CONSTRAINTS ON THE PARENT BODY OF ALMAHATA SITTA, STONE AHS 202 FROM ITS METAMORPHIC HISTORY AND THERMAL EVOLUTION MODELLING. K. H. Dodds[1], J. F. J. Bryson[2], J. A. Neufeld[1,3,4] and R. J. Harrison[1], [1]Department of Earth Sciences, University of Cambridge, Cambridge, UK, [2]Department of Earth Sciences, University of Oxford, Oxford, UK, [3]Centre for Environmental and Industrial Flows, University of Cambridge, Cambridge, UK, [4]Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, UK.

Introduction: Almahata Sitta, stone AhS 202 is an unusual carbonaceous chondritic (CC) clast that has undergone greenschist metamorphism [1]. This metamorphism requires pressures of 2-8 kbar and temperatures of 300-500 °C. The required temperature range is within that experienced by other CC groups but the pressures are higher and require the parent body (PB) of AhS 202 to have a 320-900 km radius [1], greater than that usually assumed for CC parent bodies.

Oxygen and ε^{54}Cr isotopic measurements show that AhS 202 is CR-like [2]. The CR chondrules have an age of 3.8±0.3 Myr after the formation of calcium-aluminium-rich inclusions (CAI) [3]. This provides an oldest age limit of 3.8±0.3 Myr after CAI formation for the accretion time of the AhS 202 parent body, assuming that the whole body is formed of CR-like material. However, as the short-lived radionuclides (SLRNs) such as ^{26}Al and ^{60}Fe are likely the dominant heat source for planetesimals, whether the interior of such a late-accreting body was able to reach the temperatures require for greenschist metamorphism due to radiogenic decay of SLRNs alone is uncertain.

Other possible heat sources available to the AhS 202 PB include much longer-lived radionuclides (LLRNs) e.g ^{238}U, ^{40}K, and impact heating during accretion. Alternatively, if the AhS 202 PB underwent multiple stages of accretion and growth, it may have an early accreted interior that is able to differentiate into a liquid iron core and semi-molten magma ocean with a thick chondritic crust added to its surface at >3.8 Myr after CAI formation. The heat from the magma ocean could then provide the heating power to drive greenschist metamorphism within the chondritic lid, the source region of AhS 202. In this case, the AhS 202 PB would have a partially differentiated structure (Fig. 1) instead of being purely chondritic.

In this study, we use thermal evolution models to explore which heat sources are able to provide the necessary power for the metamorphism observed in AhS 202. This also allows us to constrain the structure and accretionary history of the AhS 202 PB (Fig. 1) as well as predict the possible timing of metamorphism of AhS 202.

Methods: We have modified the 1D model described in [4] to track the thermal evolution of a planetesimal for a range of parent body radii from 300-900 km and accretionary scenarios including single-stage and two-stage accretion. These accretionary regimes can produce both undifferentiated and partially differentiated planetesimals, depending critically on whether the body grows to > ~70 km prior to 1.8 Myr after CAI formation [4]. Internal heating comes from both SLRNs (^{26}Al and ^{60}Fe) and LLRNs (^{40}K, ^{238}U, ^{235}U and ^{232}Th) and these elements partition into the core or the magma ocean accordingly if the planetesimal forms early enough to differentiate.

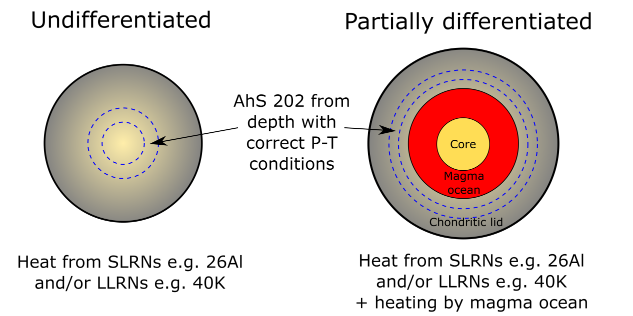

Fig. 1. Potential structures for the AhS 202 parent body. The young age of CR chondrules may require the AhS 202 PB to be partially differentiated.

We identify depths within each simulated planetesimal that are at greenschist pressures of 2-8 kbar and record if and when these depths are at 300-500 °C and thus able to experience greenschist metamorphism. The thermal evolution model ends when this depth range within the planetesimal cools below 300 °C and the metamorphic reaction can no longer proceed.

Heating by decay of short-lived radionuclides: The heating power provided by ^{26}Al and ^{60}Fe alone is unable to provide the necessary P-T conditions for the greenschist metamorphism to proceed (Fig. 2) assuming that the AhS 202 PB starts accreting at 3.8 Myr after CAI formation i.e. instantaneously after the formation of CR chondrules.

However, protracted growth of a planetesimal starting at 3-3.3 Myr and continuing to >3.8 Myr after CAI formation can result in depths within the body that experience the right P-T conditions. The material at these depths is accreted to the body earlier than 3.8 Myr after CAI formation as it then contains sufficient SLRNs to reach 300-500 °C. These depths may not be expected to have CR-like isotopic measurements as observed for AhS 202. However, there are several CR-like achondritic meteorites [5], suggesting that CR-like

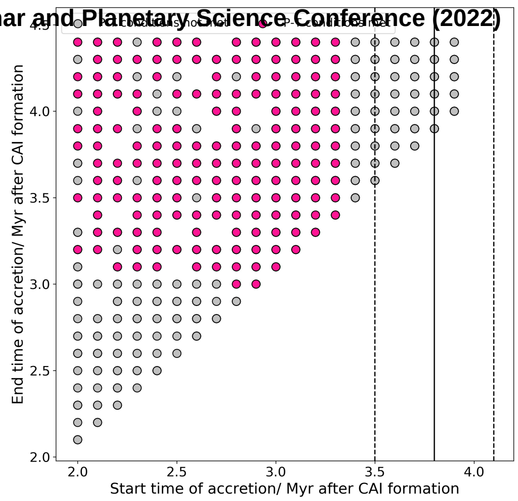

Fig. 2. Possible planetesimal accretion start and end times required to create greenschist P-T conditions with heat provided by ^{26}Al and ^{60}Fe alone. Mean CR chondrule age of 3.8 Myr after CAI formation is given by the black line and the dashed lines give the uncertainty in this age [3].

material may have been present in the solar nebula prior to 3.8 Myr after CAI formation

In this case, greenschist metamorphism could have started as early as ~10 Myr after CAI formation and continued until ~ 1 Gyr after CAI formation, depending on parent body size and accretion start time.

Heating by decay of short- and long-lived radionuclides: The heating power provided by the decay of long-lived radionuclides in addition to the SLRNs discussed above is able to heat up the interior of large, >550 km radius undifferentiated planetesimals to the temperatures requires for greenschist metamorphism (Fig. 3). In this case, AhS 202 would originate from a depth of 100-200 km within a >550 km radius body that accreted >3.3 Myr after CAI formation and greenschist metamorphism would occur from ~100 – 1200 Myr after CAI formation, dependent on exact parent body size and accretion time. The delay in the onset of metamorphism is due to billion year half-lives of these radionuclides that result in a far slower release of heat energy than the SLRNs.

Heating by an internal magma ocean: Our model produces partially differentiated planetesimals when the body starts growing prior to 1.8 Myr after CAI formation and continues to accrete material to its surface after this time. The interior early-accreted portion contains sufficient SLRNs to cause widespread melting, differentiation and core formation whereas the younger SLRN-poor layer retains its primitive chondritic texture. This undifferentiated lid is then heated efficiently from below by a semi-molten magma ocean which can lead to depths which experience greenschist P-T conditions anytime starting from > 2 Myr and ending at >1 000 Myr after CAI formation if the lid thickness is greater than 270 km. The radius of the differentiated interior portion must be >70 km. This is in order to allow differentiation.

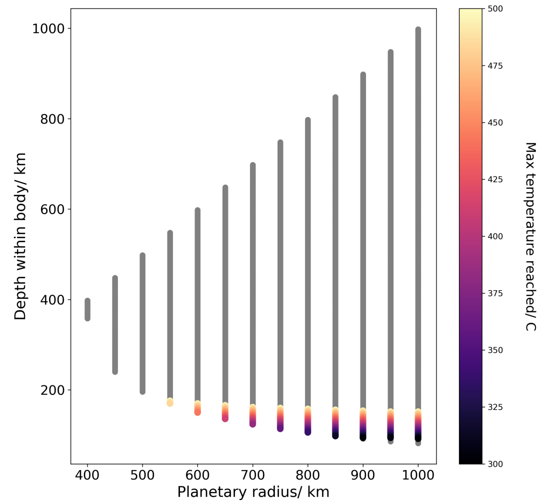

Fig. 3. Depths within a purely chondritic PB that reach greenschist P-T conditions due to heating by the decay of LLRNs. The grey markers denote depths at the correct pressures but wrong temperatures. Parent body in this case accretes at 3.8 Myr, the mean age of CR chondrules [3].

In this case, any two stage model that consists of the growth of a seed to > 70 km in the first 1.8 Myr of the solar system followed by the late addition of > 270 km material to its surface at > 3.7 Myr after CAI formation will produce material that experiences the necessary P-T conditions to undergo greenschist formation. These bodies also have a liquid iron core that will eventually crystallize and potentially generate a dynamo field that could be recorded as a partial thermoremanent magnetization in AhS 202 as these fields may be contemporaneous with the metamorphism.

Conclusions: Short-lived radioisotopes such as ^{26}Al are unlikely to be able to provide the necessary heating power alone for the greenschist metamorphism observed in AhS 202 unless CR-like material was present in the solar nebula at 3.0 – 3.3 Myr after CAI formation. Dating the chondrules in AhS 202 using a precise high-temperature geochronometer could allow us to determine whether this is possible.

Otherwise the heat required for this metamorphism could have been provided either by long-lived radionuclides or an internal magma ocean. These two mechanisms could be discriminated between by dating the time of metamorphism in AhS 202 as the magma ocean scenario leads to rapid heating within ~ 10 Myr whereas heating by LLRNs leads to > 100 Myr delay to the metamorphism. Additionally, if the AhS 202 PB was partially differentiated, its core may have generated a dynamo field during its crystallization which may be detectable from a pTRM recorded by AhS 202.

References: [1] Hamilton et al. (2021) *Nat. Astron* 5, 350-55. [2] Miller et al. (2021) *LPSC 52,* A2360. [3] Tenner et al. (2019) *GCA* 260, 133-60. [4] Dodds et al. (2021) *JGR: Planets* 126.3, e2020JE006704. [5] Sanborn et al. (2019) *GCA* 254, 577-96