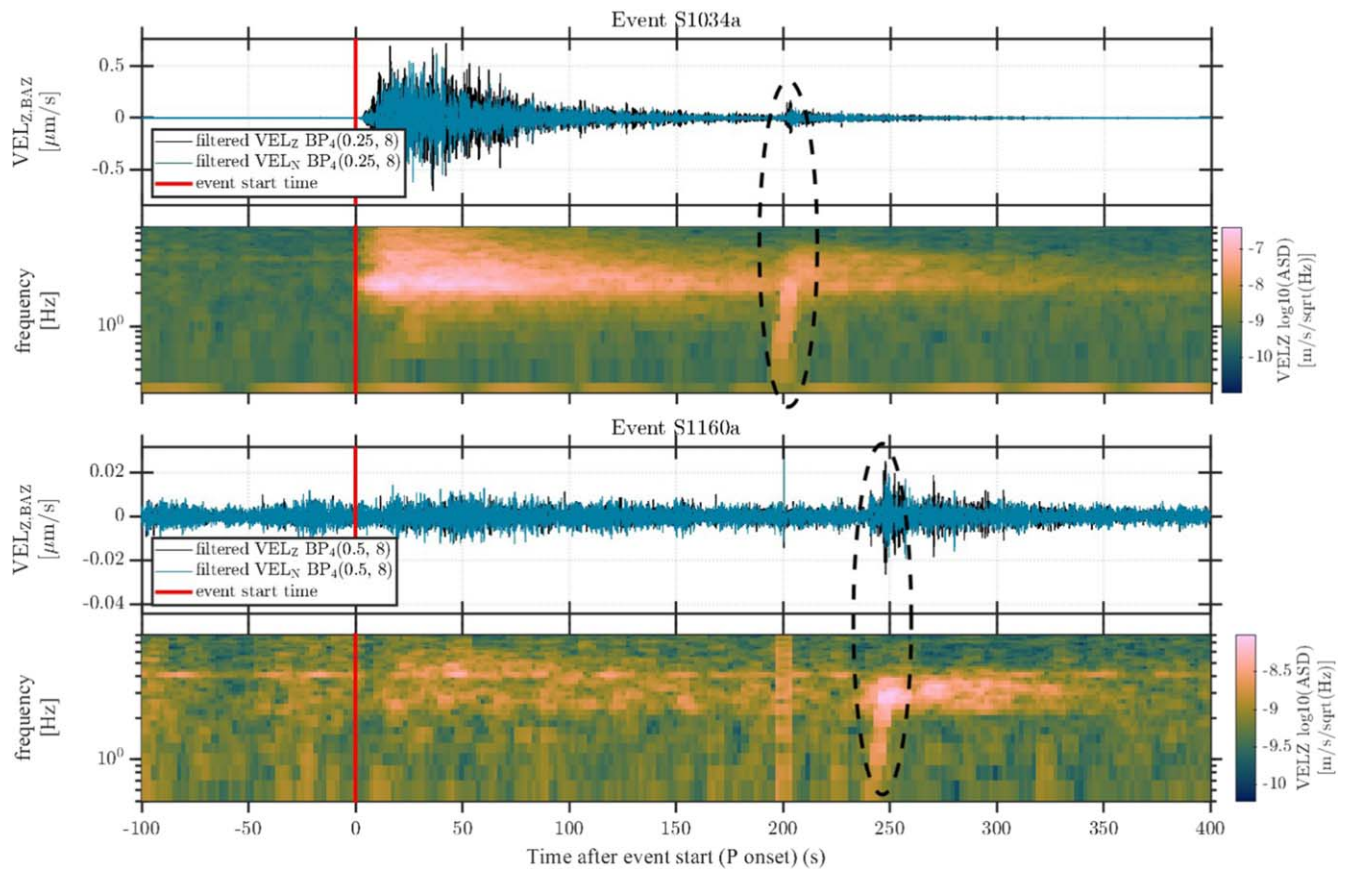
(Daubar et al. 2020). Two other nondetections of (artificial) impacts also enabled constraints to be placed on Martian seismic efficiency: impacts of the NASA Mars 2020 Perseverance ballast mass impacts (Fernando et al. 2021a, 2022), and the Chinese Space Agency Tianwen-1 mission landing (Fernando et 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 (naming convention: the third seismic event occurring on Martian sol 0986 of InSight's mission): 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 (Figure 1) and have proved to be

<sup>16</sup> Equal contribution.





**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).

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). These were larger broadband (BB)-type events at much greater, teleseismic distances. These events allowed the deeper crustal structure of Mars to be probed (Kim et al. 2022) and also uncovered the nearest-equatorial water ice ever found on Mars (Dundas et al. 2022).

In this paper, we report two additional verified impacts within 60 km of the lander. Both had their locations estimated using their acoustic chirps and were subsequently found by orbital imaging. 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 Seismic Experiment for Interior Structure (SEIS) very broad band (VBB) and short-period (SP) seismometers (InSight Mars SEIS Data Service et al. 2019; Lognonné 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, identification of the arrival times of individual seismic waves (phases) 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 October 23) and S1160a (2022 March 2). 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 (Figure 1). Analysis of the chirps using the technique of Garcia et al. (2022) allowed for estimation 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)

**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	<b>VF</b>	BB	<b>VF</b>
Chirp	Yes	Yes	Yes	Yes	No	<b>Yes</b>	No	<b>Yes</b>
Date	2020 May 27	2021 Feb 18	2021 Aug 31	2021 Sep 5	2021 Sep 18	<b>2021 Oct 23</b>	2021 Dec 24	<b>2022 Mar 2</b>
Magnitude $M_w$	2.3	1.4	1.6	1.2	4.1	<b>3.0</b>	4.0	<b>1.5</b>
°N Lat (estimated)	8.63	4.74	-0.04	3.93	26.98	<b>3.92</b>	41.21	<b>5.12</b>
°E Lon (estimated)	135.62	134.22	135.62	136.96	257.86	<b>135.05</b>	188.49	<b>134.88</b>
Date of prior image	2019 Apr 17	2020 Dec 03	2018 Mar 25	2021 Apr 02	2021 Sep 17	<b>2021 Sep 24</b>	2021 Dec 24	<b>2022 Feb 26</b>
Date of after image	2021 Jul 31	2021 Jun 10	2021 Dec 28	2021 Nov 30	2021 Sep 19	<b>2021 Dec 28</b>	2021 Dec 25	<b>2022 Sep 24</b>
Constraining imager	CTX	CTX	CTX	CTX	MARCI	<b>CTX</b>	MARCI	<b>CTX</b>
°N lat (actual)	9.382	4.606	0.397	3.974	38.107	<b>3.866</b>	35.109	<b>5.099</b>
°E lon (actual)	135.377	134.087	135.689	136.963	280.128	<b>135.107</b>	189.829	<b>134.807</b>
Distance (km)	286	91	241	85	7476	<b>48</b>	3462	<b>60</b>
Crater (Eff Diam (m))	11.9 (cluster)	3.9 (single)	7.24 (single)	6.1 (cluster)	~140 (cluster)	<b>9.2 (single)</b>	~150 (single)	<b>3.2 (cluster)</b>
HiRISE obs ID	ESP_070864_1895 <sup>a</sup>	ESP_070073_1845 <sup>b</sup>	ESP_072644_1805 <sup>c</sup>	ESP_072222_1840 <sup>d</sup>	ESP_073522_2185 <sup>e</sup>	<b>ESP_074701_1840<sup>f</sup></b>	ESP_073077_2155 <sup>g</sup>	<b>ESP_076877_1850<sup>h</sup></b>
Reference	Garcia et al. (2022)	Garcia et al. (2022)	Garcia et al. (2022)	Garcia et al. (2022)	Posiolova et al. (2022)	<b>This work</b>	Posiolova et al. (2022)	<b>This work</b>

**Notes.** Columns in bold 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).

<sup>a</sup> [https://www.uahirise.org/ESP\\_070864\\_1895](https://www.uahirise.org/ESP_070864_1895)

<sup>b</sup> [https://www.uahirise.org/ESP\\_070073\\_1845](https://www.uahirise.org/ESP_070073_1845)

<sup>c</sup> [https://www.uahirise.org/ESP\\_072644\\_1805](https://www.uahirise.org/ESP_072644_1805)

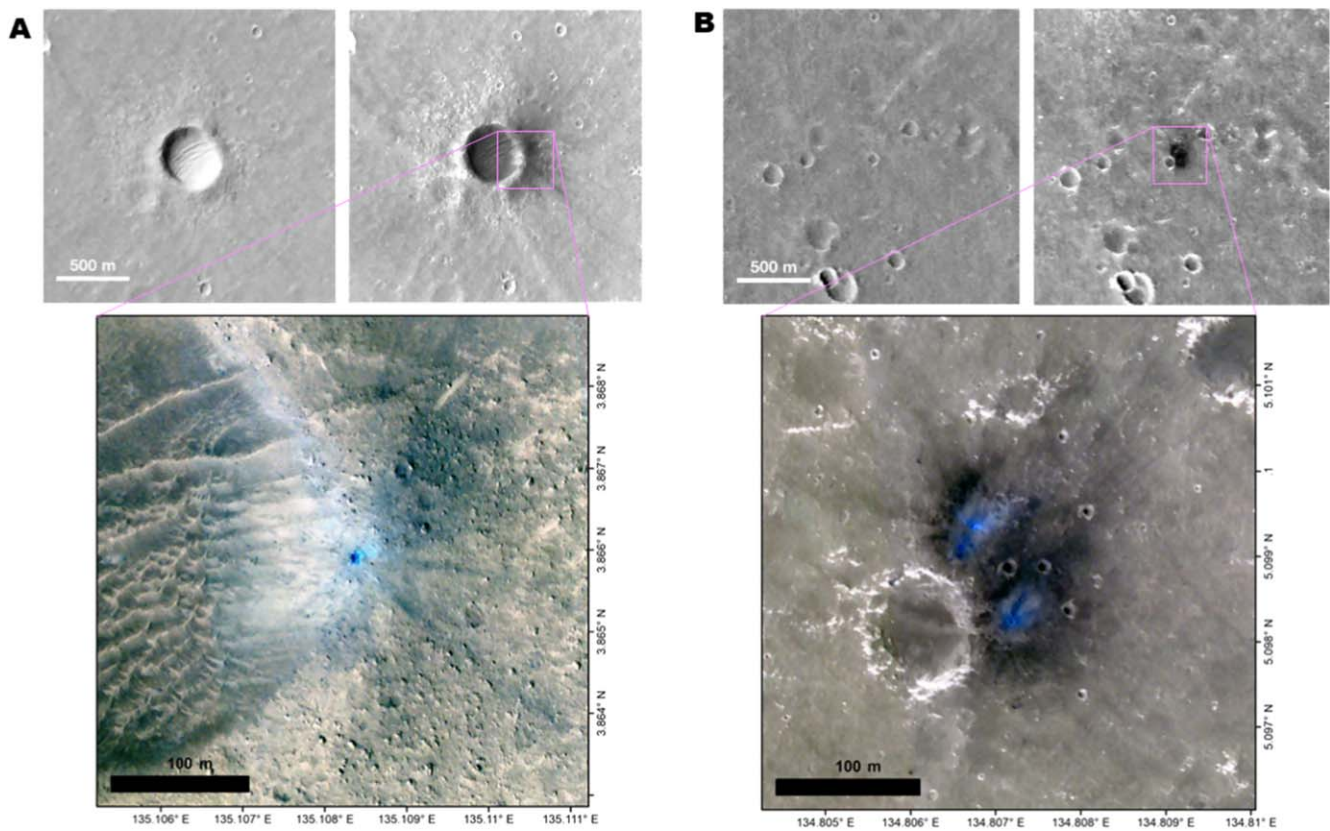
<sup>d</sup> [https://www.uahirise.org/ESP\\_072222\\_1840](https://www.uahirise.org/ESP_072222_1840)

<sup>e</sup> [https://www.uahirise.org/ESP\\_073522\\_2185](https://www.uahirise.org/ESP_073522_2185)

<sup>f</sup> [https://www.uahirise.org/ESP\\_074701\\_1840](https://www.uahirise.org/ESP_074701_1840)

<sup>g</sup> [https://www.uahirise.org/ESP\\_073077\\_2155](https://www.uahirise.org/ESP_073077_2155)

<sup>h</sup> [https://www.uahirise.org/ESP\\_076877\\_1850](https://www.uahirise.org/ESP_076877_1850)



**Figure 2.** Constraining and confirmation images for InSight seismic events (A) S1034a and (B) S1160. (A) Cutouts of CTX images (top left) N22\_071075\_1861\_XN\_06N225W (2021 September 24) and (top right) U03\_072288\_1821\_XI\_02N224W (2021 December 28) constraining the formation of a new darkened area. (bottom) Cutout of HiRISE enhanced color RDR image ESP\_075901\_1840 of new impact crater corresponding to InSight seismic event S1034a. (B) Cutouts of CTX images (top left) U05\_073066\_1852\_XI\_05N225W (2022 February 26) and (top right) U12\_075756\_1829\_XN\_02N225W (2022 September 24) constraining the formation of a new darkened area. (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.

could be measured by SEIS, and thus allowed measurements of the chirp signals.

We note that the chirp-to-P-wave energy ratio is clearly different between these events. This is likely due to a complex interaction of physical effects, including time of day/year and resulting wind conditions, impactor entry properties, and the characteristics of nearby surface topography.

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 (dark, low-albedo areas) 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).

## 2.2. Imaging

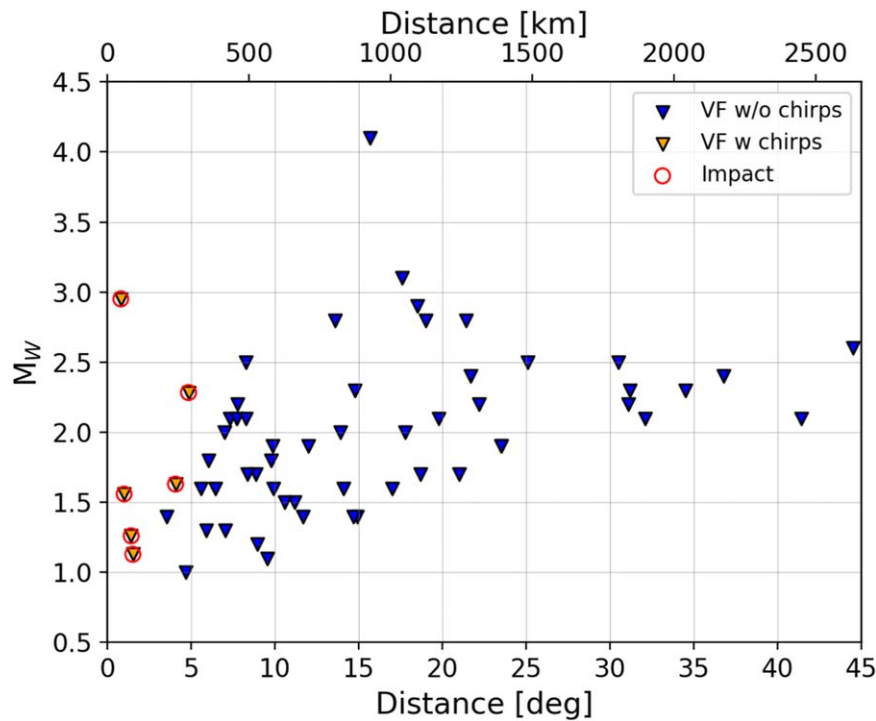
Imaging campaigns were conducted near the predicted locations by the Context Camera (CTX; Malin et al. 2007) and High Resolution Imaging Science Experiment (HiRISE; McEwen et al. 2007) on the NASA Mars Reconnaissance Orbiter and by the Color and Stereo Surface Imaging System

(CaSSIS; Thomas et al. 2017) on the European Space Agency Trace Gas Orbiter.

No crater was initially identified at the center of the estimated locations derived from analysis of the chirps using CTX's  $6 \text{ m pixel}^{-1}$  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

Analysis of CaSSIS images led to the identification of a candidate impact near the S1034a estimated source location (P. Grindrod, in preparation). Subsequent reanalysis of CTX images identified changes in the surface albedo near the S1160a estimated source location. The craters themselves were resolved when high-resolution HiRISE images were acquired (Figure 2). Crater diameters and the nature of the impacts were determined from  $25 \text{ cm pixel}^{-1}$  HiRISE Reduced Data Record images (Figure 2).



**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 (InSight Marsquake Service 2023) for nonimpacts, while impact events are set to their known respective crater distances from InSight in degrees. Event magnitudes are also from the MQS catalog, but are recalculated for impact events using the correct distances.

The HiRISE images reveal small fresh craters surrounded by extensive low-albedo blast zones where dust was disturbed by the impact, forming linear rays and diffuse halos. In the enhanced color images, relatively blue material shows where dust has been removed and subsurface material of differing composition exposed. These types of features are not uncommon around new date-constrained impact sites on Mars (Daubar et al. 2022).

The source for the S1034a event is a single crater, 9.2 m in diameter (Figure 2(A)). The source for the S1160a event is a cluster of craters (Figure 2(B)), including five craters with diameters  $>1$  m, the largest of which is 2.2 m in diameter. An effective combined diameter of 3.2 m for this cluster was calculated using  $D_{\text{eff}} = \sqrt[3]{\sum_i D_i^3}$ , where  $D_i$  is the diameter of individual craters in the cluster (Malin et al. 2006).

#### 4. Discussion

The predicted crater diameter, based on the previously established empirical relationship between seismic moment and diameter (Wojcicka et al. 2020), is 2.7 times larger than the observed crater diameter for event S1034a. Likewise, the effective diameter of the impact cluster for the S1160a event is 1.7 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 (Figure 3 and Table 1). This includes all seismic activity within 100 km ( $1.7^\circ$ ) of the lander and two out of the four seismic (VF) events with inferred

source locations between 100 and 300 km ( $5^\circ$ ) from the lander (Figure 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 are the 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 favorable.

#### 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 BB type, with seismic energy over a wide range of frequencies.

Work currently in progress includes using this catalog to constrain impact rates on Mars and potential enhancements (G. Zenhausern et al. 2023, in preparation; I. J. Daubar et al. 2023, in preparation) and to study chirp dynamics (Z. Xu et al. 2022, in preparation; M. Froment et al. 2023, in preparation; R. F. Garcia et al. 2023, in preparation) and atmospheric fragmentation (Collins et al. 2022; Neidhart et al. 2023).

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## Data Availability

SEIS data are available from the SEIS data service (InSight Mars SEIS Data Service 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.

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