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Context matters – Ar–Ar results from in and around the Manicouagan Impact Structure, Canada: Implications for martian meteorite chronology

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ABSTRACT

As an analog for interpretations of the ages of martian shergottite meteorites, we have conducted an argon isotopic study of plagioclase feldspars exhibiting varying levels of shock from in and around the Manicouagan impact structure, Canada. Plagioclase from the impact melt sheet at Manicouagan yields an age of 215.40 ± 0.16 Ma, which indicates the time of impact. Plagioclase from a clast within melt-bearing breccias of the melt sheet and a hornfels adjacent to the melt sheet yield ages of 216 ± 3 Ma and 218 ± 7 Ma, respectively, which are interpreted to have been reset by contact metamorphism from the impact melt. Country rocks that were unaffected by the impact gives ~849 Ma ages, consistent with the known Grenvillian target rock history. Maskelynite (amorphous plagioclase, which has been transformed in the solid state) yields an age of 567 ± 6 Ma. This age is geologically meaningless because it is not consistent with the target age, the impact age, or regional metamorphic ages at Manicouagan. Our results show that maskelynite argon ages are not meaningful, and that context is critical for proper interpretation of impact-affected argon ages.

1. Introduction

Determining the timing of impact events and the dating of shocked material is important for studies of extraterrestrial samples. Presently, our collection of samples from beyond Earth are dominated by meteorites, many of which have experienced violent and complex histories involving at least one large impact event. Therefore, it is critical to understand how impacts have altered our ability to date primary events on meteorite parent bodies. This is particularly the case for Mars, where ages of martian meteorites are debated, and where the degree to which impacts affect radioisotopic chronometers is the topic of much debate (Bouvier et al., 2008, 2009; Stephan and Jessberger, 1992; Park et al., 2013). As such, the interpretation of ages obtained from shocked meteorites can be contentious. The goal of this study is to examine ^{40}Ar/^{39}Ar ages from a terrestrial impact structure, where both the impact and original target ages of the rocks are known in order to assess the effects of impact.

1.1. Martian chronology and impacts

Our understanding of martian geology would benefit from absolute chronology. Although there have been attempts to obtain absolute ages directly on Mars (Farley et al., 2014), high precision martian geochronology measurements are presently best obtained from martian meteorites in terrestrial laboratories. Current absolute age estimates for martian samples range from ~150 Ma to more than ~4.3 Ga (Bouvier et al., 2009, 2008; Nyquist et al., 2001). K–Ar analyses by the Curiosity rover of the Sheepbed mudstone yields an age of 4.2 ± 0.35 Ga (Farley et al., 2014). The orthopyroxenite martian meteorite ALH84001 has an Rb–Sr crystallization age of ~4 Ga (Lapen et al., 2010; Nyquist et al., 2001). Nakhlites and Chassignites give Rb–Sr and Sm–Nd ages of 1.4 Ga (Korochantseva et al., 2011) and argon ages of between 1416 ± 7 Ma and 1322 ± 10 Ma (Cohen et al., 2017). U–Pb ages from

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Table 1
Compilation of radiometric ages of martian meteorites. In addition to there being a variety of ages reported depending on chronometer, there are also differences depending upon what phase was measured.

Meteorite	Ar age (Ma)	Phase	Reference	Notes
Los Angeles	165	'plag'	Bogard et al., 2009	'Plagioclase' is used in this publication for all phases of plagioclase-composition regardless of structural state. No detailed description of shock state is given.
	318	whole rock	Bogard et al., 2009	The methods sections says this sample was taken from an impact melt vein, but no description of this material is presented.
	1428	melt pocket	Walton et al., 2007	Spatially resolved laser probe was used to maintain petrographic context
	1290	matrix adjacent to melt	Walton et al., 2007	Spatially resolved laser probe was used to maintain petrographic context
NWA 3171	232	'plag'	Bogard et al., 2009	The methods sections says this sample was taken from an impact melt vein, but no description of this material is presented
NWA 2975	672	'plag'	Bogard et al., 2009	The methods sections says this sample was taken from an impact melt vein, but no description of this material is presented
Dho 019	721	'plag'	Bogard et al., 2009	The methods sections says this sample was taken from an impact melt vein, but no description of this material is presented
	849	whole rock	Bogard et al., 2009	The methods sections says this sample was taken from an impact melt vein, but no description of this material is presented
Dho 019	643 ± 72	maskelynite	Korochantseva et al., 2009	The methods sections says this sample was taken from an impact melt vein, but no description of this material is presented
Dag 476	1000	'plag'	Bogard et al., 2009	reported as a 'total age.' Does not yield a plateau age
	1400	whole rock	Bogard et al., 2009	reported as a 'total age.' Does not yield a plateau age
	1427	matrix	Walton et al., 2007	Spatially resolved laser probe was used to maintain petrographic context
	2324	shock melt	Walton et al., 2007	Spatially resolved laser probe was used to maintain petrographic context
Zagami	∼217	coarse grained 'plag'	Bogard and Park, 2008	plagioclase and maskelynite are used interchangeably. No detailed characterization of the samples measured is given.
	∼2350	fine grained 'plag'	Bogard and Park, 2008	plagioclase and maskelynite are used interchangeably. No detailed characterization of the samples measured is given.
	242	'feldspar'	Bogard and Garison, 1999	no description of shock level is presented. Note: Park et al. (2013) cites an age of 175 attributed to Bogard and Garison (1999), but that age was not found in the original paper.
	592	mixed phase near melt vein	Walton et al., 2007	Spatially resolved laser probe was used to maintain petrographic context. They note ranges for this sample between 443 and 1049 Ma
SaU 005	>850	maskelynite	Korochantseva et al., 2009	
Shergotty	∼370	maskelynite	Korochantseva et al., 2009	
	387, 167 and 195	'feldspar'	Bogard and Garison, 1999	no description of shock level is presented. Note: Park et al. (2013) cites an age of 175 attributed to Bogard and Garison (1999), but that age was not found in the original paper.
	254 ± 10	maskelynite	Bogard et al., 1979	Uses plagioclase and maskelynite interchangeably
NWA 1068	2308 and 4439	melt pocket	Walton et al., 2007	Spatially resolved laser probe was used to maintain petrographic context
ALH 7005	2700	shock melt	Walton et al., 2007	less shocked maskelynite than ALH 7005
ALH 7005	373–>4000	highly shocked plagioclase	Walton et al., 2007	less shocked maskelynite than ALH 7005
ALH 1951	4600	shock melt	Walton et al., 2007	less shocked maskelynite than ALH 7005
ALH 1951	382	maskelynite	Walton et al., 2007	less shocked maskelynite than ALH 7005

zircons within the "Black Beauty" breccia yield ages of 4.4, 1.7, and 1.4 Ga (Agee, 2014). The shergottites, which make up the majority of the martian meteorite collection, yield younger and more varied argon ages, between 150 and 500 Ma (Table 1). Shergottites have experienced moderate shock levels, with the majority of plagioclase converted to maskelynite (Tschermak, 1872; Fritz et al., 2005). Additionally, these samples have discrepancies between chronometers, such as Sm–Nd or Rb–Sr, used for the same samples, which has led to the suggestion that the "young" argon ages date a resetting event, presumably by impact or aqueous processes (Gaffney et al., 2011).

Bouvier et al. (2008, 2009) challenged the notion of "young" ages for the martian shergottites based on Pb isotopes. Using reversed Pb–Pb isochrons of step-wise leached whole rocks, they showed that the common lead-stripped $^{207}Pb/^{206}Pb$ dates representing the radiogenic end-member point to consistently older ages (>4 Ga) for shergottites. They attribute the younger argon ages to resetting due to post-crystallization impact(s).

1.2. *Shock resetting of the K–Ar system*

Attempts to understand impact-resetting have focused primarily on the K–Ar isotopic system. Of the long-lived chronometers (Rb–Sr, Sm–Nd, U–Pb, K–Ar), the K–Ar system is the easiest to reset during conventional regional and thermal metamorphism (e.g., Bickford and van Schmus, 1979). Shock resetting of the K–Ar system, however, is a complex, disequilibrium process. During impacts, deformation occurs in two fundamentally different ways: isochemical, pressure dominated changes (e.g., formation of high pressure polymorphs and the development of diaplectic glasses), and thermally controlled processes (e.g., impact melting). Coherent impact melt rocks are known to yield ages consistent with the time of impact (Young, 2014) because these rocks crystallized directly from the impact melt just after the impact event. Resetting of the K–Ar system is predominantly understood as a thermal process, and shock-deformed, unmelted material has been thought to be resistant to complete argon resetting because the thermal