IMPACT-GENERATED SEISMIC WAVES: DID THE T. REX QUAKE IN FEAR? C. A. Bill[1], B. A. Fernando[2], G. S. Collins[3] & P. Koelemeijer[1]. [1]Department of Earth Sciences, University of Oxford, UK (email: carys.bill@st-annes.ox.ac.uk), [2]Department of Physics, University of Oxford, [3]Imperial College London, UK.

Introduction: Large impact events can change the course of a planet's evolution. For example, the 66 Ma Chicxulub impact event has been linked to one of the biggest mass-extinction events in Earth's history [1]. Seismic waves generated on planetary bodies by impact events of this scale remain to be fully understood.

The Chicxulub Event: The impact hypothesis is now widely accepted as a cause of the End-Cretaceous mass extinction [2], well-known for ending the reign of the non-avian dinosaurs, including the infamous Tyrannosaurus-Rex [3]. A ~10-km wide asteroid crashed into the Earth with profound consequences [4]. 76% of species could not adapt to survive in the new harsh environmental conditions resulting from the impact, and consequently disappear in the fossil record [5].

Geophysical surveying and drilling helped identify the ~180 km wide Chicxulub crater structure on the Yucatan Peninsula, Mexico [6]. Studies of the impact crater have provided parameters which enable us to model and better understand the impact process, including its trajectory [7], crater and peak ring formation [8, 9], impact plume and ejecta curtain [10], and induced seismic waves [11]. Such models help explain how a large impact event like Chicxulub can lead to such unprecedented environmental and biological consequences.

Seismic Impacts: Over 90% of the energy from an impact event is converted into internal energy through vaporization, melting and heating processes [12]. Values for the seismic efficiency, *k*, the ratio between the seismic energy produced during the impact and the impactor's kinetic energy, are consequently small - estimated around ~ 10^{-4} for Chicxulub-like terrestrial impacts [11]. Impacts with greater mass or velocity are more likely to produce detectable seismic signals. Seismic waves propagating from impact events have been recorded by seismometers on Earth, the Moon and Mars [13]. Figure 1 shows the signal recorded for the largest impact event recorded on Mars, S1094b, associated with a 150m-wide crater [14].

Due to the rarity of Chicxulub-scale events, a seismometer has never recorded a comparably large event on any planetary body. Nevertheless, combining the knowledge we have gained from recording the seismic signatures of smaller impact events with geophysical and geological evidence, we can attempt to model impact-generated seismic waves for bigger events like Chicxulub. Previous modelling suggests that the seismic waves generated by the Chicxulub impact were equivalent to a moment magnitude ~10-11.5 earthquake [15]. We aim to model these waves, and understand their implications, on both regional and global scales.

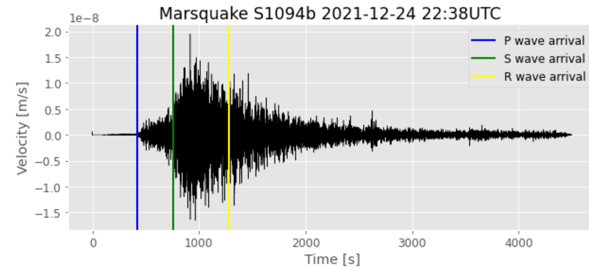

Figure 1: The seismic wave signal recorded by the InSight Mission's SEIS instrument for Marsquake event S1094b, which is recognised as a seismic impact event. The signal is bandpass filtered between 1 and 5s. P, S & Rayleigh wave phase arrivals can be identified [14].

Methodology: We numerically simulate seismic waves from the impact in Salvus, a spectral-element full waveform propagation modelling software [16]. Our initial simulations use a Gaussian source time function, a PREM anisotropic one-dimensional crust background model and modern-day moho and topography. We model the source as a point source at 0m depth, and incorporate the following parameters from Mechede et al [11]:

- velocity = 20km/s;
- momentum = $2x10^{19}$Nm;
- diameter = 10km.

The trajectory in our initial simulations is vertical, therefore generating axially symmetric seismic waves. Later work will incorporate different trajectory angles between 45-60° to better reflect the interpreted asymmetry of the crater [7].

In previous work, a modern-day crust-mantle model was used [11]. Our simulations will incorporate a crust-mantle model and topography based on plate configurations 66 millions years ago. This will better reflect the existence of the Western Interior Seaway, due to dynamic topography in the Northern American continent [17], in our continental scale simulations,

To explore the extent of seismic waves generated by the impact, we place simulated receivers at 3 different distances from the crater: at 35°, 130° and 180° degrees.

Continental Scale - 35°: The Tanis K-Pg Fossil Site, part of the Hell Creek Formation in North Dakota, is a treasure chest for paleontologists, hosting the greatest abundance of T. Rex fossils found worldwide [18]. There is well-preserved evidence here of the impact event including elevated iridium levels, ejecta spherules, tsunami deposits and shocked minerals. Located ~3050 km away from the impact site in the north of the ancient Western Interior Seaway, previous work suggests that P, S and Rayleigh seismic waves arrived here 6, 10 and 13 minutes respectively post impact. These seismic waves may have induced a seiche or tsunami, characterizing the K-Pg boundary deposits present here [15]. Running our simulations with a synthetic receiver placed in North Dakota, will reveal if impact-generated ground motions were sufficient to trigger seismic disturbances, such as tsunamis, potentially preserved in the geological record in this region. Constraining peak amplitudes and the timing of seismic waves, will also help reveal whether the T. Rex fossilized here experienced impact-induced earthquakes.

Our simulation configuration for our initial continental scale simulation is shown in Figure 2.

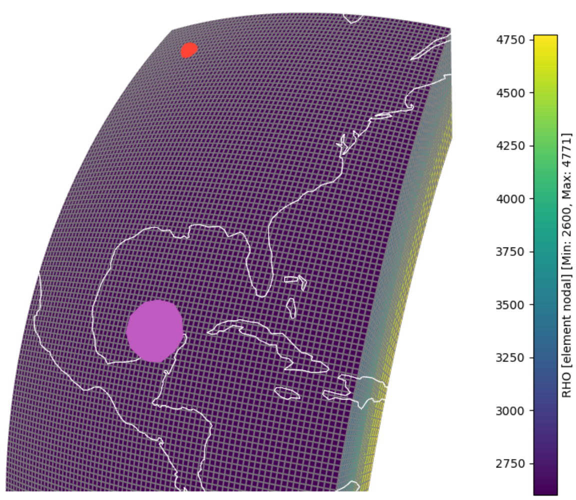

Figure 2: Simulation configuration mesh, with a minimum period of 16s, produced using Salvus. The receiver is located in North Dakota and source at the Chicxulub crater, Yucatan.

Deccan Traps - 130°: The timing of the Deccan Traps Large Volcanic Province (LVP), overlaps the end of the Cretaceous, and provides an alternative extinction mechanism hypothesis due to volcanism. It has been proposed that impact-induced seismic waves may have triggered volcanic eruptions that led to the emplacement of the Deccan Traps' Wai Subgroup [19]. To test this hypothesis, we place a synthetic receiver at the centre of the Deccan Traps.

The Antipode - 180°: Previous modelling of Chicxulub impact-generated seismic waves at the antipode revealed that seismic waves are focussed due to the nearly spherical shape of the Earth [11]. Using a minimum period of 16s, their simulations produced displacements of ~4m at this location. To further explore this result, we place a receiver at the antipode. Our global simulation mesh is shown in figure 3.

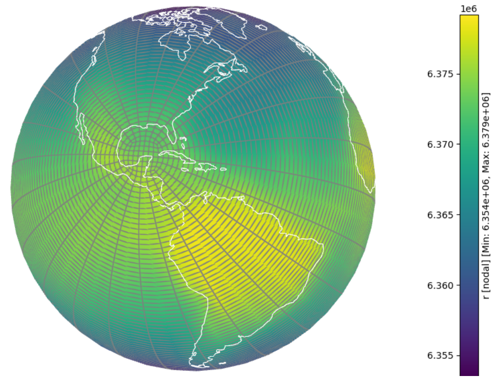

Figure 3: Global-scale simulation configuration mesh.

Discussion and conclusions: By simulating impact-generated seismic waves at different locations, we improve our understanding of the role and extent of seismic signals induced by large impact events. Further work will involve continuing to build and refine our models, including the source parameters, mesh resolution, and incorporating our 66Ma crust-mantle model. The accuracy of our models will be limited by the parameter constraints currently available and numerical simulation computational capabilities. Expanding this work across more locations will help us better understand if the impact-generated seismic waves caused depositional episodes such as tsunamis or triggered volcanism. Analysing peak amplitudes and seismic signal timings at different locations, compared to fossil assemblage distribution, will also help reveal whether the T. Rex really did quake in fear.

Acknowledgments: Use of the Archer 2 UK Supercomputer made this work possible. Mars seismic data is accessed through IRIS-DMC and processed using ObsPy.

References: [1] Alvarez L. W. et al (1980) *Science, 208,* 1095-1108. [2] Morgan J. V. (2022) *Nat. Rev. Earth Environ., 3*, 338-354. [3] Nebitt S. J. et al (2019) *Nat. Ecol. Evol., 3*, 892-899. [4] Schulte P. et al (2010) *Science, 327,* 1214 - 1218. [5] Lowery C. M. et al (2018) *Nature, 55*, 288-291. [6] Hildebrand A. R. et al. (1991) *Geology, 19*, 867. [7] Collins G.S. et al (2020) *Nat. Commun. 11,* 1480. [8] Ivanov B. A. (2005) *Sol. Syst. Res., 39*, 381-409. [9] Collins G.S. et al (2002) *Icarus, 157,* 24-33. [10] Artemieva N. and Morgan J. (2020) *Geophys. Res. Lett., 47*, 1-8. [11] Mechede M. A. et al (2011) *Geophys. J. Int.,187*, 529-537. [12] Melosh H. J. (1989) *Oxford Univ. Press.* [13] Daubar I. et al (2018) *Space Sci. Rev. 214* 132. [14] Posiolova L. et al (2022) *Science 378* 412-417. [15] DePalma R. A. et al (2019) *Proceedings of the Nat. Acad. Sci. of the USA 116*, 8190-8199. [16] Afanasiev M. et al (2019) *Geophys. J. Int. 216* 1675-1692. [17] Lithgow-Bertollini C. and Gurnis M. (1997) *Geology 25, 8,* 735–738. [18] Marshall C. R. (2021) *Science 372* 284-287. [19] Richards M. A. et al (2015) *GSA Bulletin 127*, 1507-1520.