Introduction: Igneous rims provide insight into chondrule formation mechanisms through indicating that chondrules experienced multiple heating episodes [1]. Previous studies of igneous rims from ordinary and carbonaceous chondrites [2-5] suggest they form from dust particles accreting onto the surface of solidified chondrules, followed by melting. Many type I (FeO-poor) porphyritic chondrules in CR chondrites are surrounded by igneous rims, typically consisting of low-Ca and high-Ca pyroxene, ± Fe,Ni metal, ± plagioclase ± olivine ± glass, and they commonly contain primary silica [2, 6]. The formation mechanism for silica-rich rims around CR chondrules is unclear. Various formation mechanisms have been proposed including dust accretion, as above [3-5], as well as direct condensation of SiO-rich gas onto the outer zones of molten chondrules [6]. Rim accretion is suggested to occur at high temperature but details of formation conditions are not understood [3-4].

We aim to define the formation conditions of silica-rich rims by reproducing the texture, mineral compositions, and silica polymorphs present in natural rims using experimental analogues. Peak temperature information can be determined using silica polymorphs, as several stable polymorphs exist at low pressures below 1700°C (quartz, tridymite, and cristobalite). The presence of particular polymorphs within a rim can therefore inform on the rim’s thermal history, thus giving quantitative constraints on its formation [7].

Methods: We examined the textures and mineralogy of natural silica-rich rims in several CR chondrites: Graves Nunataks (GRA) 95229, Queen Alexandra Range (QUE) 99177, Meteorite Hills (MET) 00426, LaPaz Icefield (LAP) 04516, Elephant Moraine (EET) 92042 and 92062. These are all relatively pristine CR chondrites, to ensure Si-rich phases are primary. Using the classification of [8], all samples studied are of petrologic type 2.8, except GRA 95229, which is type 2.7.

Experiments were conducted using a Deltech one-atmosphere furnace with programmable temperature control. Peak temperatures of experiments range from 1360-1510°C with linear and multi-stage linear cooling rates ranging from 6-90°C/hr. Starting materials were prepared from a dry powder mix of oxides (SiO₂, MgO, TiO₂, Al₂O₃, Na₂O, and CaO), with a bulk composition analogous to silica-rich rims in CR chondrites [2]. Initial experiments have been conducted in an FeO-free, CMAS-based system: silica-rich igneous rims around CR chondrules have a low FeO content, < 3 wt.% [3].

Liquidus temperatures for the experimental bulk composition calculated using MELTS software [9-10] and from the quartz - anorthite - forsterite phase diagram were 1352°C and ~1610°C respectively. Our experiments at 1556°C did not exceed the liquidus. MELTS may not be appropriate for the experimental bulk composition due to the high silica content (80.6 wt.%).

Both natural and experimental samples were analysed using the JEOL JSM-6400 Scanning Electron Microscope (SEM) and the JEOL JXA-8530F electron microprobe at the University of Manchester (UoM). Silica polymorphs were identified using Raman spectroscopy on the Horiba XploRA (UoM).

Results: Natural samples. Not all porphyritic type I chondrules are surrounded by silica-rich rims and where present, they surround the chondrule core either completely or partially, with variable widths. Rims range in thickness from 60-500 µm and are finer grained than the chondrule core. The boundary between the chondrule core and the rim is usually sharp. Some chondrules also have an Fe,Ni-rich mantle surrounding the chondrule followed by a silica-rich igneous rim. It is unclear if the Fe,Ni metal grains are a separate rim, or part of the silica-rich rim. Low and high-Ca pyroxene (sometimes zoned) are the dominant minerals in rims, ± Fe,Ni-metal ± plagioclase ± olivine (Fig. 1a). The main Si-rich phase present in chondrule cores is Si-rich glass. Chondrule rims can contain both Si-rich glass and silica mineral grains. Silica mineral grains range in size from 3-50 µm and are typically sub-angular to sub-rounded. Raman spectroscopy conducted on silica from natural samples shows sharp peaks at ~110 cm⁻¹, 220 cm⁻¹, and 420 cm⁻¹, diagnostic of cristobalite. This is consistent with [11].

Experimental samples. We have conducted 15 experiments so far. Experiments with peak temperatures between 1360-1510°C and linear cooling rates between 30-90°C/hr exhibit a similar mineralogy and texture to natural silica-rich rims (Fig. 1b). They contain low and high-Ca pyroxene and silica grains of similar size and morphology to natural samples. Glass rather than plagioclase is present in these samples. Experiments with higher peak temperatures (1556°C) and faster cooling rates (50-90°C/hr) produce forsterite needles in addition to Si-rich glass and silica grains. A slower cooling rate of 30°C/hr at this peak temperature (1556°C) results in silica grains, elongate low-Ca pyroxene, glass, but no high-Ca pyroxene. These higher temperature experi-
ments therefore fail to reproduce observations from natural samples. Multi-stage linear cooling rates (e.g., 90°C/hr to 1200°C then 6°C/hr to 800°C) from a peak temperature of 1556°C also do not reproduce natural sample mineral assemblages and textures.

Raman spectroscopy conducted to date indicates that cristobalite is the dominant silica polymorph in experimental samples with peak temperature ranging from 1360-1556°C.

Cristobalite is the dominant polymorph in both natural samples, and experimental samples with peak temperatures from 1360-1556°C. Cristobalite is expected in experimental samples with a high peak temperature (1556°C). However, cristobalite is not expected in experimental samples at lower peak temperatures (< 1470°C) because the silica phase diagram shows that tridymite (stable from ~857-1470°C), not cristobalite (≥ 1470°C) should be present (Fig. 2). There are several possibilities as to why this is the case, including: (1) the tridymite/cristobalite phase boundary on the silica phase diagram is not accurate; (2) cristobalite is forming metastably; (3) we are dealing with a multi-component system (CMAS + Ti + Na) rather than the one component (SiO$_2$) phase diagram. Whichever of these is the case, previous studies of silica polymorphs in chondrites [7,14] have assumed that the presence of cristobalite indicates a peak temperature ≥ 1470°C. Our experiments indicate that lower peak temperatures are permissible.

**Fig.1**: Backscattered electron images of (a) a silica-rich rim from QUE 99177 chondrule (Ch) 11 and (b) experimental sample CR 08 highlighting the similarity in mineralogy and texture.

**Discussion**: We find that experiments with peak temperatures between ~1350-1500°C and linear cooling rates between 30-90°C/hr exhibit a similar mineralogy and texture to natural silica-rich rims. These conditions are similar to those predicted in the shock wave and impact jetting models of chondrule formation [12-13]. The experiments show that thermal histories for formation of rims by accretion of dust followed by melting are similar to those of chondrules.

**Fig.2**: Phase diagram for SiO$_2$ showing the stability fields of the low pressure SiO$_2$ polymorphs (SERC, 2017). Red bar shows the range of peak temperatures of our experiments.

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