MARTIAN SEISMIC EVENTS CONFIRMED AS IMPACTS TO DATE. Ingrid J. Daubar[1], B. Fernando[2], R. F. Garcia[3], Gareth S. Collins[4], M. P. Golombek[5], N. Teanby[6], P. Grindrod[7], L. Posiolova[8], M. Banks[9], P. Lognonné[10], and the InSight Impacts Working Group. [1]Brown University, Providence, RI, USA (ingrid_daubar@brown.edu); [2]University of Oxford, Oxford, UK; [3]ISAE-SUPAERO, Université de Toulouse, Toulouse, France; [4]Imperial College, London, UK; [5]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA; [6]University of Bristol, Bristol, UK, [7]Natural History Museum, London, UK; [8]MSSS, San Diego, CA, USA; [9]NASA Goddard Space Flight Center, USA; [10]IPGP-Sorbonne Paris Cité, Paris, France.

InSight history of impact detection: One of the original scientific goals of the InSight mission was to seismically detect meteoroid impacts on the surface of Mars [1]. The first martian year (sols 1-668) saw no impact events positively identified at the time, despite predicted detection frequencies ranging from a few to tens per Earth year [2], [3]. However, in the second martian year of the mission, a number of impacts were positively identified, underscoring the scientific importance of extended missions [4].

Four newly detected impact events were the first recorded seismically on another planet [5], and then two larger distant impacts were detected [6]–[8]. The first of these identifications was made based on analyses of an unusual seismic phase following in the coda of event S0986c: a 'chirp' due to dispersion of the acoustic waves propagating through the atmosphere from the impact. Analysis of the chirp signal yielded an estimated source location (distance and backazimuth). Follow-up imaging by orbital cameras showed a new cluster of craters in the predicted location with before and after image constraints bounding the event time [5]. All four of the nearby events were found to be of the 'VF' type, Very High Frequency events [9]. Here we make the first report of two additional verified impacts, for a total of eight seismically detected impact events on Mars.

Seismic results: Chirp signals were identified for two additional events, both VF type, estimated to be located near the InSight lander: S1034a and S1160a (Fig. 1). Analysis of the chirps allowed for estimated source locations (Table 1), and orbital searches were then conducted for any associated surface changes.

Imaging results: Imaging campaigns were conducted by CTX [10], HiRISE [11], and CaSSIS [12] near the predicted locations. Searches were unsuccessful until new HiRISE images showed evidence of distant fresh ejecta near the S1034a estimated location. The location of the source crater was then estimated using CaSSIS images, and then a CTX image of that location showed a dark blast zone. The source crater was then identified in a subsequent HiRISE image (Fig. 2).

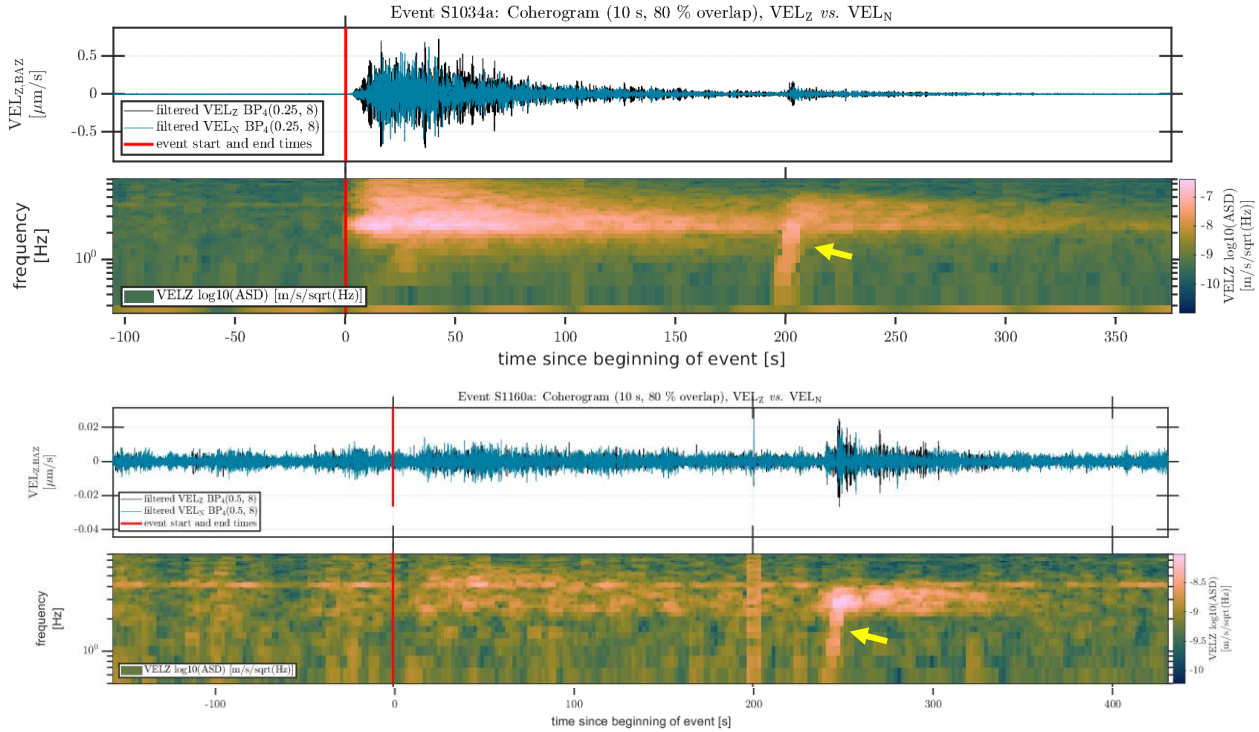

Fig. 1: Seismograms and spectrograms of InSight events S1034a (top) and S1160a (bottom), showing the acoustic chirp signals (yellow arrows) following the first P wave arrivals (red lines).

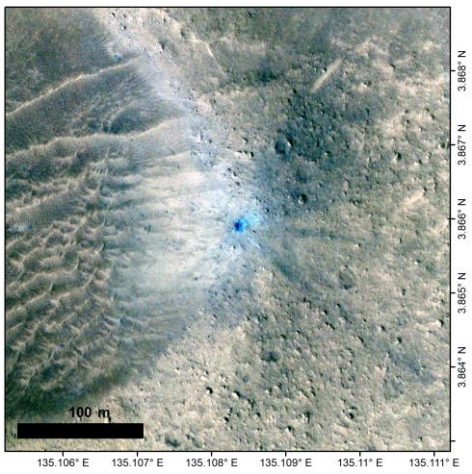

Fig. 2: Cutout of HiRISE image ESP_075901_1840 of new impact crater corresponding to InSight seismic event S1034a. Image: NASA/JPL/University of Arizona.

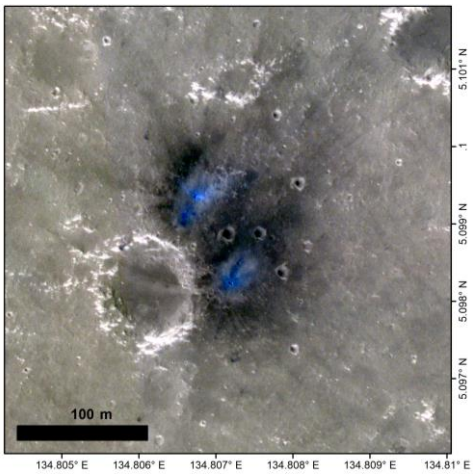

Fig. 3: Cutout of HiRISE image ESP_076877_1850 of new impact crater cluster corresponding to InSight seismic event S1160a. Image: NASA/JPL/University of Arizona.

Images from CTX have recently revealed a new albedo marking near the S1160a estimated location, which was confirmed to be a new crater with a follow-on HiRISE image (Fig. 3).

Conclusions: All six VF type seismic events with chirps have now been positively associated with fresh craters on Mars. This brings the total number of confirmed seismically detected impacts to eight, of which four formed single craters and four formed a cluster of craters, roughly the proportion expected based on orbital detections of new craters [13]. All of the detected events occurred in the northern equatorial to mid-latitudes of Mars.

It is possible that additional events of different seismic types will 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. Other VF events without chirps may also be confirmed as impacts in the future [14].

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References: [1] Banerdt W. B. *et al.*, *LPSC 48*, 2017. [2] Daubar I. J. *et al.*, *SSR*, 2018. [3] Daubar I. J. *et al.*, *JGR-P*, 2020. [4] Daubar I. J. *et al.*, 2021. [5] Garcia R. F. *et al.*, *Nat. Geosci.*, 2022. [6] Posiolova L. V. *et al.*, *Science*, 2022. [7] Kim D. *et al.*, *Science*, 2022. [8] Dundas C. M. *et al.*, *GRL*, 2022. [9] Clinton J. F. *et al.*, *Phys. Earth Planet. Int.*, 2021. [10] Malin M. C. *et al.*, *JGR*, 2007. [11] McEwen A. S. *et al.*, *JGR*, 2007. [12] Thomas N. *et al.*, *SSR*, 2017. [13] Daubar I. J. *et al.*, *JGR-P*, 2022. [14] Zenhäusern G. *et al.*, *AGU Abs.*, 2022.

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
°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	2022-09-24
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	2022-02-26
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)	289.0	90.8	240.0	79.1	7460	48.4	3460	59.7
Crater (effective) Diameter (m)	11.9 (cluster)	3.9 (single)	7.24 (single)	6.1 (cluster)	~140 (cluster)	9.2 (single)	~150 (single)	3.2 (cluster)
HiRISE observation 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	[5]	[5]	[5]	[5]	[6]	This work	[6]	This work

Table 1. Confirmed seismically-detected impact parameters