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Highlights

- The eucrites and diogenites are differentiated meteorites whose genetic link with the crust of asteroid Vesta was confirmed, together with the survival of said crust, by the NASA mission Dawn
- The composition of some eucrites and diogenites suggests an enrichment in water and highly-siderophile elements in the parent melt of Vesta's crust, interpreted as the record of a late veneer
- The ages of the oldest eucrites and diogenites indicate that Vesta's differentiation occurred early in the history of the Solar System and predates the formation of Jupiter and the other giant planets
- We explore how a late veneer can compositionally and erosionally influence Vesta's crust in a proof-of-concept study focusing on the bombardment triggered by the formation and migration of Jupiter
- The late veneer and the erosion experienced by Vesta's crust during the early collisional history of the asteroid can be jointly used as astrochemical constraints on the early evolution of the Solar System

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The late accretion and erosion of Vesta's crust recorded
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15 Abstract

The circumsolar disc was the birthplace of both planetesimals and giant 16 planets, yet the details of their formation histories are as elusive as they 17 are important to understand the origins of the Solar System. For decades 18 the limited thickness of Vesta's basaltic crust, revealed by the link between 19 the asteroid and the howardite-eucrite-diogenite family of meteorites, and its 20 survival to collisional erosion offered an important constraint for the study 21 of these processes. Some results of the Dawn mission, however, cast doubts 22 on our understanding of Vesta's interior composition and of the characteris-23 tics of its basaltic crust, weakening this classical constraint. In this work we 24 investigate the late accretion and erosion experienced by Vesta's crust after its differentiation and recorded in the composition of eucrites and diogenites 26

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and show that it offers an astrochemical window into the earliest evolution 27 of the Solar System. In our proof-of-concept case study focusing on the late 28 accretion and erosion of Vesta's crust during the growth and migration of 29 Jupiter, the water enrichment of eucrites appears to be a sensitive function 30 of Jupiter's migration while the enrichment in highly-siderophile elements of 31 diogenites appears to be particularly sensitive to the size-frequency distribu-32 tion of the planetesimals. The picture depicted by the enrichments created 33 by late accretion in eucrites and diogenites is not qualitatively affected by 34 the uncertainty on the primordial mass of Vesta. Crustal erosion, instead, is 35 more significantly affected by said uncertainty and Vesta's crust survival ap-36 pears to be mainly useful to study violent collisional scenarios where highly 37 energetic impacts can strip significant amounts of vestan material while lim-38 itedly contributing to Vesta's late accretion. While our proof-of-concept case 39 study is based on a simplified physical model and explores only a limited 40 set of scenarios, our results suggest that the astrochemical record of the late 41 accretion and erosion of Vesta's crust provided by eucrites and diogenites 42 can be used as a tool to investigate any process or scenario associated to the 43 evolution of primordial Vesta and of the early Solar System. 44

⁴⁵ Keywords: Asteroid Vesta, Planetary formation, Meteorites, Impact
⁴⁶ processes, Jupiter

47 1. Introduction

⁴⁸One of the most challenging tasks in the study of the Solar System is that ⁴⁹of disentangling the steps of its formation process that took place during the ⁵⁰life of the circumsolar disc, specifically over the timespan extending from the

condensation of the Calcium-Aluminum-rich Inclusions (CAIs) 4568.2 $^{+0.2}_{-0.4}$ Ma 51 ago, (Bouvier and Wadhwa, 2010) to the dissipation of the gas from the disc 52 4-5 Myr later (Scott 2006; Johnson et al. 2016; Wang et al. 2017; Kruijer 53 et al. 2017, but values up to 10 Myr are possible based on the comparison 54 with circumstellar discs, see e.g. Fedele et al. 2010). Among the most im-55 portant events that occurred during this timespan are the formation of the 56 planetesimals, the appearance of the giant planets, and their migration due 57 to their interaction with the nebular gas (see Morbidelli and Raymond 2016 58 and references therein). 59

Our understanding of these three processes, however, has been put under 60 scrutiny by new ideas and scenarios. In particular, various authors have 61 argued that the giant planets formed at locations different from their current 62 ones and underwent a period of extensive migration during the life of the 63 circumsolar disk (see Morbidelli and Raymond 2016 and references therein). 64 Such an extensive early migration was shown to be associated with a period 65 of dynamical excitation and orbital remixing of the planetary bodies in the 66 circumsolar disc, with major implications for the evolution of the primordial 67 asteroid belt (Walsh et al., 2011; O'Brien et al., 2014). 68

However, compositional studies of the asteroid belt (DeMeo and Carry, 2014; Michtchenko et al., 2016) disagree on whether an extensive migration of the giant planets is consistent with the current radial distribution of the different kinds of asteroids. On the other hand, the very mass growth of the giant planets was shown to also be capable of triggering phases of dynamical excitation and radial mixing of the planetesimals even in absence of migration (see Fig. 1 and Turrini et al. 2011, 2012; Turrini 2014; Turrini & Svetsov ⁷⁶ 2014; Turrini et al. 2015; Raymond & Izidoro 2017). This ambiguity in the
⁷⁷ early history of the giant planets severely hinders our understanding of the
⁷⁸ formation of the Solar System.

Most signatures left by these ancient events, like their cratering records. 79 were removed or altered by the later evolution of the individual planetary 80 bodies or of the Solar System as a whole, making it difficult to verify conclu-81 sively the different models and scenarios (see Morbidelli and Raymond 2016 82 and references therein). As our most reliable and temporally resolved source 83 of information on the early life of the Solar System is offered by meteorites, 84 our best chance to solve this conundrum lies in identifying those meteoritic 85 properties that can be linked to the evolution of the nebular environment in 86 which their parent bodies were embedded. 87

The aim of this work is to investigate how three specific compositional 88 characteristics of the Howardite-Eucrite-Diogenite (HED) family of basaltic 89 achondritic meteorites and of their parent body asteroid (4) Vesta can be 90 jointly used to constrain in a quantitative way the early collisional history 91 of the asteroid and, through that, the dynamical evolution of the circumso-92 lar disc, as first suggested by Turrini (2014) and Turrini & Svetsov (2014). 93 The three compositional characteristics we will focus on are: the survival of 94 Vesta's basaltic crust, the enrichment in water of eucrites, and the enrichment 95 in highly-siderophile elements of diogenites. 96

In exploring the working of the astrochemical constraints provided by these three compositional characteristics, we will consider a proof-of-concept case study focusing on the collisional evolution of primordial Vesta across Jupiter's mass growth in different migration scenarios for the giant planet

(the event also labelled as *Jovian Early Bombardment* or JEB, see Fig. 1
and Turrini et al. 2011, 2012; Turrini 2014; Turrini & Svetsov 2014; Turrini
et al. 2015). This case study has been selected as it allows us to reuse previous simulations and results to explore the sensitivity of these astrochemical
constraints to a number of physical parameters (namely flux, physical characteristics, size distribution and impact velocity distribution of the impactors
and the mass of the primordial Vesta).

The rest of this work is organized as follows. In Sect. 2 we will overview 108 the current state of our understanding of asteroid (4) Vesta and of the HEDs. 109 In Sect. 3 we discuss in more details the compositional characteristics of the 110 HEDs and Vesta we aim to use to constrain the early evolution of the Solar 111 System. In Sect. 4 we describe the theoretical tools and the simulations used 112 to in our proof-of-concept case study. Readers interested in the working of 113 the compositional constraints from Vesta and the HEDs can skip this section 114 bearing in mind that, due to the exploratory nature of this work, some of 115 the approximations adopted in the case study will be made for reasons of 116 convenience (e.g. minimizing the need for additional simulations) and will 117 not fit equally well all investigated scenarios. 118

The numerical results we will discuss in Sect. 5 should therefore be considered only as illustrative of the joint working of the three compositional constraints and the consistency of the investigated scenarios with these compositional constraints will need to be reassessed in more details in future works using more complete physical models. Finally, in Sect. 6 we discuss the general application of the compositional constraints from Vesta and the HEDs to other scenarios beyond the simplified ones considered in this work.

¹²⁶ 2. Vesta and the HEDs: witnesses of the beginning

Asteroid (4) Vesta was identified as the possible source of the Howardite-127 Eucrite-Diogenite (HED) family of basaltic achondritic meteorites more than 128 40 years ago (McCord et al., 1970; Consolmagno and Drake, 1977). The 129 NASA mission Dawn, which explored the asteroid between 2011 and 2012 130 (Russell et al., 2012, 2013), recently provided a strong confirmation to the 131 proposed Vesta-HED genetic link (De Sanctis et al., 2012; Prettyman et 132 al., 2012). Because of this genetic link, the achondritic nature of the HEDs 133 implies that Vesta is a differentiated asteroid that experienced global melting 134 (see e.g. Greenwood et al. 2014; Steenstra et al. 2016). 135

Members of the HEDs family possess some of the oldest formation ages 136 among the meteoritic samples currently available (see e.g. Scott 2007 and 137 Day et al. 2016 and references therein). These ages date the completion of 138 Vesta's differentiation to no later than 3 Myr after the condensation of CAIs 139 (Bizzarro et al., 2005; Schiller et al., 2011). Based on current estimates, this 140 event occurred immediately before the formation of Jupiter and the other 141 giant planets, which is dated between 3 and 5 Myr after CAIs (Scott, 2006; 142 Johnson et al., 2016; Wang et al., 2017; Kruijer et al., 2017). These data 143 therefore imply that the JEB was most plausibly the first violent collisional 144 event experienced by the partially molten crust of Vesta after the differenti-145 ation of the asteroid. 146

Meteoritic data from the HEDs provide us also indications on the duration of the volcanic resurfacing of Vesta and on the timescale of solidification of its crust after the differentiation process completed (see McSween et al. 2011 for a discussion). Specifically, the basaltic eucrites indicate that the outer

basaltic crust of Vesta formed over several episodes of magmatism through 151 a solid conductive lid (Roszjar et al., 2016) that spanned at least 10 Myr 152 (McSween et al., 2011) and possibly up to 35 Myr (Roszjar et al., 2016). 153 Thermal and geophysical models suggest that the conductive lid was a few 15 km thick (3-5 km, see e.g. Formisano et al. 2013; Tkalcec et al. 2013) 155 In parallel, diogenites indicate that the underlying lower crust slowly so-156 lidified over tens of Myr (see McSween et al. 2011 and references therein). 157 Because of the timing of Jupiter's formation mentioned above (i.e. the first 158 ~ 2 Myr after Vesta's differentiation) and of the duration of the bombard-159

ment it triggered (~1 Myr, Turrini et al. 2014, 2012), across the JEB both
the eucritic and the diogenitic layers were in a partially molten state (see e.g.
Formisano et al. 2013; Tkalcec et al. 2013 for the results of thermal and geophysical models and McSween et al. 2011; Greenwood et al. 2014; Steenstra
et al. 2016; Roszjar et al. 2016 for the meteoritic evidences).

The most recent compositional models of Vesta combining the informa-165 tion provided by the HEDs (in particular in terms of elemental abundances) 166 and by the Dawn mission (in particular the survival of Vesta's basaltic crust 167 and the size of Vesta's metallic core, as discussed below) with astrochemical 168 constraints have eucrites and diogenites as the main components of the up-169 per and lower layers of Vesta's basaltic crust, whose total thickness should 170 range between 20 and 40 km (Mandler and Elkins-Tanton, 2013; Toplis et 171 al., 2013; Consolmagno et al., 2015). The astrochemical constraints used in 172 these models implicitly assume a chondritic or solar composition (in terms of 173 relative abundances, not absolute ones) for the major rock-forming elements, 174 in particular the abundant lithophiles Si, Mg, Ca and Al (see Consolmagno 175

et al. 2015 and in particular their Sects. 3.2, 3.3 and 4.3 for a more detailed discussion of this subject).

As all these elements are expected to condense at temperatures greater 178 than 1500 K in the circumsolar disc (see e.g. Consolmagno et al. 2015), this 179 implicit assumption is expected to hold throughout all but the innermost and 180 hottest region of the circumsolar disc, spanning a fraction of au. According 181 to these compositional models, Vesta's Fe-rich core, which the Dawn mission 182 estimated to possess a radius of 110-140 km (Russell et al., 2012; Ermakov et 183 al., 2014), is overlaid by a mantle composed of harzburgite containing 60-80% 184 olivine (Mandler and Elkins-Tanton, 2013; Toplis et al., 2013; Consolmagno 185 et al., 2015). 186

Vesta's differentiated nature and the limited thickness of its crust in-187 ferred by the Vesta-HED link made the survival of this crust an important 188 constraint for the study of the evolution of the asteroid belt and the Solar 180 System (see Davis et al. 1985; Coradini et al. 2011; O'Brien and Sykes 2011 190 and references therein, Turrini et al. 2011; Brož et al. 2013; Turrini 2014; 191 Turrini & Svetsov 2014; Consolmagno et al. 2015; Pirani and Turrini 2016). 192 However, some of the very results of the Dawn mission cast doubt on the 193 reliability of the assumption of chondritic bulk composition for the major 194 rock-forming elements of the present-day Vesta (Jutzi et al., 2013; Clenet et 195 al., 2014; Consolmagno et al., 2015; Turrini et al., 2016). 196

¹⁹⁷ Specifically, the Dawn mission revealed the existence of two giant, partly ¹⁹⁸ overlapping impact basins, named Rheasilvia and Veneneia, in the South-¹⁹⁹ ern hemisphere of Vesta (Schenk et al., 2012) and confirmed the survival of ²⁰⁰ Vesta's crust at all spatial scales, including inside these two giant basins (De

Sanctis et al., 2012; Ammannito et al., 2013; Ruesch et al., 2014). Simu-201 lations of the formation of both impact basins suggested a total excavation 202 depth of 40-80 km (Jutzi et al., 2013) and indipendent impact and geologic 203 studies (Ivanov and Melosh, 2013; Ruesch et al., 2014) reported an excava-204 tion depth of about 30-45 km for the Rheasilvia basin alone, values at odds 205 with the thickness of Vesta's crust reported by the most recent compositional 206 models (Mandler and Elkins-Tanton, 2013; Toplis et al., 2013; Consolmagno 207 et al., 2015). 208

More precisely, it has been pointed out that the lack of olivine signatures 209 inside the two partly overlapping impact basins Rheasilvia and Veneneia and 210 on Rheasilvia's central peak (Jutzi et al., 2013; Clenet et al., 2014; Ruesch et 211 al., 2014), Vesta's density profile and the mass balance of its interior struc-212 ture estimated by Dawn (Consolmagno et al., 2015), and the likely exogenous 213 origin of the limited olivine-rich material on Vesta's surface in the Northern 214 hemisphere (Turrini et al., 2016) are all inconsistent with the limited thick-215 ness of said crust associated with a chondritic bulk composition in terms of 216 the major rock-forming elements (Consolmagno et al., 2015). This argues 217 for a thicker crust of Vesta, which in turns argues for a non-chondritic bulk 218 composition of the present-day asteroid in terms of its major rock-forming 219 elements (Consolmagno et al., 2015). 220

²²¹ Consolmagno et al. (2015) discussed this apparent mismatch between the
²²² information provided by the HEDs and that coming from Dawn and proposed
²²³ a possible solution, postulating that the asteroid formed from chondritic ma²²⁴ terial and, after differentiating but before solidifying completely, underwent
²²⁵ some altering event that changed its bulk composition to its present one.

One proposed event that could produce the required alteration would be a grazing collision of a larger primordial Vesta with a body of comparable size stripping a significant fraction of its mantle while preserving most of its crust (Consolmagno et al., 2015).

Another possibility is that, following the catastrophic disruption of pri-230 mordial Vesta, the mantle olivine would be more easily fragmented into 231 smaller bits which could be preferentially swept away by gas drag, leaving 232 larger basaltic fragments to reaccrete onto an intact metallic core (Consol-233 magno et al., 2016). Other scenarios might be possible, including the ex-234 istence of many HED parents whose material might have been reaccreted 235 into the asteroid we today call Vesta (Consolmagno et al., 2015). Nonethe-236 less, three common traits to all scenarios discussed to date are that pri-237 mordial Vesta should have been more massive than present-day Vesta, that 238 the altering event is suggested to be linked to impacts, and that the altering 230 event should have occurred while Vesta was still partially molten or possessed 240 enough radiogenic heat to eliminate any macroporosity created during the 241 alteration in order to fit the constraints posed by Dawn (Consolmagno et al., 242 2015).243

In principle, finding those evolution tracks for the early Solar System that, within this scenario for Vesta's evolution, can produce the required altering event or collision can offer a substitute for the classical constraint posed by the survival of Vesta's basaltic crust. However, as the primordial mass of Vesta is currently unconstrained and different evolution tracks can produce the required alteration (Consolmagno et al., 2015, 2016), attempting to study the early evolution of the Solar System using one of these scenarios alone represents an ill-posed problem. What is required, therefore, is a new
and general constraint that does not strongly depends on Vesta's primordial
mass and that could be applied to all possible scenarios.

²⁵⁴ 3. Eucrites and diogenites: astrochemical constraints on the late ²⁵⁵ accretion and erosion of Vesta

From the time Vesta differentiated to the moment its crust solidified com-256 pletely, the eucritic and diogenitic layers were altered by impacts (Turrini et 257 al., 2011, 2012; Day et al., 2012; Turrini, 2014; Turrini & Svetsov, 2014; 258 Sarafian et al., 2014). This alteration manifested in two ways. On one hand, 259 impacts removed material from the vestan crust by ejecting part of the mass 260 excavated during the crater formation process at speeds exceeding the ejec-261 tion velocity of the asteroid. This mass loss process is also known as *cratering* 262 erosion (Davis et al., 1979). On the other hand, impacts delivered mass to 263 the vestan crust in the form of the material from the impacting bodies that 264 survives the collision. This mass accretion process is known as *late accretion* 265 or, when specifically referring to the alteration of the crust of planetary bod-266 ies by impacts, late veneer (see e.g. Day et al. 2016). From a geologic point 267 of view, in this work we will specifically focus on the late veneer process. 268

As discussed in Sect. 2, from the meteoritic data supplied by the HEDs we know that Vesta's basaltic crust formed over several magmatic effusive events through a conductive solid lid (Roszjar et al., 2016) with an estimated thickness of a few km (Formisano et al., 2013; Tkalcec et al., 2013). These effusive events could have been either volcanic (the "heat-pipe" mechanism, Moore et al. 2017) or impact-triggered (Turrini, 2014; Turrini & Svetsov, 2014): the shock wave created by an impact, in fact, damages the surface

material at greater depths than those excavated by the crater itself (Melosh, 1989), therefore creating paths for the magma to reach the surface. During this global effusive resurfacing, the outer layer of Vesta's crust acting as the conductive lid would be in a dynamic equilibrium state, with newer material replacing and pushing downward the older one (Moore et al., 2017) together with any contaminant delivered by impacts.

As a consequence, the late veneer of the basaltic eucritic layer could span 282 an interval of at least 10 Myr (see McSween et al. 2011 and references therein, 283 Roszjar et al. 2016). During this temporal interval, material delivered to 284 Vesta's surface would contaminate the basaltic eucrites either by direct in-285 jection into the melt or by later incorporation into the magma (Turrini & 286 Svetsov, 2014). The late veneer of the diogenitic layers should in principle 287 last longer (at least a few tens of Myr, see McSween et al. 2011 and references 288 therein), but in order to reach the diogenitic melt the material delivered by 280 later impacts would need to either penetrate thicker layers of solid crust or 290 be pushed at depth by the reprocessing and sinking of the conductive lid. 291

After the complete solidification of Vesta's crust, impacts would contam-292 inate only the howarditic layer formed by the brecciation of solid eucritic 293 and diogenitic materials (see e.g. Turrini et al. 2014, 2016 for an in-depth 294 discussion of this process on Vesta). Consequently, the composition of eu-295 crites and diogenites records the early collisional evolution of Vesta when 296 the crust of the differentiated asteroid was still partially molten. Since the 297 collisional history of a planetary body is strongly coupled to the evolution 298 of the surrounding environment, the composition of eucrites and diogenites 299 provides constraints on the evolution of the circumsolar disc and the early 300

Solar System. As we will show in the following, these constraints do not depend on the specific value of the unknown primordial mass of Vesta (see Sect. 2 and Consolmagno et al. 2015) but only on the assumption that the primordial Vesta was characterized by a chondritic bulk composition of the major rock-forming elements.

306 3.1. Eucrites, diogenites and mass loss

For a primordial Vesta with chondritic bulk composition in terms of the 307 major rock-forming elements, the composition of eucrites and diogenites and, 308 in particular, their abundance in rare earth elements allows one to constraint 309 the fractional thickness of the original vestar crust (see Consolmagno et al. 310 2015 and references therein). Specifically, based on astrochemical abundances 311 (see e.g. Lodders 2010 and references therein) the basaltic crust represented 312 15 - 21% of the primordial mass of the asteroid (see Consolmagno et al. 313 2015 and references therein). This result is independent on the primordial 314 mass of Vesta and depends only on the asteroid possessing chondritic bulk 315 composition in terms of its major rock-forming elements at the time of its 316 differentiation (Consolmagno et al., 2015). 317

Even if Dawn confirmed the survival of Vesta's crust at all spatial scales 318 (De Sanctis et al., 2012; Ammannito et al., 2013; Ruesch et al., 2014), the 319 historical constraint posed by such survival is weak due to our ignorance of 320 the absolute value of the initial thickness of Vesta's crust (in place of the 321 relative one supplied by astrochemical constraints), of the original mass of 322 the primordial Vesta and, should it have been larger than that of present 323 Vesta, of the amount of crustal material that could have been removed by 324 the altering event together with the excess mantle material (Consolmagno et 325

³²⁶ al., 2015).

Until these unknown factors are more precisely quantified, it is difficult to pinpoint the amount of crustal material that can be removed by cratering erosion without producing an asteroid inconsistent with the present-day Vesta (Turrini, 2014). As such, in our proof-of-concept case study we will limit ourselves to discuss how the estimated mass losses caused by cratering erosion compare to this upper bound of 15 - 21% of the primordial mass of Vesta.

334 3.2. Eucrites and water accretion

The first piece of the puzzle provided by Vesta's late veneer is supplied by 335 basaltic eucrites. While Vesta is globally a volatile-depleted body (see Con-336 solmagno et al. 2015 and references therein), the discovery of small apatite 337 crystals in some basaltic eucritic meteorites (Sarafian et al., 2013) indicates 338 that small quantities of water were present while the eucritic layer was so-339 lidifying. While measurements of the D/H ratio in apatites were interpreted 340 as suggestive of a carbonaceous chondritic origin of Vesta's water (Sarafian 341 et al., 2014; Barrett et al., 2016), the results of Hartogh et al. (2011) on the 342 D/H ratio of comet 103P/Hartley 2 indicate that comets could also be a com-343 patible source (Turrini & Svetsov, 2014). However, an incompatibility with 344 a cometary origin, if confirmed, would allow to reject all scenarios invoking 345 major role for comets in delivering water to Vesta. a 346

While the uncertainty associated to such estimates is large, recent work (Stephant et al., 2016a,b; Sarafian et al., 2017a,b) attempts to constrain quantitatively the amount of water initially present in the eucritic melt. Sarafian et al. (2017a,b) report an upper bound to the water content of

the eucritic parent melts ranging between 260-1000 μ g/g, i.e. 0.026-0.1 wt%. 351 Independently, Stephant et al. (2016a,b) suggest that water should have rep-352 resented less than 0.2 wt.% of the eucritic parent melts. For a primordial 353 Vesta characterized by a chondritic bulk composition, eucrites should repre-35 sent about 2/3 of the vestan crust and the latter should represent no more 355 than 15-21% of the vestan mass (see Consolmagno et al. 2015 and references 356 therein). The values estimated by Sarafian et al. (2017a,b) and Stephant et 357 al. (2016a,b) therefore translate in an upper bound to the water accreted by 358 primordial Vesta of $1-3 \times 10^{-4}$ the mass of the asteroid, which we will adopt 359 as our constraint on the maximum amount of water that could be delivered 360 by Vesta's late veneer. 361

362 3.3. Diogenites and mass accretion

The second piece of the puzzle provided by Vesta's late veneer is sup-363 plied by diogenites. Specifically, some diogenites show an over-abundance in 364 highly-siderophile elements (HSEs) with respect to what would be expected 365 following their preferential migration to the vestan core during differentiation 366 (Day et al., 2012; Dale et al., 2012). While this over-abundance in princi-367 ple could be explained in different ways (e.g. as the result of variations in 368 the local concentration in the vestan magma, see Day et al. 2016 and refer-369 ences therein), the fact that over-abundances in HSEs are often paired with 370 chondritic elemental ratios of this elements suggests that they result from a 371 late accretion or late veneer of chondritic material (see Day et al. 2016 and 372 references therein). A similar pattern was shown to hold also for the most 373 HSE-enriched eucrites, while eucrites containing low abundances of HSEs 374 presented markedly non-chondritic elemental ratios for these elements (see 375

³⁷⁶ Day et al. 2016 and references therein, Dhaliwal et al. 2016).

Assuming a chondritic bulk composition for Vesta at the time of this late 377 veneer or accretion, Day et al. (2012) associated the measured enrichment to 378 a total accreted chondritic mass of about 1 - 2% the primordial mass of the 379 asteroid. Because of the uncertainties in this kind of computations and on 380 the amount of chondritic material delivered to the mantle instead of the crust 381 (late accretion vs. late veneer), and because the temporal interval considered 382 in this work (the duration of the bulk of the bombardment triggered by 383 Jupiter's mass growth is ~ 1 Myr, see Turrini et al. 2011, 2012) is much 384 shorter than the timespan over which diogenites can be altered (at least 10 385 Myr or more, see above and McSween et al. 2011), we will adopt the range of 386 values estimated by Day et al. (2012) as an upper bound to the total accreted 387 chondritic mass delivered to Vesta by the late veneer, which should therefore 388 not exceed 1-2% the mass of the asteroid, keeping in mind that because of 380 said uncertainties the real upper limit could be much lower. 390

³⁹¹ 4. Modelling Jupiter's formation and Vesta's collisional evolution

In this section we provide a synthetic description of the previous results 392 and of the methods and approximations we used in our proof-of-concept case 393 study to model the collisional evolution of Vesta during the formation and 394 migration of Jupiter, its effects on the eucritic and diogenitic crust and their 395 dependence on different factors. As mentioned in Sect. 1, due to the ex-396 ploratory nature of this work for reasons of convenience we build on the 397 simulations, methods and results of previous studies. As a result, readers 398 should keep in mind that not all the approximations made will adapt equally 399

well to the different cases explored and the numerical results should be considered only as illustrative.

For more details on the methods and the dynamical simulations used for 402 the computation of the impact probabilities and velocities we refer the readers 403 to Turrini et al. (2011), for a more detailed discussion of the collisional model 404 we refer the readers to Turrini (2014) and Turrini & Svetsov (2014), while for 405 more details on the numerical model used in the impact simulations we refer 406 the readers to Turrini & Svetsov (2014) and Turrini et al. (2016). Readers 407 interested in a more detailed discussion of the dynamical characterization 408 of the asteroidal impactors on Vesta across the formation and migration of 409 Jupiter are referred to Turrini et al. (2011) and Turrini (2014), while those 410 interested in the dynamical characterization of the cometary impactors are 411 referred to Turrini et al. (2011) and Turrini & Svetsov (2014). 412

413 4.1. Modelling Jupiter's mass growth and migration

In this study we used the n-body simulations performed by Turrini et 414 al. (2011) and the associated estimates of the impact probabilities on Vesta 415 as the base for our assessment of the erosional and accretional history of 416 primordial Vesta across Jupiter's formation and migration. Those simula-417 tions considered a template of the early Solar System composed of the Sun, 418 the forming Jupiter. Vesta and a disk of planetesimals modelled as massless 419 particles, whose dynamical evolution was followed for 2×10^6 years. From 420 a physical point of view, the starting time of this temporal window should 421 be located between 2 and 4 Myr after the condensation of CAIs to allow for 422 Jupiter to complete its formation between 3 and 5 Myr after CAIs. 423

During the first $\tau_c = 10^6$ years of this simulated timespan, Jupiter's core

would grow from its initial mass $M_0 = 0.1 M_{\oplus}$ to the critical mass $M_c = 15 M_{\oplus}$ as:

$$M_{2} = M_0 + \left(\frac{e}{e-1}\right) (M_c - M_0) \times \left(1 - e^{-t/\tau_c}\right)$$

(1)

where τ_c can be interpreted as the oligarchic growth timescale of Jupiter's core (see e.g. D'Angelo, Durisen & Lissauer 2011 and references therein). When Jupiter's core reached the critical mass value M_c , the nebular gas surrounding Jupiter was assumed to rapidly accrete on the planet, whose

431 mass would grow as:

$$M_{2} = M_c + (M_J - M_c) \times \left(1 - e^{-(t - \tau_c)/\tau_g}\right)$$
(2)

where $M_J = 317.83 M_{\oplus}$ is the final and present mass of Jupiter. The efolding time $\tau_g = 5 \times 10^3$ years adopted by Turrini et al. (2011) was derived from the hydrodynamical simulations described in Lissauer et al. (2009) and Coradini, Magni, & Turrini (2010).

In their simulations, Turrini et al. (2011) considered four different mi-436 gration scenarios: 0 AU (no migration), 0.25 au, 0.5 au and 1 au (see Fig. 437 1). In their simulations Jupiter always started on circular and planar or-438 bits and, in those scenarios where migration was included, started migrating 439 inward as soon its core reached the critical mass of $15 M_{\oplus}$. This approxi-440 mation is equivalent to neglecting the distinction between Type I and Type 441 II migration and starting the migration of the accreting planet as soon the 442 characteristic migration timescale of the forming Jupiter became of the order 443 of 10^6 years (see D'Angelo, Durisen & Lissauer 2011 and references therein). Given that the effects on the asteroid belt of the dynamical excitation of 445 the planetesimals triggered by the mass growth of the forming Jupiter are 446

negligible before the gas accretion phase (see Turrini et al. 2011 and Raymond 447 & Izidoro 2017), from a physical point of view this approximation can be 448 treated as assuming that Jupiter's core started forming farther away and 440 migrated to its initial position due to Type I migration before the beginning 450 of the simulations. Moreover, because of the negligible effects of the forming 451 Jupiter on Vesta before the gas accretion phase, to first order the adopted 452 approximated treatment of Jupiter's mass growth is not in contrast with the 453 shorter timescales and outer formation regions predicted by the so called 454 "pebble accretion" scenario (Bitsch et al., 2015). 455

After the giant planet begins to migrate, Jupiter's orbital radius would
evolve as:

$$R_{2} = R_0 + (R_J - R_0) \times \left(1 - e^{-(t - \tau_c)/\tau_r}\right)$$
(3)

where R_0 is Jupiter's orbital radius at the beginning of the simulation, R_J is the final orbital radius and $\tau_r = 5 \times 10^3$ years. The simulations performed by Turrini et al. (2011) using a slower migration ($\tau_r = 2.5 \times 10^4$ years) indicate that the flux of impactors on Vesta is not significantly affected by the migration rate.

463 4.2. Modelling the primordial Vesta

In the simulations of Turrini et al. (2011), Vesta was initially placed on a circular, planar orbit with semimajor axis $a_v = 2.362$ AU. The asteroid was characterized using the best pre-Dawn estimates of its mass ($m_v = 2.70 \times 10^{23}$ g, Michalak 2000) and mean radius ($r_v = 258$ km, Thomas et al. 1997), whose values differ by 2 - 4% from the ones later estimated by the Dawn mission (2.59×10^{23} g and 262.7 km respectively, Russell et al. 2012).

While these values were reasonable before the arrival of Dawn, the results 470 of Consolmagno et al. (2015) suggest that primordial Vesta could have been 471 more massive (see Sect. 1). Because of this uncertainty on primordial Vesta's 472 mass and because a precise assessment of the latter is beyond the scope of 473 this work, we maintained the template of primordial Vesta used by Turrini et 474 al. (2011) and took advantage of the link between impact probabilities and 475 diameter of the asteroid to rescale the impact fluxes to a more massive pri-476 mordial Vesta's and explore how the three compositional constraints offered 477 by Vesta and the HEDs responded to this change. 478

We therefore initially considered a primordial Vesta characterized by a 479 diameter similar to its current mean one. This allows us to take advantage 480 of the fluxes of impactors on the asteroid estimated by Turrini et al. (2011) 481 (see Sect. 4.4). Similarly, in simulating the outcomes of impacts at different 482 impact velocities on Vesta, we characterized the target body with the current 483 diameter and surface gravity of Vesta (see Sect. 4.4). This choice allows us 484 to take advantage of the simulations of rocky impactors on Vesta performed 485 by Turrini et al. (2016) and to simulate only the effects of more realistic 486 cometary impactors than those originally considered by Turrini & Svetsov 487 (2014) (see Sect. 4.4). 488

The probabilistic method used by Turrini et al. (2011) to estimate impact fluxes on Vesta links impact probabilities to Vesta's diameter. As long as Vesta's mass is not so large that the gravity of the asteroid significantly enhances its effective cross-section (see Turrini et al. 2011 and references therein), impact fluxes will scale with the diameter of the asteroid. For the impact velocities estimated by Turrini et al. (2011), this condition is

satisfied for a primordial Vesta no more massive than a few times the present
asteroid. Similarly, both the mass erosion (Holsapple and Housen, 2007) and
the mass accretion (Svetsov, 2011) efficiencies scale with the surface gravity
of the target asteroid, which for a given average density will scale with its
diameter.

This approach allowed us to estimate, to first order, the mass loss and mass accretion experienced by primordial Vesta for different values of its original mass without the need of performing a large number of additional simulations. More details on the parameters describing Vesta in our collisional simulations are provided in Sect. 4.4, while a discussion of the effects of a larger mass of the primordial Vesta on our results is presented in Sect. 5 and 6.

507 4.3. Modelling the planetesimal disk

The planetesimal disk was modelled by Turrini et al. (2011) as a disk 508 of massless particles evolving under the gravitational influence of the Sun, 509 Jupiter and Vesta. The disk of massless particles was composed by 8×10^4 510 particles and extended from 2 au to 10 au. The massless particles initially 511 possessed eccentricity and inclination (in radians) values comprised between 512 0 and 3×10^{-2} (Turrini et al., 2011) and were used as dynamical tracers of 513 the evolution of the planetesimal disk, each particle representing a swarm of 514 real planetesimals. 515

The number of real planetesimals populating each swarm and their characteristic diameter depend on the adopted size-frequency distribution (SFD) for the planetesimal disk. In this work we considered a total of four SFDs: two for primordial planetesimals and two for collisionally evolved planetes-

imals. Each pair of SFDs (primordial and collisionally evolved) refers to a 520 specific nebular environment, namely quiescent or turbulent circumsolar disc. 521 The massless particles where associated to their diameters by means of 522 Monte Carlo methods. Since this procedure was performed while processing 523 the output of the simulations, the latter did not include the effects of gas 524 drag as they are size-dependent. The choice of neglecting the effects of gas 525 drag allowed us to explore the effects of different SFDs on Vesta's crustal 526 late accretion and erosion without the need to perform a large number of 527 computationally expensive n-body simulations. 528

While computationally convenient, however, this choice is not dynam-529 ically accurate, particularly for km-sized planetesimals, as gas drag acts 530 to damp orbital eccentricities and inclinations, diminishing the population 531 of dynamically excited planetesimals. At the same time, the radial drift 532 caused by gas drag brings more planetesimals into the orbital resonances 533 with Jupiter, which appear to play the leading role in producing the popula-534 tion of impactors on Vesta (see Turrini et al. 2011 and Sect. 5). The results 535 of analogous simulations performed by Weidenschilling, Davis & Marzari 536 (2001), Grazier et al. (2014) and Raymond & Izidoro (2017) indicate that 537 neglecting the effects of gas drag should not alter the results of this study in 538 a qualitative way by cancelling the JEB. 539

Differently from the previous studies of Turrini (2014) and Turrini & Svetsov (2014), all four considered SFDs where associated to a circumsolar disc possessing a dust-to-gas ratio $\xi_i = 0.005$ inside the water ice condensation line and $\xi_i = 0.01$ outside(see below for details on the density profiles of the individual discs). The water ice condensation line was assumed at 4 au.

The mass of solids comprised between 2 and 3 au amounted to about 2 M_{\oplus} for all four SFDs, consistent with the planetesimals having formed within a Minimum Mass Solar Nebula (see also Morbidelli et al. 2009 and Weidenschilling 2011).

All planetesimals inside 4 au were assumed to be rocky asteroids with an 549 average density of 2.4 g/cm^3 (chosen as a compromise between the densities 550 of volatile-poor and volatile-rich asteroids, see Britt et al. 2002; Carry 2012; 551 Turrini et al. 2014 and references therein) while those beyond were assumed 552 to be ice-rich cometary bodies, constituted at 50% of their mass by water 553 ice and at 50% by rock, with an average density of 1 g/cm^3 . Planetesimals 554 formed between 3 and 4 au were assumed to possess 10% of their mass as 555 water in the form of hydrated minerals, similarly to carbonaceous chondrites 556 (Jarosewich, 1990; Robert, 2003). 557

The transition at 3 au, while somewhat arbitrary, is consistent with the 558 current distribution of low albedo volatile-rich asteroids being the result of 559 their inward radial diffusion over the life of the Solar System (Michtchenko et 560 al., 2016). Moreover, the flux of impactors on Vesta originating from beyond 561 3 au is due to the 2:1 resonance with Jupiter (located at 3.3 au or outward 562 depending on the Jovian migration, see Fig. 1 and Turrini et al. 2011), so 563 our analysis is not particularly sensitive to the actual heliocentric distance 564 of this transition. 565

The four SFDs we considered in our case study are described in more detail in the following. A comparison of the average diameters of the planetesimals as a function of their orbital distance from the Sun for the two primordial SFDs is shown in Fig. 2, while in Fig. 3 we show the comparison between the two collisionally evolved SFDs in the reference orbital
region comprised between 1 and 4 au considered by Weidenschilling (2011)
and Morbidelli et al. (2009) (see Sects. 4.3.3 and 4.3.4 for the discussion of
their extension to the orbital region between 4 and 10 au).

574 4.3.1. Primordial planetesimals formed in a quiescent circumsolar disc

The first SFD considered was that of a disk of *primordial planetesimals* 575 formed by gravitational instability of the dust in the mid-plane of a quiescent 576 circumsolar disc (Safronov, 1969; Goldreich and Ward, 1973; Weidenschilling, 577 1980; Coradini et al., 1981). Following Coradini et al. (1981), the circumsolar 578 disc was assumed to have a density profile $\sigma = \sigma_0 \left(\frac{r}{1AU}\right)^{-n_s}$, with $\sigma_0 = 2700$ 579 g cm⁻² being the gas surface density at 1 AU and $n_s = 1.5$. For this SFD, 580 which we derived from the results of Coradini et al. (1981), the diameters 581 of the planetesimals that could impact Vesta roughly range between 1 and 582 40 km, with the bulk of the impactors being constituted by planetesimals 583 with diameters of 10-20 km (Turrini, 2014; Turrini & Svetsov, 2014). For 584 more details on the SFD and the associated Monte Carlo method we refer 585 interested readers to Turrini (2014) and Turrini & Svetsov (2014). 586

587 4.3.2. Primordial planetesimals formed in a turbulent circumsolar disc

The second SFD considered was that of *primordial planetesimals* formed by concentration of dust particles in low vorticity regions in a *turbulent circumstellar disc* (Cuzzi et al., 2008, 2010). Following Chambers (2010), the circumstellar disc was assumed to possess a density profile $\sigma = \sigma'_0 \left(\frac{r}{1 AU}\right)^{-n'_s}$, with $\sigma'_0 = 3500 \text{ g cm}^{-2}$ being the gas surface density at 1 AU and $n'_s = 1$ (see Fig. 14, gray dot-dashed line, Chambers 2010). For this SFD, which we

derived from the results of Chambers (2010), the diameters of the planetesimals that could impact Vesta roughly range between 20 and 250 km, with the bulk of the impactors being constituted by planetesimals with diameters of 100-200 km (Turrini, 2014; Turrini & Svetsov, 2014). For more details on the SFD and the associated Monte Carlo method we refer interested readers to Turrini (2014) and Turrini & Svetsov (2014).

4.3.3. Collisionally-evolved planetesimals formed in a quiescent circumstellar disc

The third SFD we considered was associated to *collisionally-evolved planetesimals* formed in a *quiescent circumstellar disc* and was derived from the results of Weidenschilling (2011). In this study we focused on the SFD of the asteroid belt that Weidenschilling (2011) referred to as the "standard case", i.e. the one produced from a disk initially populated by planetesimals with a diameter of 100 m (see Fig. 8, Weidenschilling 2011).

The resulting population of planetesimals is dominated *in number* by collisional fragments with km- or sub-km-sized diameters and *in mass* by a few large planetesimals and planetary embryos. In our estimates of the collisional evolution of Vesta we adopted as our lower-end cut-off of the SFD the diameter of 1 km, a choice motivated by the fact that the slope of the SFD causes sub-km planetesimals to cumulatively supply only a fraction of the mass contained in km-sized planetesimals (Weidenschilling, 2011).

Because of this cut-off, the bulk of the planetesimals impacting Vesta is in the form of planetesimals with diameters of 1-2 km (Turrini, 2014; Turrini & Svetsov, 2014). Lowering our cut-off to 100 m would increase the mass flux on Vesta only by about 10% with respect to that provided by km-sized

619 asteroids.

Strictly speaking, the results of Weidenschilling (2011) apply only to the inner Solar System (i.e. 1 - 4 au), so in principle they cannot be applied to the outer part of the planetesimal disk (i.e. 4 - 10 au) considered by Turrini et al. (2011). However, the results of Weidenschilling (2008, 2011) suggest that the collisionally-evolved SFD of the planetesimals in our regions of interest does not strongly depend on the radial distance.

We followed the approach used in Turrini & Svetsov (2014) and adopted a similar SFD for the planetesimals beyond 4 au, scaling it in mass by the ratio between the solid mass comprised between 4 and 10 au and that comprised between 1 and 4 au. For more details on the SFD and the associated Monte Carlo method we refer interested readers to Turrini (2014) and Turrini & Svetsov (2014).

4.3.4. Collisionally-evolved planetesimals formed in a turbulent circumstellar disc

The fourth and final SFDs we considered was associated to the case of collisionally-evolved planetesimals formed in turbulent circumstellar disc and was derived from the results of Morbidelli et al. (2009). Morbidelli et al. (2009) found that the best match with the present-day SFD of the asteroid belt is obtained for planetesimal sizes initially spanning 100 - 1000 km (see Fig. 8, Morbidelli et al. 2009), a range consistent with their formation in a turbulent nebula.

The SFD associated to the best-fit case of Morbidelli et al. (2009) shares most of the characteristics of the analogous one derived by Weidenschilling (2011), but shows a larger abundance of planetesimals with diameter comprised between 5 and 20 km (see Fig. 8a, black solid line, Morbidelli et al.
2009) than the SFD by Weidenschilling (2011), which is significantly flatter
in this size range.

While the SFD physically extends down to sub-km sizes, we focused our attention on the effects of this overabundance and maintained the lower-end cut-off of the SFD at 5 km in diameter also adopted in Morbidelli et al. (2009). Because of this, the bulk of the planetesimals impacting Vesta is in the form of planetesimals with diameters of 5-10 km (Turrini, 2014; Turrini & Svetsov, 2014).

As in the case of the SFD by Weidenschilling (2011) discussed in Sect. 4.3.3, we extended the SFD of Morbidelli et al. (2009) beyond 4 au by scaling the number of planetesimals by a factor equal to the mass ratio of the solid material contained between 4 and 10 au to that of the one contained between 1 and 4 au. For more details on the SFD and the associated Monte Carlo method we refer interested readers to Turrini (2014) and Turrini & Svetsov (2014).

660 4.4. Modelling Vesta's collisional history

Turrini et al. (2011) estimated the impact probabilities and the associated impact velocities between the massless particles and Vesta using a statistical approach based on solving the ray-torus intersection problem between the instantaneous orbital torus of Vesta and the linearized path of the massless particle¹ across the time step when the particle crosses Vesta's orbital region

¹Note that the path of the massless particle is linearized only for the computation of its impact probability with Vesta, not for that of the dynamical evolution of the particle.

(see Turrini et al. 2011 for more details on the method). This method is conceptually similar to the analytical method of Öpik (1976) but requires only to average over the mean anomaly of the target body's orbit instead of averaging on anomaly, longitude of nodes and argument of pericenter of both target and impacting bodies.

In evaluating the collisional history of Vesta we focused on the massless 671 particles impacting Vesta from the moment Jupiter's core started accreting 672 its gaseous envelope (i.e. the second 1 Myr in the simulations by Turrini 673 et al. 2011, see the highlighted area in Fig. 4). This conservative choice is 674 motivated by the need to correct for the fact that the early flux of impactors 675 on Vesta in the simulations is dominated by the impacts of those rocky 676 planetesimals orbiting nearby the asteroid that should have been removed 677 during Vesta's formation. 678

Fig. 5 shows an example of the distributions of impact probabilities and 679 impact velocities for both asteroidal and cometary impactors recorded in the 680 simulations by Turrini et al. (2011) in the scenarios of no migration and 1 au 681 migration of Jupiter. Note that the impact probabilities reported in Fig. 5 682 refer to the individual impact events recorded in the simulations and are not 683 impact probabilities averaged over the whole populations of impactors as in 684 classical collisional algorithms (see e.g. O'Brien and Sykes 2011 and refer-685 ences therein). Figs. 6 and 7 show respectively the distributions normalized 686 over the impact probabilities of the asteroidal and cometary impact velocities 687 in the four migration scenarios considered in this study (see also Turrini et al. 688 2011, Turrini 2014 and Turrini & Svetsov 2014 for a more detailed discussion 689 of the distribution of the impact velocities and their causes. Interested read-690

ers are referred to Turrini et al. (2011) and Turrini et al. (2012) for details on the algorithm.

The impact probabilities provided by the simulations were converted into 693 fluxes of impactors using the SFDs described in Sect. 4.3. Following the 694 procedure described in Turrini (2014) and Turrini & Svetsov (2014), for each 695 SFD we run a set of 10^4 Monte Carlo simulations. In each run a new mass 696 value was extracted for each impact event recorded in Turrini et al. (2011) 697 and, since each massless particle causing an impact event represents a swarm 698 of real planetesimals, we used the SFD and the impact probability of the 699 impact event to estimate the associated flux of impactors. Combining the 700 information provided by the mass and flux of impactors associated to the 701 impact event with its estimated impact velocity, the eroded mass m_e and the 702 accreted mass m_a were computed (see Sect. 4.5 for details on the method). 703

We averaged over each set of 10⁴ Monte Carlo simulations to estimate the total mass loss and accretion experienced by Vesta for each specific SFD and the associated standard deviations. If, after averaging, the total flux of impactors associated to one of the SFDs amounted to less than one real impact, we set the total mass loss and accretion values to zero for that SFD.

709 4.5. Modelling the effects of impacts on Vesta

To estimate the effects of impacts in terms of both mass loss and mass accretion, we took advantage of the results of Benz and Asphaug (1999) (see Sect. 4.5.1 for details) and Turrini et al. (2016) (see Sect. 4.5.2 for details). In parallel, we performed 3D numerical simulations of impacts of projectiles onto Vesta using a modified version (Svetsov, 2011; Turrini & Svetsov, 2014; Svetsov and Shuvalov, 2015) of the numerical hydrodynamic method SOVA ⁷¹⁶ (Shuvalov 1999; SOVA is an acronym for Solid-Vapour-Air, as the code is
⁷¹⁷ designed for simulations of multi-material, multi-phase flows) that includes
⁷¹⁸ the effects of dry friction (Dienes and Walsh, 1970).

Dry friction depends on a dimensionless coefficient of friction for which we 719 adopted a value of 0.7, typical for rocks and sand (Turrini & Svetsov, 2014; 720 Turrini et al., 2016). The behaviour and properties of target and projectiles 721 were determined, as in Turrini & Svetsov (2014) and Turrini et al. (2016), 722 through the ANEOS equations of state (Thompson and Lauson, 1972) using 723 input data (i.e., about 35 variables describing properties of a given material) 724 from Pierazzo et al. (1997) and Tillotson's equation of state for Vesta's iron 725 core (Tillotson, 1962). 726

In the simulations performed with SOVA, Vesta was modelled as a three-727 layered sphere with radius of 260 km, possessing an iron core with a radius 728 of 110 km (Russell et al., 2012, 2013; Ermakov et al., 2014) and a crust made 720 of granite with a thickness of 23 km (Consolmagno et al., 2015), separated 730 by a mantle composed of dunite. The mass of Vesta was set equal to its 731 present value, 2.59×10^{23} g (Russell et al., 2012). While Vesta was in a 732 partially molten state at the time of the Jovian Early Bombardment, the 733 approximation we adopted is justified by the following reasons. 734

First, thermal and geophysical models and meteoritic data all suggest that Vesta's basaltic crust was formed over a series of magmatic effusive events through a solid conductive lid. Second, previous studies indicates that Vesta's mass loss due to cratering erosion was mainly a surface process (Turrini, 2014; Turrini & Svetsov, 2014), hence mainly affecting this solid conductive lid. Third, mass loss occurs mainly from the central regions of

the crater where the material strength is generally unimportant (Holsapple
and Housen, 2007), since the stresses during the impacts exceed the strength
of the excavated material acquiring velocities greater than the escape velocity
of the asteroid. This approximation, however, is more realistic for impactors
not exceeding in size the thickness of Vesta's conductive lid (i.e. a few km)
than for larger impactors.

As in Turrini et al. (2016), the numerical grid consisted of $250 \times 100 \times 225$ 747 cells over azimuth, polar angle and radial distance respectively, and we as-748 sumed bilateral symmetry to model only the half-space in the zenith direc-749 tion. Cell sizes were 1/40 of the projectile's diameter around the impact 750 point and increased to the antipodal point and to the radial boundaries lo-751 cated at distances of about 10 vestan radii. In all impact simulations, the 752 impact velocity vector lied in the reference plane that passed through the 753 origin of the coordinates and was orthogonal to the zenith. 754

All simulated impacts were assumed to occur at the average impact angle 755 of 45° (Melosh, 1989), while impact velocities varied between 1 and 12 km/s 756 based on the results of the simulations performed by Turrini et al. (2011) (see 757 Figs. 6 and 7 and Turrini 2014; Turrini & Svetsov 2014 for more details on 758 the distribution of the impact velocities in the different migration scenarios). 759 We performed simulations of cometary impactors composed by a homo-760 geneous mixture of rocks and ices (see Svetsov and Shuvalov 2015, Fig. 5). 761 Among the materials supplied by the ANEOS equations of state (Thompson 762 and Lauson, 1972), we adopted water as our template for the icy component 763 and granite as our template for the rocky one. The simulations described in 764 Turrini et al. (2016) provided us with analogous results for asteroidal rocky 765

⁷⁶⁶ impactors.

Among the different kinds of rocky impactors (granite impactors, dunite impactors and differentiated impactors) simulated by Turrini et al. (2016) we adopted their results for granite impactors as our template for asteroidal impactors. The comparison between the results of impact experiments (Holsapple, 1993; Holsapple and Housen, 2007; Daly and Schultz, 2016) and those of SOVA's simulations reveals that they agree within a factor of two (Svetsov, 2011; Turrini et al., 2016).

774 4.5.1. Mass loss associated to the impact events

Following Turrini (2014) and Turrini & Svetsov (2014), we defined three classes of impact events based on their normalized specific energy Q_D/Q_D^* , where Q_D^* is the catastrophic disruption threshold of Vesta. Impacts with $Q_D/Q_D^* < 0.1$ were classified as *low-energy impacts*. Impacts with $0.1 \leq$ $Q_D/Q_D^* < 1$ were classified as *high-energy impacts*. Impacts with $Q_D/Q_D^* \geq 1$ were classified as *catastrophic impacts*.

The quantity Q_D^* was computed using Eq. 6 from Benz and Asphaug (1999) with the associated coefficients for basaltic targets (see Table 3, Benz and Asphaug 1999). Following Turrini (2014) and Turrini & Svetsov (2014), we used the coefficients of the case $v_i = 5 \, km \, s^{-1}$ for impacts with velocity greater or equal than $5 \, km \, s^{-1}$, and those of the case $v_i = 3 \, km \, s^{-1}$ for all the other impacts.

We computed the mass loss associated to low-energy impacts using the results of the impact simulations with SOVA performed in the framework of this study and those performed by Turrini et al. (2016). The results of the simulations are shown in Fig. 8, where the mass loss as a function of the ⁷⁹¹ impact velocity is expressed in units of the mass of the impacting body. For
⁷⁹² comparison, in Fig. 8 we also plotted the results of the simulations by Turrini
⁷⁹³ & Svetsov (2014) for cometary impactors composed of pure water ice.
⁷⁹⁴ For high-energy impacts we used instead Eq. 8 from Benz and Asphaug
⁷⁹⁵ (1999) expressed in terms of the eroded mass:

$$\frac{m_e}{m_t} = 0.5 + s \left(\frac{Q_D}{Q_D^*} - 1.0\right) \tag{4}$$

where s = 0.5 for $v_i < 5 \, km \, s^{-1}$ and s = 0.35 for $v_i \ge 5 \, km \, s^{-1}$. To avoid overestimating the contribution of high-energy impacts to Vesta's crustal erosion, the effects of those high-energy impact events that, after renormalizing to the appropriate SFD, were associated to less than one real impact were not considered in estimating Vesta's crustal erosion.

The effects of catastrophic impacts were not accounted for in the estimates of the eroded mass: their cumulative number was used only to assess the probability of Vesta surviving its primordial collisional evolution without being shattered (see also Turrini 2014; Turrini & Svetsov 2014 for a discussion).

806 4.5.2. Mass gain associated to the impact events

To assess the mass accretion experienced by primordial Vesta we again took advantage of the results of the impact simulations with SOVA performed in the framework of this study and those performed by Turrini et al. (2016). The results of the simulations are shown in Fig. 9, where the accreted mass as a function of the impact velocity is expressed in units of the mass of the impacting body. For comparison, in Fig. 9 we also plotted the results of the simulations by Turrini & Svetsov (2014) for cometary impactors composed ⁸¹⁴ of pure water ice.

The results of the simulations in Turrini et al. (2016) indicated that the 815 composition and the diameter of rocky impactors do not change the results 816 of the simulations as much as the impact velocity (i.e. the effects of the 817 former parameters are limited to about 5 - 10%, see Turrini et al. 2016 for a 818 discussion). Both low-energy and high-energy ones contributed mass to Vesta 819 according to the results shown in Fig. 9, while catastrophic impact did not 820 contribute mass to Vesta. For consistency with the procedure adopted in 821 estimating the mass loss caused by high-energy impacts, the contribution of 822 those high-energy impact events that, after renormalizing to the appropriate 823 SFD, were associated to less than one real impact was not considered in 824 estimating Vesta's late accretion. 825

826 5. Results

In the following we present the late accretion and erosion experienced by 827 Vesta's crust across Jupiter's formation and migration, as depicted by our 828 results taken at face value. For each of the four SFDs we considered we will 820 show the average mass loss, mass accretion and water accretion produced 830 by Vesta's early collisional evolution. We will first discuss the separate con-831 tributions of asteroidal and cometary impactors, which are defined as those 832 planetesimals originating within and beyond 4 au respectively, and then their 833 cumulative effects on Vesta. When considering the cumulative collisional his-834 tory of the asteroid, we will discuss how it affects both a primordial Vesta 835 similar in mass to the present one ("intact and pristine Vesta" scenario) and 836 a Vesta two to three times larger ("altered Vesta" scenario). 837
For each of the average quantities we computed, we will also show the 838 associated standard deviations as a measure of the variability of our results. 839 The two main factors affecting the magnitude of the standard deviations are 840 the total flux of impactors and the variability of the number of the largest 841 impactors (see e.g. Turrini et al. 2014, 2016). As such, the largest standard 842 deviations will be associated to the populations of cometary impactors (more 843 affected by the effects of small-number statistics due to their lower fluxes) and 844 to the population of collisionally-evolved impactors formed in turbulent discs 845 (due to the effects of small-number statistics on the flux of large impactors). 846 847

848 5.1. Mass loss and crustal erosion

The first step of our analysis focused on the mass loss suffered by primordial Vesta in the classical "intact and pristine Vesta" scenario, where the asteroid always possessed a mass similar to its present one. The mass loss caused by asteroidal and cometary impactors individually is shown in Fig. 10 and is dominated by the effects of low-energy impacts (see also Turrini 2014; Turrini & Svetsov 2014). Catastrophic impacts have a limited probability to occur (generally less than 0.1% and never above 1%).

High-energy impacts are comparatively more probable in the case of the SFDs associated with a turbulent circumsolar disc. Also in those cases, however, the chances of high-energy impacts occurring never exceed 20-30%. The only notable exception is the case of primordial planetesimals formed in a turbulent circumsolar disc (Chambers, 2010) when Jupiter migrates by 1 au, where Vesta could experience two high-energy impacts (responsible for about 60% of the total mass loss associated to this SFD in this migration 863 scenario).

The mass loss experienced by Vesta due to asteroidal impactors (Fig. 10, 864 left panel) is limited in the cases of no migration or 0.25 au of migration of 865 Jupiter but experiences a rapid growth once Jupiter's migration reaches and 866 exceeds 0.5 au. The initial limited mass loss, of the order of $\sim 1\%$, is mainly 867 due to impactors excited by the 3:1 resonance with Jupiter. When Jupiter's 868 migration reaches 0.5 au a second family of higher-velocity impactors excited 860 by the 2:1 resonance with Jupiter appears (see Fig. 1 and Turrini et al. 870 2011). This second family causes the mass loss experienced by Vesta to grow 871 by about an order of magnitude. 872

The mass loss associated to cometary impactors shows an opposite trend, 873 being significant only when Jupiter does not experience migration and drop-874 ping by more than one order of magnitude in those scenarios where the giant 875 planet migrates (see Fig. 10, right panel). This is due to the fact that the 876 migration of the giant planet favours the trapping of more and more plan-877 etesimals in the sweeping resonances at the outer boundaries of the asteroid 878 belt, reducing Jupiter's efficiency in scattering cometary planetesimals in the 879 orbital region of Vesta (see Fig. 1 and Turrini et al. 2011). 880

The total mass loss experienced by Vesta in the different scenarios is shown in Fig. 11. As can be immediately seen, the order of magnitude of the mass loss experienced by Vesta is mainly a function of Jovian migration. The actual SFD of the impacting planetesimals appears to affect the result, within a given migration scenario, to roughly a factor of three. Fig. 11 reveals that the most favourable cases in terms of experienced mass loss and preservation of the vestan crust are that of a Jovian displacement of 0.25 au and that of no migration of the giant planet.

The cases of a Jovian migration of 0.5 and 1 au appear less favourables and, for a primordial Vesta characterized by a mass similar to its present one, they appear inconsistent with the survival of Vesta's crust (especially once the excavation caused by the two vestan South polar impact basins is taken into account). The case of a Jovian migration of 1 au, in particular, is associated to a mass loss of the same order as the expected mass of the vestan crust.

We then moved to investigate how the picture depicted by these results 896 would change in the "altered Vesta" scenario, where primordial Vesta is hy-897 pothesized to have been more massive than its present counterpart (Consol-898 magno et al., 2015). For a primordial Vesta twice as massive as present Vesta, 899 the radius of the asteroid would be larger by about 25% than the present one 900 and the escape velocity would increase by about 100 m/s, i.e about 30%. The 901 increase in the escape velocity would lower the average efficiency of impacts 902 in causing mass loss by about 30% (see Eq. 3 in System 2011). As the flux 903 of impactors on Vesta is directly proportional to the radius of the asteroid, 904 the increase in the radius would translate into a similar increase in the flux 905 of impactors (see Turrini et al. 2011 for details). The new flux almost com-906 pensates for the decrease in the erosion efficiency of the impacts, so that the 907 overall erosion decreases by about 10%. 908

Because of this, the values plotted in Figs. 10 and 11 would scale down by slightly more than the mass ratio between the primordial Vesta and the present one. For a primordial Vesta twice as massive as the present one, these values would decrease by a factor of two. The only scenario incompatible with ⁹¹³ the constraint on Vesta's mass loss would become that of a Jovian migration ⁹¹⁴ of 1 au (either due to the mass loss per se or to its combination with the ⁹¹⁵ later excavation caused by the South polar basins).

A larger primordial mass of Vesta would proportionally decrease the mass lost by the asteroid due to collisions. For a primordial Vesta three times as massive as the present one (see Fig. 11), the only cases that would be rejected by the constraint on the crustal survival would be those where Jupiter migrated by 1 au and the flux of impactors on Vesta was dominated by planetesimals with diameters larger than 10 km, as in the SFDs by Coradini et al. (1981) and Chambers (2010).

923 5.2. Mass accretion and water delivery

As discussed in Sects. 3 and 4, the impacts on Vesta would also cause 924 the asteroid to experience a phase of late accretion. The second step of our 925 analysis was to quantify how much water would be delivered to Vesta by 926 the two potential sources we considered, volatile-rich asteroids and ice-rich 927 comets (see Sects. 3 and 4), and compare the estimated amounts with the 928 upper bound set by the presence of apatites in basaltic eucrites. Again, we 929 started with the classical "intact and pristine Vesta" scenario, where the 930 asteroid always possessed a mass similar to its present one. 931

The individual contributions of asteroids and comets are shown in Fig. 12. Asteroidal impactors (Fig. 12, left panel) deliver water to Vesta only when the Jovian migration reaches or exceeds 0.5 au, as the dynamical excitation of the population of planetesimals affected by the sweeping 2:1 resonance with Jupiter allows them to reach the orbital region of Vesta and deliver water to the asteroid (see Fig. 1 and Turrini et al. 2011).

The case of cometary impactors (Fig. 12, right panel) is opposite to 938 that of the asteroidal ones, as they deliver significant amounts of water to 939 Vesta only when Jupiter does not migrate. If the giant planet migrates, the 940 amount of water accreted by Vesta drops by more than one order of mag-941 nitude, showing however a slowly increasing trend with increasing displace-942 ments of Jupiter. The SFD associated to primordial planetesimals formed in 943 a turbulent circumstellar disc (see Sect. 4.3.2) does not appear in the right 944 panel of Fig. 12 as its total flux amounts to less than one impact event. 945

The cumulative water enrichments produced by asteroidal and cometary 946 impactors in the different migration scenarios for Jupiter are shown in Fig. 947 13, where they are compared with the range of values for Vesta's water 948 mass fraction derived from the estimates of Stephant et al. (2016a,b) and 940 Sarafian et al. (2017a,b). The cases where Jupiter migrated by 0.5 au or 950 more appear inconsistent with the observational data, as the volatile-rich 951 asteroidal impactors would produce a water enrichment from a few times to 952 an order of magnitude larger. 953

The case of no migration of Jupiter also shows inconsistencies with the 954 observational data, but in this case the inconsistencies appear to be also SFD-955 dependent. Collisionally evolved SFDs produce water enrichments greater 956 than the ranges of values derived from the estimates of Stephant et al. 957 (2016a,b) and Sarafian et al. (2017a,b) while primordial SFDs are associated 958 to lower ones. In the case of primordial planetesimals formed in quiescent 959 discs the produced water enrichment is just below the range of values derived 960 from eucrites, while in the extreme case of primordial planetesimals formed 961 in a turbulent circumsolar disc no water enrichment is produced (beyond 962

⁹⁶³ Vesta's initial water budget, if different from zero).

As in the case of mass loss, we tested how these results would change in 964 the "altered Vesta" scenario, where primordial Vesta is hypothesized to have 965 been more massive than its present counterpart (Consolmagno et al., 2015). 966 If we consider again a primordial Vesta twice as massive as present Vesta, 967 the increase in the escape velocity should increase the average efficiency of 968 impacts in delivering water by about 5% (see Eq. 8 in Svetsov 2011). At 960 the same time, the increase in the radius would translate in a proportional 970 increase in the flux of impactors. 971

Therefore, a larger primordial Vesta would accrete material more efficiently from a larger number of bodies, partially counteracting the drop in the water enrichment caused by the increase in the crustal mass over which to distribute the accreted water. As a result, the values shown in Figs. 12 and 13 would decrease only by about 33% for a primordial Vesta twice as massive as the present one. For a primordial Vesta three times as massive as the present one, the decrease would amount to about 50%.

As one can see from Fig. 13, such a decrease does not qualitatively change the outcome of our earlier analysis. Jovian displacements of 0.5 au or larger would still be inconsistent with the constraint posed by the water enrichment of eucrites. Likewise, a lack of migration by Jupiter would be inconsistent with said constraint for collisionally evolved SFDs of the impactors dominated in number by planetesimals smaller than about 10 km (as in the SFDs by Weidenschilling 2011 and Morbidelli et al. 2009).

986 5.3. Mass accretion and HSEs enrichment

The final step of our analysis was to compare the effects of the global 987 accretion of chondritic material experienced by Vesta with the HSEs enrich-988 ment of diogenites, starting also in this case with the classical "intact and 980 pristine Vesta" scenario, where the asteroid always possessed a mass similar 990 to its present one. In computing such accretion we considered, alongside 991 with the contribution of asteroidal impactors, that of the non-ice component 992 of the cometary impactors (see Sect. 4.3). The individual contributions of 993 asteroidal and cometary impactors are shown in Fig. 14. 994

The accretion of chondritic material associated to asteroidal impactors 995 (Fig. 14, left panel) increases proportionally to Jupiter's displacement due 996 to the growing flux of impactors experienced by Vesta (Turrini et al., 2011). 997 The accretion associated to cometary impactors (Fig. 14, right panel) follows 998 the same pattern seen when discussing the accretion of water (see Fig. 12, 999 right panel) and proves marginal with respect to that of asteroidal impactors. 1000 The overall late accretion experienced by Vesta is shown in Fig. 15 and 1001 immediately reveals two striking features. The first one is that planetesimals 1002 formed in a turbulent circumsolar disc, independently on them being primor-1003 dial or collisionally evolved, appear to be not consistent with the constraint 1004 posed by the HSEs enrichment of diogenites. The second one is that in gen-1005 eral the mass accretion experienced by a primordial Vesta with mass similar 1006 to that of the present Vesta appears to be at most marginally consistent with 1007 said constraint. 1008

In the cases of limited (0.25 au) and no migration, planetesimals formed in quiescent discs produce a mass accretions of about 1% of the vestan mass

while those formed in turbulent discs produce a mass accretions of about 2%. 1011 In the cases of moderate (0.5 au) and large (1 au) migration, the resulting 1012 mass accretion is of about 2% of the vestan mass or larger for all kinds of 1013 impactors. As we discussed in Sect. 3, while Day et al. (2012) estimated the 1014 accreted mass to fall between 1% and 2% of the mass of Vesta, we treated 1015 this range of values as an upper limit in this study to account for the uncer-1016 tainties on the interpretation of the diogenitic data and for the fact that the 1017 process we are considering lasted only a fraction of the total time over which 1018 diogenites can be enriched in HSEs by impacts (see Sect. 3). 1019

For a primordial Vesta with a mass similar to the present one of the aster-1020 oid, therefore, the cases that best fit the HSEs data among those considered 1021 here are those of no or limited (0.25 au) migration of Jupiter in a quiescent 1022 circumsolar disc. Even these cases, however, produce an enrichment reaching 1023 the lower end of the range identified by Day et al. (2012). We therefore tested 1024 the behaviour of the accretion of chondritic mass in the "altered Vesta" sce-1025 nario considering a primordial Vesta twice or three times larger than the 1026 present one. 1027

Applying the same scaling discussed for water accretion to the values 1028 shown in Fig. 15, we can see that a primordial Vesta two to three times 1029 more massive than the present Vesta (see Fig. 15) would make planetesimals 1030 formed in turbulent discs (like in the SFDs by Chambers 2010 and Morbidelli 1031 et al. 2009) more consistent with the HSEs constraint in the scenarios of 1032 limited (0.25 au) or no migration of Jupiter. At the same time, it would make 1033 the case of collisionally evolved planetesimals formed in quiescent discs (like 1034 the SFD by Weidenschilling 2011) more consistent with the HSEs constraint 1035

¹⁰³⁶ also for a moderate displacement (0.5 au) of Jupiter.

1037 6. Discussion and conclusions

The goal we set for ourselves in this work was to investigate whether 1038 the erosional and accretional history of the primordial Vesta as recorded by 1039 the HEDs can be used to probe into the early collisional history of asteroid 1040 Vesta and, through that, into the early evolution of the Solar System. Before 1041 discussing the results we obtained, however, we emphasize once again that 1042 they should be considered only as illustrative (or just as a more refined back-1043 of-the-envelope calculation) since some of the approximations adopted in our 1044 proof-of-concept case study were motivated only by reasons of convenience 1045 and neglected important processes, like gas drag, that should be included 1046 in future more physically complete investigations. Because of this, in the 1047 following we will limit ourselves to discussing the general trends we observed 1048 in our results. 1049

Notwithstanding its limitations, the proof-of-concept case study we in-1050 vestigated appears to indicate that the three compositional characteristics 1051 of Vesta and the HEDs we considered in this work (namely, the survival of 1052 Vesta's basaltic crust, the enrichment in water of eucrites and the enrichment 1053 in HSEs of diogenites) offer complementary pieces of information that, once 1054 considered together, provide stronger constraints than when considered indi-1055 vidually. Moreover, the constraints they provide only rely on the assumption 1056 of a chondritic bulk composition of Vesta in terms of its major rock-forming 1057 elements and, as the comparison between the "intact and pristine Vesta" sce-1058 nario and the "altered Vesta" scenario highlights, they appear to be limitedly 1059

¹⁰⁶⁰ influenced by the proposed uncertainty on Vesta's primordial mass.

In our proof-of-concept case study the crustal survival to cratering erosion 1061 allows to reject only the case of a Jovian migration of 1 au. The constraint 1062 offered by the survival of Vesta's basaltic crust to cratering erosion would 1063 therefore appear to be the least powerful among those we investigated, as 1064 the information it provides is already contained within that provided by 1065 the two constraints associated to late accretion. The accretion history of the 1066 primordial Vesta appears instead to provide stronger constraints: both water 1067 accretion and mass accretion agree in rejecting the cases of Jovian migration 1068 of 0.5 and 1 au, with water accretion also indicating that the case of no 1069 migration of the giant planet is inconsistent with the HEDs data, particularly 1070 if the D/H ratio of the planetesimal population represented by our cometary 1071 impactors was inconsistent with that reported for Vesta's source of water 1072 (Sarafian et al., 2014). 1073

Among the three constraints, water accretion appears more sensitive to 1074 the effects of Jupiter's migration, effectively pinpointing it to about 0.25 au 1075 among the simplified cases considered. Mass accretion appears more capable 1076 of discriminating between the effects of different size distributions of the im-1077 pacting planetesimals, favouring the collisionally-evolved SFDs in contrast to 1078 primordial ones and the SFDs associated to quiescent nebular environments 1079 in contrast to those associated to turbulent nebular environments. Notwith-1080 standing its apparent weakness, the survival of Vesta's basaltic crust remains 1081 an important constraint when studying more violent collisional scenarios than 1082 those here considered. 1083

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Specifically, the collisional evolution of the primordial Vesta in those sce-

narios dominated by high-velocity or even high-energy impacts (e.g. the 1085 so-called "Grand Tack", Walsh et al. 2011; O'Brien et al. 2014) will be deter-1086 mined by mass loss without mass accretion playing a significant role. This 1087 leading role of mass loss will be particularly true for scenarios invoking a 1088 major role of "hit-and-run" collisions, like those suggested to be responsible 1089 for the "altered Vesta" scenario (Consolmagno et al., 2015), in the collisional 1090 evolution of the inner Solar System, as in those cases the contribution of said 1091 impacts to mass accretion will be null or negligible. 1092

It should be noted, moreover, that in case of stochastic large impacts it 1093 is possible for a scenario to be characterized by a moderate or even limited 1094 global crustal erosion but a large local excavation. This is indeed the case 1095 of the last 4 Gyr of collisional evolution of Vesta, where the total crustal 1096 erosion was limited to about 30 m but the impacts that produced Veneneia 1097 and Rheasilvia locally excavated tens of km. As proposed in Turrini et al. 1098 (2011) and further discussed in Turrini (2014) and Turrini & Svetsov (2014), 1099 impacts of this kind occurring on primordial Vesta could cause effusive events 1100 where the magma originates from the mantle and could in principle produce 1101 compositional signatures in Vesta's crust incompatible with Dawn's measure-1102 ments. Given the degree of collisional remixing of Vesta's crust suggested by 1103 Dawn's observations (De Sanctis et al., 2012; Prettyman et al., 2012), these 1104 scenarios should be investigated on a case-by-case basis if they can success-1105 fully pass the test on the global crustal survival. It is interesting to note, 1106 however, that those scenarios that could produce the excavation or effusion 1107 of mantle material in Turrini (2014) and Turrini & Svetsov (2014) are among 1108 those rejected by the three constraints. 1109

The scenarios we considered in our proof-of-concept case study represent 1110 only a limited subset of all proposed evolutionary tracks for the early Solar 1111 System. As an example, it has been proposed that Vesta could have formed 1112 on an inner orbit located between the orbit of Mars and the inner edge of 1113 asteroid belt (Bottke et al., 2006) instead of in the inner asteroid belt. It 1114 is also possible for the giant planets to have undergone a more extensive 1115 migration than that considered in this work (Walsh et al., 2011; Bitsch et 1116 al., 2015). This extensive migration, in turn, could have kept them in the 1117 outer Solar System (Bitsch et al., 2015) or could have brought them to cross 1118 the inner Solar System (Walsh et al., 2011). All these different possibilities 1119 will be associated to different fluxes of impactors on Vesta and will need to be 1120 tested case by case against the three astrochemical constraints we identified. 1121 Also the scenarios we considered for primordial Vesta do not exhaust all 1122 the different possibilities. As an example, it has been proposed that a slower 1123 formation of Vesta could cause the heat released by the short-lived radioac-1124 tive elements not to be enough to melt the conductive lid of the asteroid, 1125 which would preserve its original undifferentiated composition (Formisano 1126 et al., 2013). This undifferentiated crust would be reprocessed over time by 1127 the effusive processes responsible for the creation of Vesta's basaltic crust, as 1128 discussed in Sect. 3, and could therefore represent a source of HSEs and pos-1129 sibly water for the vestan magma, whose effects on the enrichment of eucrites 1130 and dibgenites need to be verified against the astrochemical constraints on 1131 Vesta's late accretion. 1132

Finally, the temporal interval covered by our proof-of-concept case study spans only a fraction of the temporal windows (see Sect. 3) over which Vesta's

crust can be compositionally altered or eroded by impacts: later events, 1135 therefore, are also expected to leave their marks on Vesta and the HEDs. In 1136 particular, in the scenarios we investigated it is expected that, after Jupiter's 1137 formation, the interplay between the gravitational perturbations of the giant 1138 planet and those of the planetary embryos embedded into the primordial 1139 asteroid belt will start a phase of dynamical excitation and clearing of the 1140 belt itself (Wetherill, 1992; Petit, Morbidelli & Chambers, 2001; O'Brien, 1141 Morbidelli & Bottke, 2007), changing its orbital structure to its present one 1142 (albeit with a larger population of asteroids). Planetesimals impacting Vesta 1143 during this phase of dynamical excitation and clearing will also contribute 1144 to the mass accretion and mass loss histories of the asteroid and their effects 1145 will cumulate with those of the Jovian Early Bombardment. 1146

Applying the three astrochemical constraints we investigated to a more 1147 deterministic study of the history of the early Solar System is beyond the 1148 scope of our proof-of-concept case study and is left to future works based on 1149 a more complete physical model and spanning longer temporal intervals. In 1150 particular, future works will need to include the effects of gas drag, which 1151 will change both the flux of impactors on Vesta and the distribution of the 1152 impact velocities, and of the population of planetary embryos embedded 1153 into the planetesimal disk, which is expected to both dynamically excite the 1154 planetesimals and start a process of depletion of the asteroid belt once Jupiter 1155 has completed its formation (the latter process becoming more efficient in 1156 case of an eccentric orbit of the forming Jupiter), in assessing the collisional 1157 evolution of primordial Vesta. 1158

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In conclusion, the main result of this work is the identification of the

constraints offered by eucrites and diogenites and the showcasing of their joint 1160 use as a window into the ancient past of the Solar System. Our take home 1161 message can be summarized by the following "Lather, Rinse, Repeat" recipe 1162 for future studies. Pick the scenario for Vesta that you consider most realistic, 1163 put it into the scenario for the evolution of the early Solar System that you 1164 want to investigate, and include all the necessary physical ingredients. Let 1165 it evolve and check if Vesta's resulting accretional and erosional histories 1166 are consistent with the global constraints offered by eucrites and diogenites. 1167 Start over as many time as needed. 1168

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Figure 1: Dynamical excitation and radial mixing of the planetesimals in the circumsolar disc in response to Jupiter's mass growth and migration in the simulations by Turrini et al. (2011). The plots show snapshots of the Jovian Early Bombardment 0.2 Myr after the beginning of Jupiter's rapid gas accretion in the four migration scenarios considered by Turrini et al. (2011). The open red circles are the positions of Jupiter at the beginning of the simulations, the bigger red filled ones are the positions of Jupiter once fully formed (see Sect. 4.1). The smaller black filled circles at 2.36 au mark the orbital position of Vesta. The rocky asteroidal planetesimals analogous to ordinary chondrites that formed between 2 and 3 au are indicated in red (see Sect. 4.3). The rocky but water-enriched asteroidal planetesimals analogous to carbonaceous chondrites that formed between 3 and 4 au are indicated in dark cyan (see Sect. 4.3). The ice-rich cometary planetesimals that formed beyond 4 au are indicated in blue (see Sect. 4.3). Planetesimals inside the region delimited by the two black dotted curves are those that can impact Vesta.



Figure 2: Comparison between the average diameters of the planetesimals as a function of their orbital distance from the Sun for the two primordial SFDs considered in our case study (see Sects. 4.3.1 and 4.3.2 for details).



Figure 3: Comparison between the two collisionally-evolved SFDs considered in our case study in the orbital region comprised between 2 and 3 au (see Sects. 4.3.3 and 4.3.4 for details).



Figure 4: Normalized temporal distribution of the fluxes of asteroidal impactors (the orange and red lines) and cometary impactors (the light and dark blue lines) on Vesta in the no migration scenario (the solid lines) and the 1 au migration scenario (the dashed lines) for Jupiter. The highlighted area indicates the temporal interval over which we computed the late accretion and erosion of Vesta's crust, i.e. the Jovian Early Bombardment. Asteroidal impacts before this time were characterized by low velocities (< 1 km/s) and were not considered to account for the clearing effects of Vesta's formation on the orbital region surrounding the asteroid. As can be immediately seen, the Jovian migration enhances the flux of high-velocity (> 1 km/s) asteroidal impactors on Vesta while at the same time decreasing and making more erratic the flux of cometary impactors (see also Fig. 1).



Figure 5: Distribution of the impact probabilities and impact velocities of the asteroidal and cometary impactors in the scenario of no migration of Jupiter and in the 1 au migration scenario for the giant planet in the simulations from Turrini et al. (2011). Note that the impact probabilities reported here refer to the individual impact events and are not impact probabilities averaged over the whole populations of impactors as in classical collisional algorithms (see e.g. O'Brien and Sykes 2011 and references therein).



Figure 6: Normalized distribution of the impact velocities of the asteroidal impactors (i.e. the impactors originating between 1 and 4 au in the simulations of Turrini et al. 2011) on Vesta in the four migration scenarios considered in our case study (see Turrini et al. 2011 and Turrini 2014 for more details).



Figure 7: Normalized distribution of the impact velocities of the cometary impactors (i.e. the impactors originating between 4 and 10 au in the simulatios of Turrini et al. 2011) on Vesta in the four migration scenarios considered in our case study (see Turrini et al. 2011 and Turrini & Svetsov 2014 for more details).



Figure 8: Fraction of the mass of the target body Vesta that is eroded and lost due to the impact, in units of the mass of the projectile. The different curves show the results from the simulations of Turrini et al. (2016) for asteroidal impactors made of granite (red solid line with filled squares), the simulations performed in this work for mixed granite-water ice cometary impactors (light blue dashed lines with filled diamonds), and, for comparisons, the results of the simulations of Turrini & Svetsov (2014) for cometary impactors made of pure water ice (blue solid line with filled circles).



Figure 9: Fraction of the mass of the projectile that survives the impact and is accreted by Vesta, in units of the mass of the projectile. The different curves show the results from the simulations of Turrini et al. (2016) for asteroidal impactors made of granite (red solid line with filled squares), the simulations performed in this work for mixed granite-water ice cometary impactors (red dashed lines with filled squares for the rocky component and blue dashed lines with filles circles for the icy component), and, for comparisons, the results of the simulations of Turrini & Svetsov (2014) for cometary impactors made of pure water ice (blue solid line with filled circles).


Figure 10: Mass loss experienced by a primordial Vesta with mass similar to that of the present Vesta due to (*left*) asteroidal impactors and (*right*) cometary impactors during Jupiter's mass growth in the different migration scenarios and for the different SFDs considered. For each SFD we report the characteristic diameter of the planetesimals producing the bulk of the impact flux as computed with our Monte Carlo methods. The horizontal regions highlighted in red mark the range of values of Vesta's crustal mass fraction and represent our upper boundary to Vesta's mass loss (see Sect. 3 and Consolmagno et al. 2015). Note that, given that the temporal interval considered in this proof-of-concept study is smaller than the timespan over which Vesta's crust can be eroded, only those scenarios producing mass losses *below* the red regions should be considered compatible with present-day Vesta.



Figure 11: Total mass loss experienced by (*left*) a primordial Vesta with the same mass as present Vesta and (*right*) a primordial Vesta three times as massive during Jupiter's mass growth in the different migration scenarios and for the different SFDs considered. For each SFD we report the characteristic diameter of the planetesimals producing the bulk of the impact flux as computed with our Monte Carlo methods. The horizontal regions highlighted in red mark the range of values of Vesta's crustal mass fraction and represent our upper boundary to Vesta's mass loss (see Sect. 3 and Consolmagno et al. 2015). Note that, given that the temporal interval considered in this proof-of-concept study is smaller than the timespan over which Vesta's crust can be eroded, only those scenarios producing mass losses *below* the red regions should be considered compatible with present-day Vesta.



Figure 12: Water accretion experienced by a primordial Vesta with mass similar to that of the present Vesta due to (*left*) asteroidal impactors and (*right*) cometary impactors during Jupiter's mass growth in the different migration scenarios and for the different SFDs considered. For each SFD we report the characteristic diameter of the planetesimals producing the bulk of the impact flux as computed with our Monte Carlo methods. The horizontal regions highlighted in red mark the range of values of Vesta's water enrichment and represent our upper boundary to Vesta's water accretion (see Sect. 3 and Stephant et al. 2016a,b; Sarafian et al. 2017a,b). Note that, given that the temporal interval considered in this proof-of-concept study is smaller than the timespan over which Vesta's crust can be enriched in water, only those scenarios producing water enrichments *below* the red regions should be considered compatible with present-day Vesta.



Figure 13: Total water accretion experienced by (*left*) a primordial Vesta with the same mass as the present Vesta and (*right*) a primordial Vesta three times as massive during Jupiter's mass growth in the different migration scenarios and for the different SFDs considered. For each SFD we report the characteristic diameter of the planetesimals producing the bulk of the impact flux as computed with our Monte Carlo methods. The horizontal regions highlighted in red mark the range of values of Vesta's water enrichment and represent our upper boundary to Vesta's water accretion (see Sect. 3 and Stephant et al. 2016a,b; Sarafian et al. 2017a,b). Note that, given that the temporal interval considered in this proof-of-concept study is smaller than the timespan over which Vesta's crust can be enriched in water, only those scenarios producing water enrichments *below* the red regions should be considered compatible with present-day Vesta.



Figure 14: Mass accretion responsible for the HSEs enrichment experienced by a primordial Vesta with mass similar to that of the present Vesta due to (*left*) asteroidal impactors and (*right*) cometary impactors during Jupiter's mass growth in the different migration scenarios and for the different SFDs considered. For each SFD we report the characteristic diameter of the planetesimals producing the bulk of the impact flux as computed with our Monte Carlo methods. The horizontal regions highlighted in red mark the range of values of Vesta's mass accretion needed to produce the observed HSEs enrichment and represent our upper boundary to Vesta's mass accretion (see Sect. 3 and Day et al. 2012). Note that, given that the temporal interval considered in this proof-of-concept study is smaller than the timespan over which Vesta's crust can be enriched in HSEs, only those scenarios producing mass accretions *below* the red regions should be considered compatible with present-day Vesta.



Figure 15: Total mass accretion responsible for the HSEs enrichment experienced by (left) a primordial Vesta with the same mass as present Vesta and (right) a primordial Vesta three times as massive during Jupiter's mass growth in the different migration scenarios and for the different SFDs considered. For each SFD we report the characteristic diameter of the planetesimals producing the bulk of the impact flux as computed with our Monte Carlo methods. The horizontal regions highlighted in red mark the range of values of Vesta's mass accretion needed to produce the observed HSEs enrichment and represent our upper boundary to Vesta's mass accretion (see Sect. 3 and Day et al. 2012). Note that, given that the temporal interval considered in this proof-of-concept study is smaller than the timespan over which Vesta's crust can be enriched in HSEs, only those scenarios producing mass accretions *below* the red regions should be considered compatible with present-day Vesta.