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Research Paper

Challenges of identifying putative planetary-origin meteorites of non-igneous material

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ABSTRACT

This paper summarizes the challenges of identifying planetary-origin meteorites of non-igneous composition - particularly those of sedimentary origin. Evidence for putative sedimentary-origin (sed-type) meteorites and their potential parent bodies is reviewed, suggesting that the list of candidate parent bodies for sed-type meteorites includes, but is not limited to, Mars, Enceladus, Ganymede, Europa, Ceres, Vesta, and other hypothetical planets that existed between the orbits of Mars and Jupiter in the past. The extraterrestrial origin and probable parent body for sed-type meteorites should be assessed based on multiple lines of evidence, and not solely limited to tests of oxygen and noble gas isotopes, whose signatures may undergo terrestrial contamination and which may exhibit significant heterogeneity within both the Solar System and parent cosmic bodies. The observed fall of a cosmic body, evidence of hypervelocity fall, signs of impact, presence of fusion crust, melting, and/or shock deformation features in impactor fragments should be considered as priority signs of meteoritic origin.

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1. Introduction

The SNC group of meteorites are petrologically-similar achondrites named for the locations where they were first found: Shergotty (India), Nakhla (Egypt), and Chassigny (France) (Sohl and Spogn, 2011). All SNC meteorites display igneous features (Papike et al., 2009), and are the only commonly accepted group of planetary-origin meteorites, most probably coming from Mars. Initial suggestions that SNC meteorites came from Mars were based on their late crystallization ages and the lack of available explanations of igneous activity on asteroids (Mcsween et al., 1979). More definitive evidence was subsequently based on isotopic measurements of trapped Ar within inclusions of shock-melted glass in the EET79001 shergottite (Bogard and Johnson, 1983). However, the noble gas patterns of nakhlites and Chassigny meteorites are controversial (Ott and Begemann, 1985). Trapped gas Xe isotopes in Chassigny are similar to solar wind rather than the Martian atmosphere, and could represent noble gases in the planet's interior; Nakhla trapped gas requires the addition of a third component

(McSween, 1994). Collisional stripping of planetary crusts occurred during accretion (Carter et al., 2018), while magma oceans were common on asteroids in the early Solar System (Hublet et al., 2017).

Ashley and Delaney (1999) suggested that sed-type meteorites should be sampled on Earth in proportion to the surface area covered by sedimentary rocks on Mars. In support of this idea, they present compositions of Barnacle Bill and Yogi from Sagan Station, Mars on a classification diagram for igneous rocks with the composition ranges of typical sedimentary rocks superimposed. According to this diagram, SNC meteorites represent only a small portion of the different types of meteorites that could originate from Mars (Ashley and Delaney, 1999). Ashley and Delaney (1999) emphasized that the fusion crust of meteorites is a marker of their extraterrestrial origin, stating that 'if a consolidated siliciclastic sediment were ejected from Mars, the fusion crust formed during its deceleration and descent to Earth could be quite unlike anything that previous meteoritic experience defines as true fusion crust'. Enormous impacts could potentially cause an ejection of abyssal sedimentary rocks into space; these rocks may differ significantly from what is seen on the surface of Mars and other bodies in the Solar System. Peer-reviewed articles similar in focus to the paper by Ashley and Delaney (1999) are unavailable, emphasizing our assertion that this topic is understudied and

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underappreciated, given its relevance in astrobiology and for Solar System exploration.

In this paper, we discuss the challenges of identifying putative sed-type meteorites. Potential parent bodies for such rocks are also reviewed, as is the isotopic heterogeneity of unmixed silicate reservoirs on Mars, possible terrestrial loss or contamination in noble gas signatures of meteorites that spend time in extreme weather conditions, and the shielding factor of cosmogenic isotopes that hamper the identification of new types of meteorites. The first macroscopic candidate meteorite composed of planetary sediments, from Tunguska, is also discussed to emphasize the significance of studying this phenomenon.

Sed-type meteorites, found on Earth, may significantly elucidate the history of the Solar System and contribute to the search for possible extraterrestrial life forms. The field of astrobiology addresses questions about life in the universe. Improved capabilities in biosciences, informatics, and space exploration (Morrison, 2001) can complement the discovery, identification, and thorough examination of putative sedimentary meteorites, to help address fundamental questions in astrobiology and facilitate further exploration of the Solar System.

2. Simulation modeling experiments

In the early 2000s, an international team performed a simulation modeling experiment (the STONE 6 experiment) aimed at identifying the effects of thermal alteration on Martian analog sediments on their entry into Earth's atmosphere (Brack et al., 2002; Foucher et al., 2009). Silicified volcanic sediment, containing living microorganisms and microfossils, from the 3.5-byr-old Kitty's Gap Chert (Pilbara, Australia) was embedded in the heat shield of a space capsule of a Foton series robotic spacecraft developed by Russia and the European Space Agency. This sediment represented an analog for Martian volcanic sediments of Noachian age. Living microorganisms (*Chroococcidiopsis*) embedded within the sample were used to assess whether endolithic life forms could survive atmospheric entry (Foucher et al., 2009). On re-entering Earth's atmosphere, shock heating mineralogically altered the specimen embedded in the outer shell of the Foton spacecraft forming a fusion crust, alpha quartz changed to beta quartz resulting in cracks in the chert, fluid inclusion sizes increased, and dehydration of the hydromuscovite-replaced volcanic protoliths. The post-flight sample exhibited a flat bright white vitreous surface, in comparison to the matt-variegated cream-colored cupola of the pre-flight reconstituted rock. During re-entry, the sample lost 9–10 mm of its surface layer. The fusion crust itself was approximately 0.8 mm thick, had a bright white color and a glassy reflective surface. Deeper portions of the sample appeared to have blackened, but thin sections revealed that only the cement became black. The sample between the fusion crust and the lower blackened layer had a dull creamy-white color. In the fusion crust, chert fragments were completely fused to a glassy material; no protoliths were distinguishable. Raman analyses showed several bubbles of trapped air incorporated during rapid cooling of the melted material after atmospheric entry (Foucher et al., 2009). The carbonaceous microfossils embedded in the chert matrix survived towards the core of the rock, away from the fusion crust. Living microorganisms did not survive as their rock shield was only 2 cm thick; calculations suggest at least 5 cm of rock may protect organisms from the intense heat of entry (Foucher et al., 2009). Meter-sized meteoroids composed of sedimentary rocks could potentially provide enough shielding to protect microscopic life forms naturally embedded in a rock's interior.

The recognizability and characteristics of a fusion crust on putative sed-type meteorites may depend on rock type. Although its

presence is undoubtedly one of the hallmarks of meteoritic origin, fusion crust may be mechanically stripped away when an impactor hits the surface of the Earth. Considering that the original chert sample from Kitty's Gap fragmented on entry into Earth's atmosphere, the question of whether silicified layered volcanics and other siliciclastics are sufficiently indurated to reach Earth's surface as potential meteorites remains. However, an exotic bolder in the epicentral area of the Tunguska catastrophe, regarded as a candidate for sed-type meteorites, shows high strength (Anfinogenov et al., 2014) and is evidence that they could potentially survive entry into Earth's atmosphere.

3. Sed-type meteorites

3.1. Candidates for sed-type meteorites

Available literature contains a few reports on likely candidates for sed-type meteorites from observed falls. Cross (2012) reported on three rocks, including two grayish fine-grained sandstone specimens found in the United States in 1947 that were, in his opinion, of cosmic origin. Hadding (1940) described two specimens, one of limestone and one of sandstone, that he believed were meteorites.

An unusual quartz pebble shower occurred during a snowstorm in Trélex, Switzerland on February 20, 1907 (Rollier, 1907). Composed of milky quartz, the pebbles ranged in size from peas to hazelnuts, some of which were shattered. The origin of these pebbles was not identified. It remains unclear whether these pebbles were meteorites or if they came from the Hyères Islands in the Mediterranean Sea, or the Meseta (Spain) which is even farther away from Trélex. The current availability and whereabouts of these samples are unknown, though some information might be obtained from the archives of ETH Zurich, where Rollier worked.

An exotic gravelite sandstone boulder (Figs. 1 and 2), found in association with a fresh hypervelocity disruption in the permafrost on the Stoykovich Mountain, in the epicenter area of the 1908 Tunguska catastrophe, was also proposed as a candidate for sed-type meteorites (Anfinogenov et al., 2014). No other reports concerning potential sed-type meteorites are currently available.

3.2. An exotic rock from the epicenter of the 1908 Tunguska catastrophe

On 30 June 1908, a cosmic body catastrophically collided with Earth above the Tunguska region of Siberia, devastating about 2000 km² of taiga forest by shock waves and fire. Studies suggest that the Tunguska projectile may have been either a comet (Gladysheva, 2011, 2013) or an asteroid (Chyba et al., 1993; Sekanina, 1998). Kvasnytsya et al. (2013) believed it was an iron meteorite, though no sizable fragments were recovered from the affected region. A possible impact crater, covered by a 300 m wide lake (Lake Cheko), was reported about 8 km NNW of the Tunguska event epicenter (Gasperini et al., 2007, 2008, 2009), though we agree with Collins et al. (2008) that the lake itself cannot be an impact crater. The region affected by the Tunguska catastrophe hosts several karst caves, and we hypothesize that a piece of the Tunguska projectile may have impacted and punctured the 'roof' of one such cave, resulting in the formation of Lake Cheko in its current form. It may explain the unusual depth of the lake and eyewitness reports stating that water appeared to burst out of the ground after the catastrophe. The karstic nature of the lake might mask the impactor, fragments of which could disappear through the karst dolines. Several alternative hypotheses have been proposed to explain the nature of the 1908 Tunguska projectile that exploded in the atmosphere. However, the airburst of the

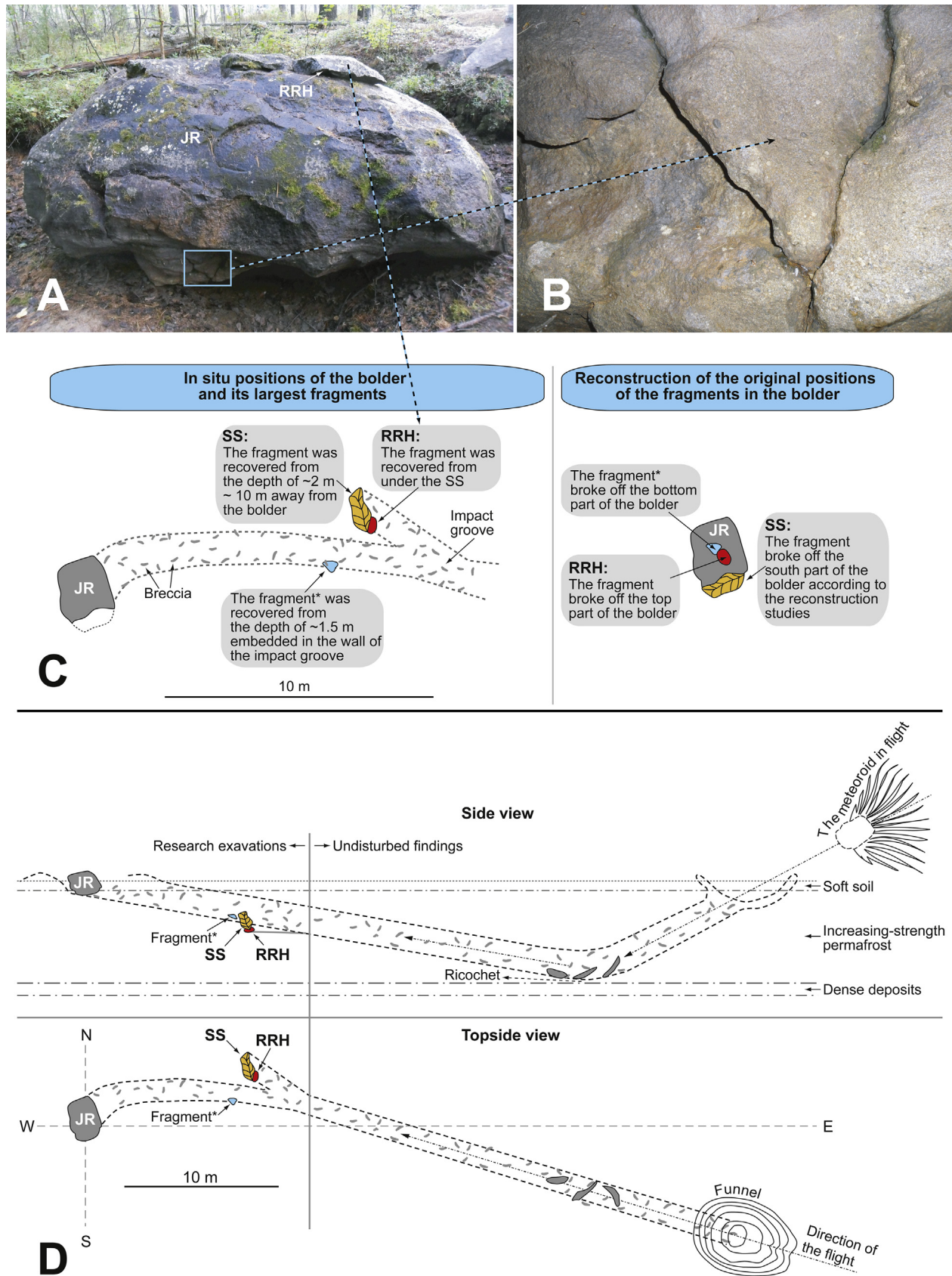


Figure 1. (A) John's Rock, photographed in 2015; (B) signs of melting; possible shatter cones associated with John's Rock; (C) spatial scheme of John's Rock and its largest fragments found at the top of the Stoykovich Mountain in 1972, and its reconstruction before breakage; (D) side and top views of the hypervelocity entry, ricochet, and breakage of John's Rock. For detailed descriptions and images of the fragments see [Anfinogenov et al. \(2014\)](#). Abbreviations - JR: John's Rock; SS: fragment called 'Satellite Stone'; RRH: fragment named 'Red Riding Hood' due to its reddish color upon recovery.

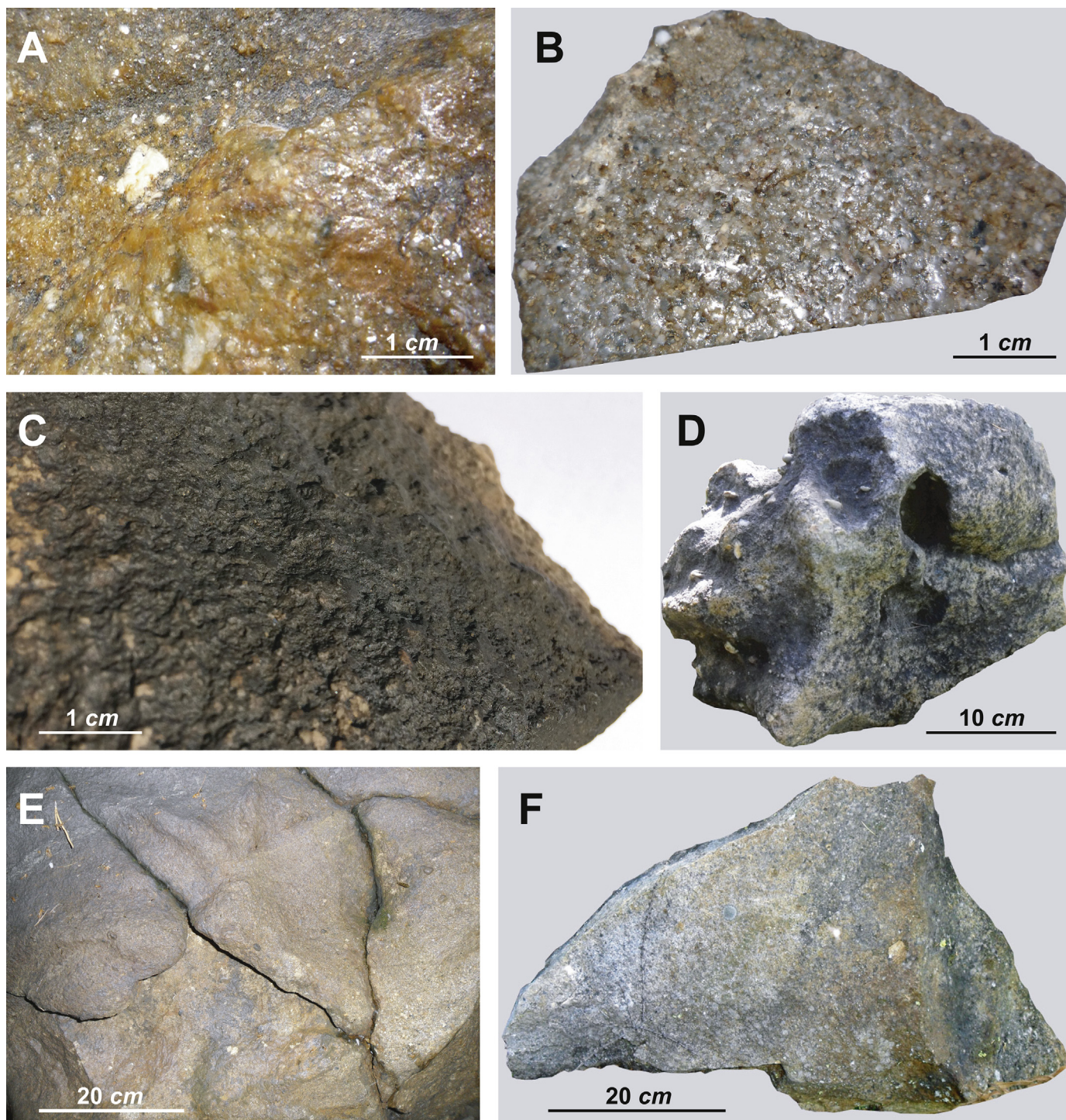


Figure 2. Fragments of John's Rock bearing signs of hypervelocity fall and impact; photographs taken in 2014 and 2015. (A, B) Glassy cover and (C) scorched coating on fragments; (D) regmaglypt-like features on the surface of a fragment that weighs ~10 kg; (E) signs of fusion along fracture lines and shatter cone-like structures at the bottom of the boulder; (F) shear-fractured fragment (~50 kg) broken off from the main boulder due to the fall.

Chelyabinsk meteoroid (Popova et al., 2013; Artemieva and Shuvalov, 2016) clearly demonstrated that an explosion in the atmosphere is the typical fate of large meter-sized meteoroids entering Earth's atmosphere.

A hypothesis for the existence of sed-type meteorites was proposed in 1972 after the discovery of a fresh impact-like structure located on the Stoykovich Mountain near the epicenter of the 1908 Tunguska explosion. This disruption in the permafrost contained

the exotic sedimentary boulder known as John's Stone or John's Rock (Figs. 1 and 2); some of its splinters display a glassy surface reminiscent of fusion crust (Anfinogenov, 1973; Anfinogenov and Budaeva, 1998a, b; Anfinogenov et al., 2014, 2017a). Research excavations and modeling studies suggest a geologically recent, hypervelocity fall for this rock (Anfinogenov, 1973; Anfinogenov and Budaeva, 1998a, b; Anfinogenov et al., 2014, 2017a). The pattern of permafrost destruction suggests a hypervelocity collision leading

to a lateral ricochet of John's Rock, followed by further deceleration and breakage producing a $\sim 50 \text{ m}^3$ impact groove in the permafrost (Fig. 1C, D). The landing velocity of John's Rock was estimated to be at least 547 m/s (Anfinogenov et al., 2014) and may have been much higher. The fall occurred on poorly consolidated ground (Anfinogenov et al., 2014), for which there are few commonly accepted markers of hypervelocity impact (French and Koeberl, 2010). The unique phenomenon of John's Rock may extend the phenomenology of impact structures and contribute to identification of markers for small- and medium-scale impacts in unconsolidated or poorly-consolidated targets.

John's Rock is composed of abyssal highly-silicified gravelite sandstone ($\sim 99 \text{ wt.}\% \text{ SiO}_2$). The outer surface of some splinters of this rock shows a continuous glassy coating, similar to a fusion crust. However, much of the glassy coating and fusion crust was stripped away due to friction on impact. There is clear consistency of the meteoroid flight trajectory with locations of John's Rock fragments and cleaved pebbles, as well as with directions of impact grooves left by its largest fragments decelerating in the permafrost (Anfinogenova et al., 2017a). John's Rock is found atop quaternary deposits at the top of the Stoykovich Mountain; it is mineralogically exotic to the territory, for at least a few hundred kilometers around the epicenter (Sapronov, 1986) and significantly differs from local tufogenic sandstones (Sapronov, 1986; Anfinogenov et al., 2014). There are no signs of recent glaciation throughout the region of the 1908 Tunguska catastrophe (Sapronov, 1986) negating the possibility of John's Rock being brought to the top of the Stoykovich mountain by glacial movement. The possibility of John's Rock being ejected from a diatreme is rejected by field studies and aerial

survey photographs, which cover an area of 40 km from the Tunguska epicenter, and show a marked absence of active diatremes (Anfinogenov et al., 2014).

John's Rock did not produce a typical impact crater; instead, it formed a massive pipe and groove structure in the water-rich permafrost (Fig. 1C, D). The absence of a classic impact crater is similar to several other cases, usually the result of large meteorites landing on hydric soils, sands, or even mountain shoulders sloping downhill in the direction of motion of the incoming cosmic body, which produces atypical impact structures (Anfinogenova et al., 2017a). For example, from the thousands of fragments of the 1947 Sikhote-Alin meteorite, several large fragments fell on frozen hydric soils, forming up to 8-m long narrow canals despite having disproportionately small entry holes (Fig. 3) (Krinov and Fonton, 1959). The absence of a significant impact crater was also noted for the largest fragment of the Chelyabinsk meteorite at Lake Chebarkul. This fragment weighs approximately 570 kg and its velocity at the time of impact was estimated to be 19 km/s (Chapman, 2013; Popova et al., 2013). The numerical value of its velocity may have been overestimated; it corresponds to a kinetic energy of 25 t of TNT, which would be significantly more destructive.

It is more likely that both the largest Chebarkul fragment of the Chelyabinsk meteorite and John's Rock, as a putative fragment of the Tunguska event, landed at low supersonic speeds without producing major impact craters. The failure to find well-defined impact structures associated with the 1908 Tunguska event may be also partially explained by the fact that the airburst of the meteoroid caused a major earthquake whose maximum magnitude

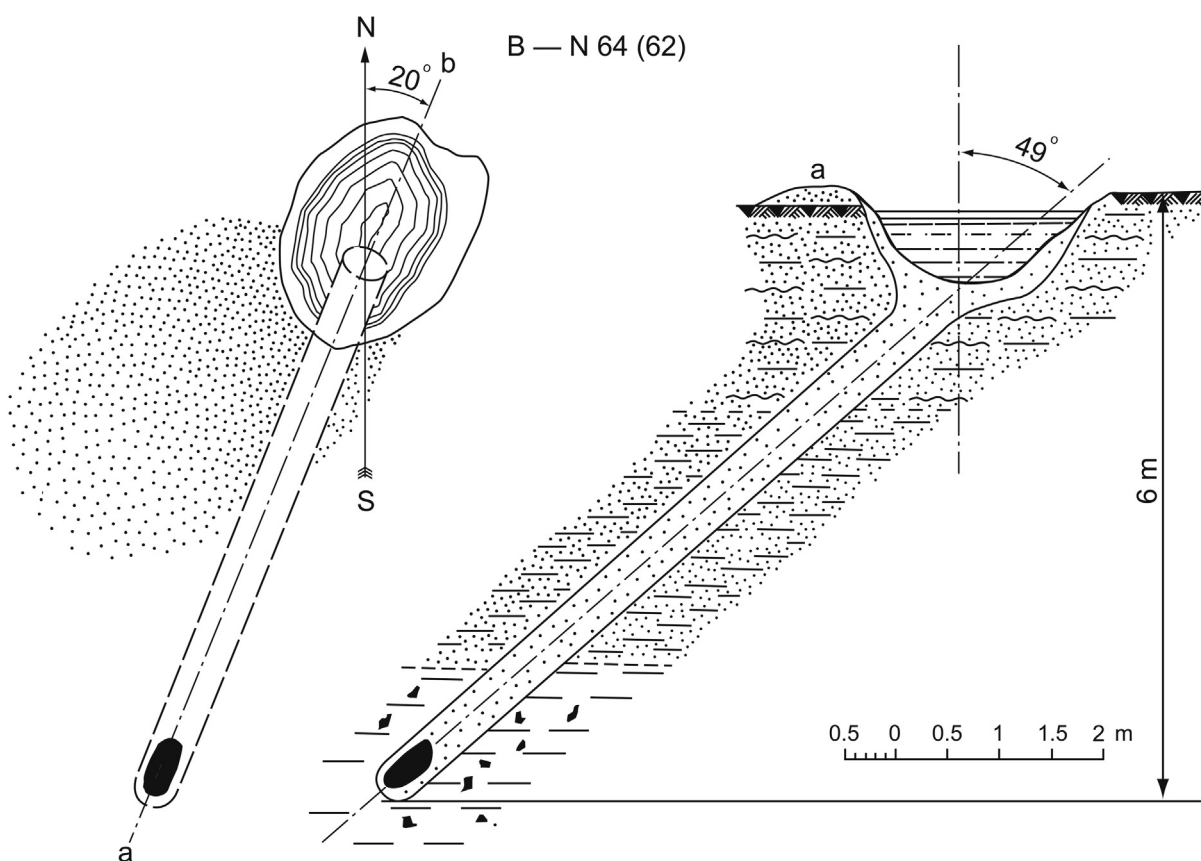


Figure 3. An example of the absence of a typical impact crater. A 255.6 kg fragment of the Sikhote-Alin iron meteorite fell on wet sandy ground in 1947, producing a small funnel (2.3 m $\times$ 1.8 m $\times$ 0.9 m). The ground was composed of soil (0.2 m), underlain by clay (1.8 m), and sand mixed with red clay. An intact individual exemplar of this meteorite was recovered from the bottom of the channel at a depth of 6 m (Krinov and Fonton, 1959).

is estimated at 8, which could largely level the disruptions produced in poorly consolidated ground by the fallen fragments of Tunguska (Anfinogenov and Budaeva, 1998a, b).

Recent studies on the structure, mineralogy, and chemistry of John's Rock confirm that the rock originated by silica deposition from hydrothermal solutions. Oxygen isotope data suggests that the precipitation of SiO₂ could have occurred in equilibrium with hydrothermal water ($\delta^{18}\text{O}_w \approx -16\text{‰}$) at a temperature of about 80 °C (Bonatti et al., 2015). High-precision triple-oxygen isotope data reveal inconsistencies with the composition of known Martian meteorites (Bonatti et al., 2015; Haack et al., 2015). In addition to SiO₂, the Tunguska boulder contains traces of a Ti-oxide phase (Bonatti et al., 2015), and its bulk composition is similar to the composition inferred from APXS data for the silica deposits of the Gusev crater on Mars (Squyres et al., 2008; Karunatillake et al., 2010). These findings are consistent with data from shergottites and nakhlites, which also contain titanomagnetite (Gattacceca et al., 2013; Stopar et al., 2013; Richter et al., 2014; Udry et al., 2017). Multidomain titanomagnetite contributes to the intensity and stability of Mars crustal magnetic anomalies (Brachfeld et al., 2014). Bonatti et al. (2015) review, in detail, sedimentary rocks and hydrothermal activity on Mars.

Data from field studies, research excavations, and modeling suggest a hypervelocity impact for John's Rock. Unlike these, instrumental data cannot unambiguously favor a terrestrial or meteoritic origin for John's Rock. Bonatti et al. (2015) summarized the pros and cons of assigning an extraterrestrial origin to this boulder. The presence of a fusion crust-like surface on fragments of the boulder and the consistent signs of hypervelocity impact associated with John's Rock represent direct evidence for its meteoritic nature (Anfinogenov et al., 2014). Further studies should include thermoluminescence analysis, rock age determination, and comparisons of John's Rock with similar terrestrial and extraterrestrial rocks. In addition to this, the site of impact requires a comprehensive interdisciplinary field examination.

John's Rock is the first macroscopic candidate fragment of the Tunguska projectile and for new sed-type meteorites composed of silica-rich metamorphic rock. The area surrounding John's Rock complies with some criteria of impact structures, though the commonly accepted markers of small- and medium-scale impacts in unconsolidated or poorly consolidated targets are as yet not well defined (French and Koeberl, 2010). There are melted, shocked, and brecciated rocks associated with John's Rock; some fill the hypervelocity disruption in the permafrost while others are transported some distance from the source impact funnel (Anfinogenov et al., 2014). Shock deformations are present in macroscopic form (Anfinogenov et al., 2014) and in microscopic forms (e.g., deformation lamellae in quartz) (Bonatti et al., 2015). Overall, macroscopic data and mathematical calculations show that John's Rock bears signs of a hypervelocity fall whose trajectory is fully consistent with the trajectory calculated from forest fall data and observations of the Tunguska meteoroid flight (Anfinogenov et al., 2014).

The inferred extraterrestrial origin of the Tunguska boulder (Anfinogenov, 1973; Anfinogenov and Budaeva, 1998a, b; Anfinogenov et al., 2014, 2017a) is compatible with the presence of hydrothermal silica-rich deposits on Mars (McLennan, 2003; Bandfield et al., 2004; Milliken et al., 2008; Squyres et al., 2008; Smith and Bandfield, 2012), as well as with the presence of liquid water (Tanigawa et al., 2014; Vance et al., 2014; Heller et al., 2015; Saur et al., 2015; Steinbrügge et al., 2015) and hydrothermal activity (Postberg et al., 2011; Hsu et al., 2015) on several bodies of the Solar System, especially the icy moons of Jupiter and Saturn. Thus, Mars is not the only candidate parent body for putative sed-type meteorites. We hypothesize that sedimentary rocks may form in the presence of flowing water, generated by tidal or volcanic forces or

both, in the oceans on the satellites of giant planets. Though the surface of the moons of Jupiter and Saturn are ice-covered, we believe that crustal or core rock/sediment release is possible from huge impacts generated by the collision of large cosmic bodies. The history of enormous impacts capable of releasing sedimentary material from the icy moons is discussed in Monteux et al. (2016).

3.2.1. Hypothesis of the Tunguska rubble-pile asteroid being partially composed of extraterrestrial sediments

In the mid 1960s, Anfinogenov carried out a microscopy study of burn injuries detected in the 1908-growth rings of the branches of surviving larch trees (conifers in the genus *Larix*, of the family Pinaceae, subfamily Laricoideae) in the epicentral area of the Tunguska catastrophe. He observed the presence of silicate microspherules and visually heterogeneous fused microparticles, similar to those found in the regional peat layer that formed in 1908 (Dolgov et al., 1973). Compared with adjacent peat layers, the 1908 peat layer contains up to hundredfold-higher count of gray and colorless transparent silicate microspherules in hundreds of samples taken over the entire area of the Tunguska catastrophe. Neutron activation analysis data shows that the chemical composition of these microspherules is distinct from that of industrial glass, local terrestrial microparticles, known stony meteorites, tektites, and Moon rocks (Kolesnikov et al., 1976). Quartz grains were found in sediment cores collected from Lake Cheko (Gasparini et al., 2009) in the epicentral area, that could be dust generated by the explosion of the silica-rich Tunguska cosmic body in the atmosphere. The presence of this regional silica anomaly is consistent with the hypothesis on the meteoritic origin of silica-rich John's Rock. The presence of a PGE anomaly was also reported for Tunguska (Rasmussen et al., 1999; Hou et al., 2004). These reports were based on data from an insignificant number of peat core samples from singular topographic locations.

Two explanations may be proposed to reconcile the finding of these two distinct anomalies. One explanation requires the occurrence of two independent impact events within a short period of time, one involving a silica-rich impactor and the other, a chondritic or cometary projectile. The second explanation is the more plausible rubble-pile asteroid hypothesis, suggesting that the impactor had a complex conglomerate composition (Anfinogenova et al., 2017b). Multiple pieces of the impactor may have merged either due to collision of parent asteroids in outer space or due to co-ejection of different types of rocks, including bedrock, intrusive igneous rocks and impactor material which could partially melt into each other due to a mega-impact on a parent planetary body (Fig. 4). Such processes could produce a rubble-pile asteroid whose fall caused the dual anomaly at the 1908 impact site in Tunguska.

Interestingly, no macroscopic pieces of chondritic or cometary projectile have been found in the area of the 1908 Tunguska catastrophe. Chyba et al. (1993) reported that carbonaceous asteroids and comets are unlikely candidates for the Tunguska object, and that the Tunguska event represents a typical fate for stony asteroids tens of meters in radius entering the Earth's atmosphere at common hypersonic velocities. In this context, John's Rock may be considered as a macroscopic candidate for a stony impactor of a previously unknown type, bearing numerous signs of hypervelocity impact and glassy fusion crust-like surface on some splinters (Anfinogenov and Budaeva, 1998a, b; Anfinogenov et al., 2014). It is also consistent with the discovery of quartz grains in sediment cores collected from Lake Cheko (Gasparini et al., 2009) in the epicentral area, and the glassy silicate microspherules associated with the entire area of the 1908 Tunguska catastrophe (Dolgov et al., 1973; Kolesnikov et al., 1976).

Data showing the presence of two distinct anomalies suggest that the 1908 Tunguska cosmic body may be a rubble pile asteroid

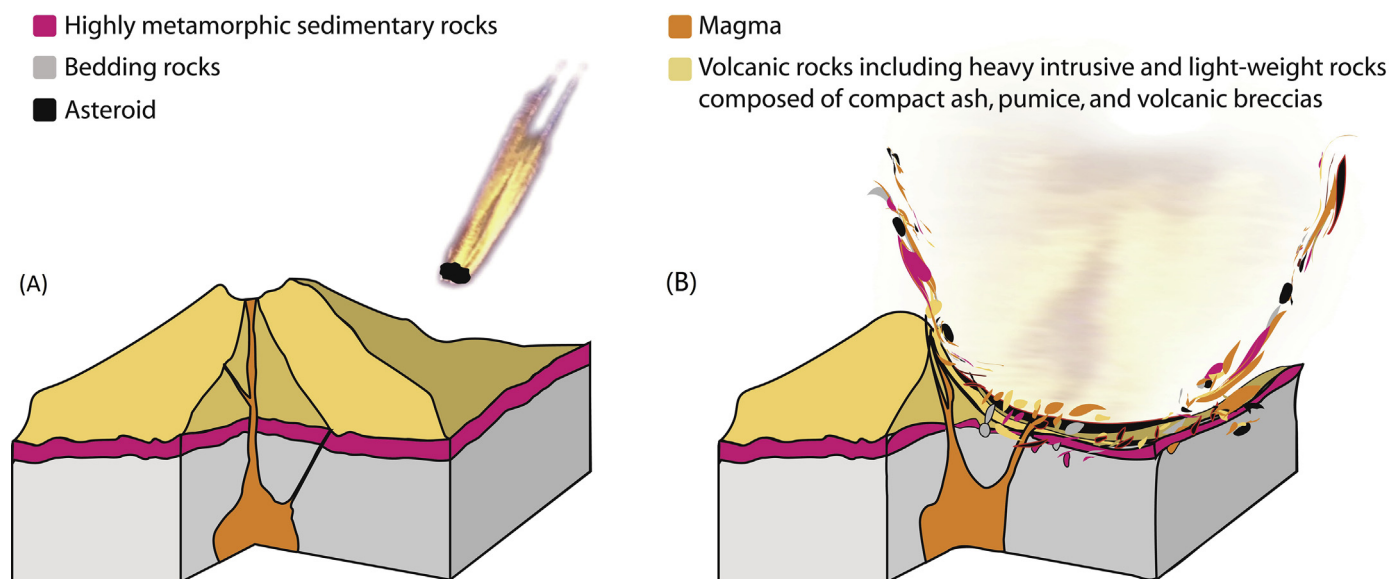


Figure 4. (A) Bombardment of a volcano by an asteroid; (B) ejection of pro-asteroid material with complex-composition into space due to the bombardment.

partially composed of material representing the planetary crust of a parent body with abundant liquid water. It is essential to note that laminated sed-type meteorites could be composed of rocks which do not require water for their formation. Indeed, sedimentary laminations in the Isheyevo (CH/CBb) carbonaceous chondrite formed in the gentle sweep-up created by the impact-plume (Garvie et al., 2017).

The conglomeratic nature of the Tunguska meteoroid may explain its atmospheric disintegration. Since 1965, integrative field studies, modeling and expert examinations of aerial photographs (from the 1938, 1949 aerial surveys) including aerial-image-3D-visualizations (stereo pairs) have produced data showing that Tunguska was not a single-point airburst; the initial blast wave had the shape of a spindle or the tip of a spear (Anfinogenov, 1966; Anfinogenov and Budaeva, 1998a, b). This data suggests that the Tunguska meteoroid probably disintegrated into ca. 20 fragments, each of which were comparable with the 2013 Chelyabinsk meteoroid. There are signs that the Tunguska cosmic body was irregular (heterogeneous) in its composition, and mechanical and thermal strengths. Initial breakage of the Tunguska meteoroid into fragments resulted in the formation of the meteoroid swarm that exploded at different altitudes, ranging from 25 km to 5 km, above ground. Cumulatively, these explosions were responsible for decimation of over 600 km² of forest. Only small fragments, similarly to the 2013 Chelyabinsk, survived atmospheric entry (composed of slightly altered matter) and reached the ground. Regenerating zones of vegetation are visible in the aerial photographs taken in 1938 and 1949 of the Southern Bog (Yuzhnoye Boloto) and near the epicenter of the Tunguska catastrophe (Anfinogenova et al., 2016).

4. Potential parent bodies

4.1. Icy moons, dwarf planets, and large asteroids

Sandstones can only form on a parent body with liquid water. In the Solar System, many bodies without a significant atmosphere have abundant liquid water (Greenwood et al., 2005; Tanigawa et al., 2014; Vance et al., 2014; Heller et al., 2015; Saur et al., 2015; Steinbrügge et al., 2015). Hydrothermal processes occur, in

particular, on Enceladus (Postberg et al., 2011; Hsu et al., 2015). The presence of powerful tidal currents of water in subsurface oceans on the icy satellites of Saturn and Jupiter may provide the conditions necessary for the formation of sedimentary and metamorphic rocks, including sandstones and pebble conglomerates with a variety of grain sizes.

The Saturnian moon, Enceladus, may be considered a candidate parent body for sed-type meteorites composed of metamorphosed rocks due to: (a) the presence of large-scale hydrothermal activity, (b) the presence of powerful tidal currents of water in its subsurface oceans potentially resulting in the formation of sediments, and (c) its history of large-scale impacts that explain the ejection of fragments of Enceladus' crust into space. Interestingly, a plume on Enceladus emits nanometre-sized SiO₂ (silica)-containing ice grains (Hsu et al., 2015) that probably form from a liquid water reservoir in contact with silica-rich rock (Postberg et al., 2011). Characteristics of these silica nanoparticles indicate ongoing large-scale high temperature (>90 °C) geothermal and hydrothermal reactions on Enceladus favored by large impacts (Hsu et al., 2015). Enceladus has a differentiated interior consisting of a rocky core, an internal ocean and an icy mantle (Monteux et al., 2016). The main characteristics of Enceladus comprise a large ocean with strong dissipation, reduced ice-shell thickness at the south pole and sea-floor activity. This endogenic activity can be sustained for billions of years (Choblet et al., 2017). Simulation studies suggest that heterogeneity in the interior, including significant core topography, may be due to collisions with large differentiated impactors, with radii ranging between 25 and 100 km (Monteux et al., 2016). Impacts played a crucial role in the evolution of Enceladus (Monteux et al., 2016), as also in the evolution of other moons of Saturn as well as on other planetary bodies, such as Ceres (Davison et al., 2015; Ivanov, 2015). We hypothesize that the presence of water ice on the surface and in subsurface oceans might not be enough to stop the ejection of rocky material from the interior of these icy satellites due to collisions with large impactors (>25 km).

A putative subsurface water ocean is present on Ganymede. The iron core of Ganymede is surrounded by a silicate rock mantle and by a briny subsurface water ocean with alternating layers of high pressure ice and salty liquid water (Vance et al., 2014; Saur et al., 2015; Steinbrügge et al., 2015). If Ganymede or Callisto had

acquired their H₂O from newly accreted planetesimals after the Grand Tack (Mosqueira and Estrada, 2003), then Io and Europa would be water-rich, too (Tanigawa et al., 2014; Heller et al., 2015).

Tidal dissipation and tidal resonance in icy moons with sub-surface oceans are major heat sources for the icy satellites of Jupiter and Saturn (Kamata et al., 2015). Tidal forces generate heat and currents of liquid water or brine powerful enough to produce sediments that undergo metamorphic transformations due to hydrothermal activity. The Galilean satellites have great potential as targets for astrobiological exploration (Greeley and Morrison, 2003). Indeed, macromolecular organic compounds from the depths of Enceladus have been reported (Postberg et al., 2018). Moreover, fluvial conglomerates were discovered at Gale Crater on Mars (Williams et al., 2013).

Sediments and sedimentary rocks may also exist on smaller bodies in the Solar System such as the comet 67P/Churyumov-Gerasimenko (Jia et al., 2017), a dwarf planet Ceres (Nathues et al., 2017) and asteroid 4 Vesta (Treiman et al., 2004). Indeed, Ceres is a thermally evolved, volatile-rich body with putative geological activity, one which was never totally molten and which has possibly partially differentiated into a rocky core and an ice-rich mantle, and may contain remnant internal liquid water (Nathues et al., 2017). Evidence from a quartz veinlet in the Serra de Mage eucritic meteorite suggests that ancient water was present on asteroid 4 Vesta (Treiman et al., 2004). Pluto, Mars, Venus, Titan, even the comet 67P/Churyumov-Gerasimenko demonstrate the mobilization and self-organization of sediments into dunes, which occur throughout the Solar System from surface winds which are expected to transport particles (Hayes, 2018; Telfer et al., 2018). However, a distinction must be made between loosely organized sedimentary material which has never been subject to hydrothermal activity and metamorphosed rocks that require hydrothermal activity for their formation. In our opinion, putative meteorites composed of metamorphic sedimentary rocks that form in the presence of hydrothermal activity are of the utmost interest as they can potentially contain signs of life or of environments favorable for harboring life on other bodies in the Solar System (Farmer and Bickford, 2013).

Metamorphic phenomena in putative sed-type meteorites has never been studied or modeled before. Degrees of shock metamorphism may vary considerably depending on likely impact scenarios and characteristics of the impactor cosmic bodies. Any signs of metasomatism occurring in native conditions on parent bodies at temperatures lower than melting point may or may not survive impact and atmospheric entry. The presence of slightly altered or unaltered material in planetary-origin meteorites capable of bearing microfossils and cell-like features remains a subject of discussion (Neveu et al., 2018).

Therefore, candidate parent bodies for hypothetical sed-type meteorites include, but are not limited to, Mars, Enceladus, Ganymede, Europa, Ceres, and Vesta.

4.2. Hypothetical planet Phaeton as a possible parent body

After the discovery of the sedimentary boulder associated with hypervelocity disruption of the ground in the epicenter of the 1908 Tunguska catastrophe, it was hypothesized (Anfinogenov, 1973; Anfinogenov and Budaeva, 1998a,b; Anfinogenov et al., 2014, 2017a,b) that sed-type meteorites on Earth may originate from a hypothetical planet called Phaeton (McSween, 1999). Finding of so-called Martian meteorites and some pseudo-meteorites belonging to upper-crust rocks (volcanic and metamorphosed igneous and sedimentary rocks) from Mars-like planets provided the rationale for reconsidering a hypothesis suggesting that a previously existing planet between the orbits of Mars and Jupiter is the parent body of

the asteroid belt. The nature of this hypothetical planet and the mechanism of its total explosive disintegration remain unresolved. Various mechanisms were proposed in support of the exploded planet hypothesis (Van Flandern, 2007). Considering the interorbital structural characteristics of the Solar System, we believe that two or even three planets could have been spaced between the orbits of Mars and Jupiter. If these hypothetical planets in the past are assigned a certain orbit geometry, and accounting for the influence of the giant planet Jupiter, these neighbor planets could have come close enough to each other resulting in a catastrophic collision.

Based on mathematical modeling with iterative refining, we proposed a scenario (Anfinogenov et al., 2017) involving two hypothetical planets Phaeton I and Phaeton II (Fig. 5) with the following characteristics: (a) masses comparable with the mass of Mars; (b) average distances of 2.4 A.U. between the Sun and Phaeton I, and 3.95 A.U. between the Sun and Phaeton II; (c) elliptic orbits like those of Pluto and Mercury with the major axes in the ecliptic plane; (d) orbital plane inclinations of 15° relative to the ecliptic plane, and an angle of 30° between the orbital planes of these planets; (e) similar Phaeton II's perihelion and Phaeton I's aphelion distances (2.9 ± 0.1 A.U., between these planets and the Sun, respectively) and a distance of ≤ 0.1 A.U. between these two planets, at their closest approach to each other.

A catastrophic collision may have occurred if (a) Phaeton II's perihelion and Phaeton I's aphelion coincided spatially and temporally; (b) the courses of these planets intersected at a 30° angle; (c) individual orbital velocities of Phaeton I and Phaeton II were ~ 16 and ~ 20 km/s, respectively; (d) their closing velocity was ~ 9 km/s at the moment of the collision. If this was the case, different variants of a spatial arrangement of the physical contact between Phaeton I and Phaeton II, relative to each other, are possible including a scenario where Phaeton I collided with a rear hemisphere of Phaeton II (billiard ball-type impact). If their closing velocity was ~ 9 km/s, the impulse of the force of impact and the kinetic energy would have been sufficient for the disintegration of both these planets and the dispersion of their fragments with velocities exceeding the second cosmic speed for their masses. In such a case, a significant portion of the mass from Phaeton II and its fragments might have acquired an additional orbital acceleration, accounting for the stretching of their orbit up to the orbit of Jupiter, and allowing the possibility of some fragments being captured and assuming orbital motion around Jupiter or even their entry into the Jovian atmosphere. A significant portion of the mass from Phaeton I may have undergone deceleration which caused the exit of its fragments from their orbit and their acceleration towards the Sun and Earth-type planets, with a possibility of their subsequent fall. The mid-section of the collision zone of these two planets may have formed the asteroid belt.

Considering its layered structure, Mars' moon Phobos may have originated as the planetary crust of Phaeton I. This notion agrees well with the work of Simioni et al. (2015), who propose an explanation of the observed distribution of the grooves on Phobos as remnant features of an ancient parent body from which Phobos could have originated, after a catastrophic impact event. We hypothesize that Olympus Mons, the largest volcano in the Solar System, could have formed when the other large fragment of Phaeton I collided with Mars, and produced a gigantic impact hole in its planetary crust.

This proposed variant of a possible collision of two hypothetical planets between the orbits of Mars and Jupiter does not contradict the existing structural characteristics of the Solar System. Physical and mathematical modeling of the retrospective motion of these planets, from their origin and up to their collision, as well as the origin of the asteroid belt is well within the scope of advancing

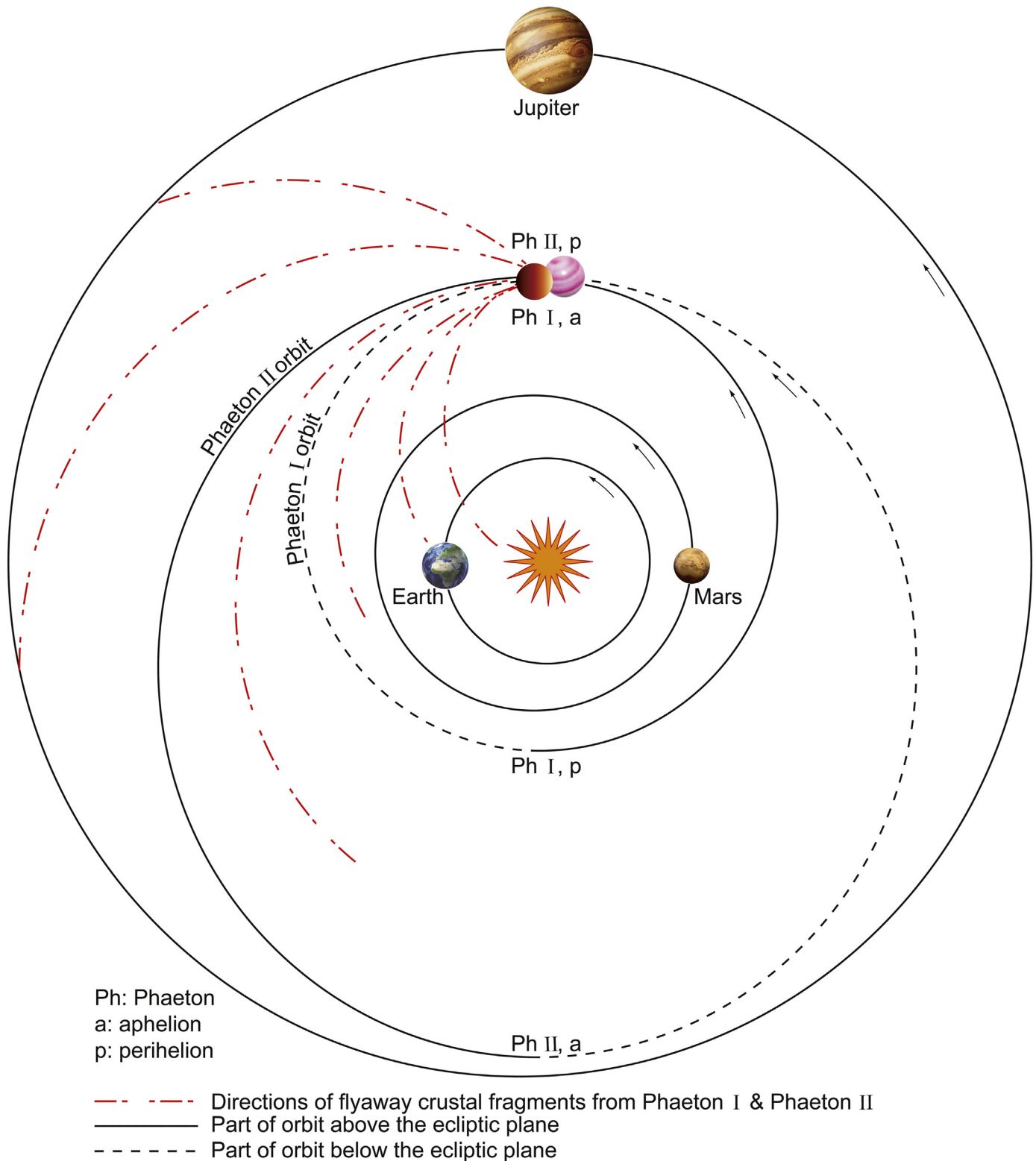


Figure 5. Scenario at the moment of collision of the hypothetical planets Phaeton I and Phaeton II (Anfinogenov et al., 2017).

planetary science and is a potential subject for future publications. It is essential for this manuscript to emphasize that potential parent bodies for asteroids of different sizes may be represented in a meteorite by diverse structural elements of mature planets, including their core and planetary crust. In the case of planetary

crust forming the body of a meteorite, remnants of metamorphically altered and hardened rocks are of utmost interest.

The proposed reconstruction of the initial planetary structure of the Solar System and its partial disruption are compatible with the structural and dynamic characteristics of the parts that are

preserved. Identification of progenitors of meteorites and the asteroid belt, as well as determining their age of formation requires the consideration that some these cosmic bodies may have started out as the planetary crust of hypothetical planets, Phaeton I and Phaeton II.

Thus, hypothetical planets Phaeton I and Phaeton II which possibly existed in the past may represent parent bodies of a putative new-type of planetary meteorites including Martian-like meteorites and meteorites belonging to upper-crust rocks such as volcanic and metamorphosed igneous and sedimentary rocks.

5. Isotope tests of candidate extraterrestrial sedimentary rocks

Improved elemental and isotopic characterizations of the exotic boulder from the epicenter of the 1908 Tunguska event are essential. High precision triple oxygen isotope data reveal that this rock is compositionally inconsistent with known Martian meteorites (Bonatti et al., 2015; Haack et al., 2015). However, numerical results of isotopic characterizations, though important, cannot prove or disprove the origin of any rock. Indeed, no rock samples from Mars or from other cosmic bodies with abundant water have ever been delivered to the Earth before. Isotopic compositions of Martian sedimentary rocks have not been tested by Mars rovers and remain unknown. Only Martian meteorites have been analyzed. The diversity in rock-forming processes and in their corresponding rock types within planets are insufficiently studied. Significant heterogeneity in $\Delta^{17}\text{O}$ in rocks of different types were reported by Wang et al. (2013), while Pack and Herwartz (2014, 2015) provided evidence that the concept of a single terrestrial mass fractionation may be invalid on small-scales. They concluded that mineral assemblages in rocks fall on individual 'rock' mass fractionation lines, with individual slopes and intercepts.

This may be valid in the case of other bodies within the Solar System, particularly the large moons of Jupiter and Saturn, and large asteroids. The idea of separate long-lived silicate reservoirs on Mars is supported by radiogenic isotope studies (Borg et al., 1997, 2003). The distinct $\Delta^{17}\text{O}$ and $\delta^{18}\text{O}$ values of the silicate fraction of NWA 7034 compared to other SNC meteorites support the idea of distinct lithospheric reservoirs on Mars that have remained unmixed throughout Martian history (Agee et al., 2013; Ziegler et al., 2013). Isotopic heterogeneity, including that of noble gases, can be significant in the Martian mantle. Models for accretion and early differentiation of Mars were tested with chronometers, several of which provided evidence of very early isotopic heterogeneity (Halliday et al., 2001). If significant heterogeneities are reported for known Martian meteorites, all of which are igneous rocks, then even greater isotopic heterogeneities may exist for rocks of different types within the planet.

Noble gas signatures of meteorites may be affected by contamination or by loss as a direct result of the time spent in terrestrial environments, especially in extreme weather conditions. In our opinion, macroscopic evidence from field studies suggesting hypervelocity fall of meteorites should be taken into careful consideration. Findings supporting the hypervelocity fall of John's Rock in Tunguska cannot be denied based solely on its isotopic signatures. Given the lack of knowledge on isotopic signatures of several admissible parent cosmic bodies for putative sed-type meteorites, data suggesting the hypervelocity fall of John's Rock must be considered.

6. Summary

Candidate parent bodies for putative sed-type meteorites include, but are not limited to, Mars, Enceladus, Ganymede, Europa,

Ceres, Vesta, and hypothetical planets that could have existed between the orbits of Mars and Jupiter in the past. Major challenges of identifying sed-type meteorites are as follows: (a) largely unknown isotopic hallmarks of various parent bodies, (b) terrestrial loss or contamination in noble gas signatures, (c) small number of discovered macroscopic candidates, (d) unknown visual characteristics of a fusion crust, (e) incomplete knowledge on Solar System history, and (f) lack of awareness of the wider scientific community regarding the potential existence of sed-type meteorites.

In this interdisciplinary review article, we largely focus on the exotic boulder found on the Stoykovich Mountain and the associated conditions from the 1908 Tunguska event because other reported candidate sed-type meteorites remain inaccessible or lost (Rollier, 1907; Hadding, 1940; Cross, 2012). Moreover, the discovery of this exotic rock in Tunguska in 1972 by Dr. John Anfinogenov led him to hypothesize the existence of sed-type meteorites coming from other planets (Anfinogenov, 1973). This boulder is perhaps the only macroscopic candidate sed-type meteorite available for the scientific community to study in the lab and *in situ*. The scientific community is encouraged to acquire and test samples of this rock, and especially of fragments with a glassy cover. The macroscopic signs of a geologically-fresh hypervelocity pipe/groove-like impact associated with John's Rock, the presence of microscopic deformation lamellae, a fusion crust-like glassy surface on some fragments, location of this boulder near the epicenter of the 1908 Tunguska catastrophe, and its starkly different mineralogy compared to the regional geology represent extraordinary evidence for its meteoritic origin. Studying this rock may contribute to gaining insights into both the 1908 Tunguska phenomenon and into hitherto unexplored physics of small-scale impacts in unconsolidated or poorly consolidated targets (see also Section 8.2.4 in French and Koeberl, 2010).

Dozens of pseudo-meteorites found in Antarctica and mentioned in the Meteoritical Bulletin Database maybe tossed away based upon an erroneous assumption that sed-type meteorites cannot exist. Maybe, 'a time to gather stones' has come. Considering the abundance of liquid water in the Solar System, the field of Astrobiology and future missions exploring the Solar System may benefit from identifying planetary-origin meteorites with non-igneous compositions.

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