

I am a planetary geoscientist who studies the evolution of rocky planets. Rocky planets retain traces of the evolution of their fluid envelopes over the long timescales that Earth's fossil record teaches us are necessary for the evolution of complex life. With emphasis on Mars and rocky exoplanets, I use models and geologic data analysis to address some of the key questions for planetary geoscience: *(i) How does Early Mars geology record past climate and how can we read that record?* *(ii) How do planets stay habitable?* *(iii) What are the controls on planetary atmosphere-interior exchange?*, all motivated by the goal *Can we identify simple rules for planetary evolution?* My approach to answering these questions combines geologic data analysis with physical and chemical modeling. This combination – applied to planetary geoscience – is what makes my research distinctive, and also what makes carrying it out fun. I design and implement algorithms and methods, write the computer code, perform the data analysis and lead the interpretation with a focus on clarifying the fundamental physical processes that stabilize or destabilize long-term planetary habitability. Highlights of my research programs include the following milestones:

1. The first direct constraint on the paleoatmospheric pressure of Mars at the time the rivers were flowing. (*key questions i, ii, iii*). (Kite et al. Nature Geoscience 2014).
2. The first model to explain sustained cryovolcanism. (*ii, iii*). (Kite & Rubin PNAS 2016).
3. The first model of the transition from primary to secondary atmospheres on exoplanets. (*ii, iii*). (Kite & Barnett PNAS 2020).
4. The first analysis of trends over time in runoff production for another planet. (*i, ii*). (Kite et al. Science Advances 2019).
5. New models for wet climates on Mars. (*i, ii, iii*). (e.g., Kite et al. Nature Geoscience 2017, & Kite et al. PNAS 2021).
6. Conceived and developed the bombardment compass, leading to the first direct retrieval of the multi-Gyr obliquity history of any planet. (*i*). (Holo\*, Kite, et al., EPSL 2018).
7. The first complete analysis of the build-up and destruction of sedimentary-rock mountains on Mars. (*i*). (Five papers starting with Kite et al. Geology 2013).
8. Magma-atmosphere interaction explains the drop-off in exoplanet abundance at  $3\times$  Earth's radius. (*iii*). (Three papers starting with Kite et al. ApJL 2019).

(\* = *student or researcher working under my supervision.*)

Over the past decade, evidence for habitable environments beyond Earth has become unequivocal. Currently, more data are returned from Mars each year than from all other interplanetary missions in the past 10 years, combined. To answer my research questions, I have established a planetary geoscience data analysis lab at the University of Chicago to distill these varied data into stratigraphically-coordinated geologic information as needed to constrain past climate and climate evolution. In the process I have developed the modeling framework needed to formulate and test hypotheses about Early Mars wet climates in relation to these data. Ultimately I seek to understand Mars climate evolution as a benchmark for rocky exoplanets. My research emphasis on planetary habitability (rather than geophysics or planetary origins) has much to gain from the ongoing shift in NASA's science goals, marked by the upcoming missions of the flagships Mars 2020, Europa Clipper, & JWST.

### **(i) How does Early Mars geology record past climate and how can we read that record?**

Mars is the only planet whose surface is known to have become uninhabitable. Rivers and lakes on Early Mars are surprising because Early Mars orbited far from a faint star (the young Sun). The Early Mars climate problem

is to determine the number, duration, intensity and intermittency of the wet climates, together with the climate regime that sustained those wet climates. There is no single Early Mars climate problem: multiple warm periods are recorded by the geology, with different runoff intensities and different characteristic timescales, strongly suggestive of multiple warming mechanisms. The most challenging observations to explain – and so my focus – are the evidence for surface liquid water over a cumulative duration of  $\gg 10$  Myr (the major sedimentary-rock basins), and separately the evidence for river-forming climates that persisted for  $>1$  Kyr. I have also developed new proxies for Early Mars climate parameters.

## **Formation and distribution of sedimentary rocks on Mars.**

**Key paper: Kite et al. *Icarus* 2013a.**

Mars' light-toned, rhythmically layered sedimentary rocks record the waning stages of aqueous activity on the planet's surface during the Hesperian-Amazonian. In contrast to the prevailing view that the water source for these sedimentary rocks was deep-sourced groundwater, my research showed that snowmelt-limited aqueous cementation of aeolian materials under unusually warm orbital conditions is an attractive explanation for the formation of these deposits. This allows for a much colder and drier global-and-annual mean Mars climate, reconciling geological data and atmospheric models. Snow stability and propensity to melt varies strongly with orbital forcing, so this analysis involved building the first orbitally integrated probabilistic model of snowmelt on Mars (Kite et al. *Icarus* 2013a). For a given paleoclimate hypothesis (pressure and temperature), snowpack energy balance models are run for all locations and all possible orbital states on Early Mars, and the summed maps are then compared to geologic observations of surface liquid water. This solved a mystery in that the global distribution of snowmelt has spatial maxima that explain spatial maxima in the rhythmically layered sedimentary rock distribution. I continue to investigate mechanisms to force intermittent bursts of late-stage habitability on Mars (e.g., Kite et al. *Nature Geoscience* 2017).

## **Construction and destruction of sedimentary mountains on Mars.**

**Key papers: Kite et al. *Geology* 2013; Steele\*, Kite et al., *JGR* 2018; Kite et al. *JGR* 2016.**

Ancient sediments provide archives of climate and habitability on Mars. Most of Mars' post-Noachian sedimentary rocks (by volume) – including the Gale crater mound targeted by MSL – are hosted within mounds. In a series of five papers, I led the first complete analysis of the build-up and destruction of these sedimentary-rock mountains. First, motivated by layer-orientation data, I used a simple model of slope winds to show how sedimentary rock mounds can emerge from feedbacks between slope winds and erodible terrain (Kite et al. *Geology* 2013). Sediment initially accretes near the crater center far from crater-wall winds, until the increasing relief of the resulting mound generates mound-flank slope winds strong enough to erode the mound. The nonintuitive result is that mountains grow taller (relative to their surrounding moats) by sediment accretion over time. This new idea linked ancient sedimentary basin analysis to modern erosional processes, and opened a new research direction: morphodynamic feedbacks between wind and topography are widely applicable to a range of sedimentary and ice mounds across the Martian surface. I subsequently led a large effort to validate and extend the HiRISE-derived measurements of layer-orientation data for Mars mounds, while using natural experiments to test the disagreement between interpretations. The resulting synthesis (Kite et al. *JGR* 2016) rigorously quantifies the (small) errors on the measurement technique, and includes the best elements from multiple published models, while using natural experiments and new lines of evidence (including mesoscale meteorological models) to support each of the elements of my original hypothesis. These ideas have received independent support from gravimetry data (as well as RMI-based stratigraphic analysis) collected by others, and have stimulated additional research in this area (e.g. Borlina, Ehlmann & Kite, *JGR* 2015).

With post-doctoral researcher Liam Steele (working under my supervision), I used mesoscale meteorological models to show that wind erosion can form Mars mounds from initially-flat infill (Steele\*, Kite, et al., *JGR* 2018). Undergraduate lead author Leila Gabasova and I evaluated the differential compaction hypothesis for layer-

orientation data at Gale, and showed that differential compaction is important at Gunjur (Gabosova\* & Kite, P&SS 2018). I led a global survey of Mars erosion rates (Kite & Mayer Icarus 2017). We found that the geologically-recent Mars dust production rate is high enough that the Mars dust likely has geologic sinks ('dust-stone'), and also ranked locations with exhumation fast enough to favor the preservation of biomarkers.

## Developing new proxies for key Early Mars parameters.

**Example paper: Kite et al. Nature Geoscience 2014.**

As a fortunate side-effect of spending a lot of time looking at data, I have twice stumbled across a new proxy for key Early Mars parameters. These accidents have both evolved into research programs: the ancient-crater paleobarometer, and the bombardment compass.

First, I discovered small craters embedded within early Mars river deposits. Planetary atmospheres brake, ablate, and fragment small asteroids and comets. A record of Martian atmospheric paleo-pressure is therefore embedded within cratered volumes of ancient sedimentary rocks: the smaller the ancient craters, the thinner the past atmosphere. Building on my earlier contribution to work on using volcanic bomb sags as a probe of paleoatmospheric pressure (Manga et al. GRL 2012), I put this paleobarometer into action (Kite et al. Nature Geoscience 2014), obtaining an upper limit of  $1.1 \pm_{0.2}^{0.1}$  bar. These results eliminate the thick atmospheres that are required for CO<sub>2</sub>-H<sub>2</sub> collision-induced absorption to produce  $T > 280\text{K}$  climates on Noachian Mars, while permitting cooler wet climates by this mechanism. With graduate student Sasha Warren, I am using additional sites that preserve ancient-crater populations to obtain a time series of early Mars atmospheric pressure stratigraphically coordinated to the great drying (Warren\*, Kite, et al., JGR 2019).

Second, I discovered anisotropies in the distribution of the orientations of the long axes of moderately-elliptical craters on Mars. These bombardment anisotropies, which cannot be explained by planetocentric impactors, record the convolution of past obliquity, past True Polar Wander (TPW), and the past relative-velocity vectors of heliocentric impactors: a bombardment compass. Because the Solar System is chaotic, planet orbits cannot be deterministically reverse-integrated beyond  $\sim 100$  Mya. Many geologic methods have been proposed to vault this fundamental barrier, but all are indirect. Now we have a direct method. With graduate student Sam Holo, I analyzed the Mars crater-orientation record for the last  $\sim 3.5$  Gyr (Holo\*, Kite, et al., EPSL 2018). For this period I have previously shown that TPW is small (Kite et al. EPSL 2009). Obliquity variations are critical to post-Noachian climate on Mars. Combining our probabilistic ensemble of  $10^3$  multi-Gyr Mars obliquity tracks (Kite et al. Icarus 2015) with N-body simulations of Mars-crossing impactors, we showed that Mars' mean obliquity was  $< 33^\circ$  ( $2\sigma$ ), with  $< 20\%$  of time spent at obliquity  $> 40^\circ$  (Holo\*, Kite, et al., EPSL 2018). These updated estimates are key to assessing the cumulative effects of obliquity on snow/ice melting, as well as on fast loss of water to space during stormy high obliquity climates. Moreover,  $> 99\%$  of the data remains to be analyzed, showing the potential for future work to resolve obliquity versus time by comparing less-cratered to more-cratered terrain. Next, I plan to analyze the first Gyr of Mars history, marginalizing over obliquity to probe the polar wander history and bombardment history of Mars (it is straightforward to deconvolve these two factors). We have also shown (Holo\* & Kite Icarus 2020) that, despite erosion, differences between the last-3-Gyr and first-Gyr Mars crater size frequency distribution make Mars a witness plate for changes in the Mars bombarder population. The possibility of using bombardment anisotropy to constrain the source population of the Mars bombarders (e.g. clean-up of the terrestrial planet region vs. asteroidal) is particularly intriguing because this method is independent of geochemistry.

An unresolved question is whether warm Mars climates had a frozen season. Chloride-lake deposits constrain this question because large salt volumes require deep groundwater circulation. Using reaction-transport models and HiRISE DTMs, post-doctoral researcher Mohit Melwani Daswani and I showed that salt volumes match calculations for within-watershed leaching from a seasonally frozen active layer (Melwani Daswani\* & Kite JGR 2017). The results from this new method are consistent with Mars having a continuous permafrost layer by the time chloride lakes formed.

## Data for river-forming climates on Mars.

**Example paper: Kite et al. Science Advances 2019.**

The key constraints for Early Mars climate research are the number, duration, intensity, evaporation/runoff ratio (aridity index), and intermittency of the wet events. A synthesis framing my contributions to this topic and providing an intellectual road map for the field was recently published (Kite, Space Science Reviews 2019). Mars' river-forming climates extended later into Mars history than previously thought, with intense and globally distributed runoff production persisting intermittently over  $>1$  Ga. Our results suggest strong positive feedbacks in the Early Mars climate system and feed into our climate modeling (discussed in the next section).

A key unknown in Early Mars research is - for how long did wet climates occur? A stopwatch for sediment accumulation is provided by syn-sedimentary craters. Using this proxy for the first time for Mars river deposits, in combination with stratigraphic analyses, I correlated the meander belts to an interval of  $>1$ -20 Ma (Kite et al. Icarus 2013b) and the separate, later alluvial-fan-forming climate to an interval of  $>(100-300)$  Myr (Kite et al. GRL 2017). We used bedrock erosion and sediment transport models to show that fans were active for only  $10^2$ - $10^6$  yr, implying long dry spells during this interval of wet climates (Stucky de Quay\*, Kite, et al. JGR 2019). For meandering Martian floodplains preserved in inverted relief, DTMs allowed quantification of stratigraphic architecture including, for the first time, a constraint ( $>100$  Myr) on the time gap on an Early Mars unconformity (Kite et al. Icarus 2015). Graduate student Sam Holo and I used statistical methods more advanced than any previously applied to Mars chronology data (Holo\* & Kite in revision) to confirm that the river-forming events extended well into the Amazonian, and my group analyzed overspilling Amazonian craters (Warren\*, Holo\*, Kite, et al., EPSL 2021), eliminating the hypothesis that exit breaches formed in a single climate-driven fill-and-spill event. Paleodischarge for catchments of known area directly constrains paleoclimate models. Using lateral-accretion deposits as a guide to paleochannel locations, I showed that river-deposit dimensions record a paleodischarge decrease in Aeolis Dorsa (Kite et al. EPSL 2015). Measurement of paleo-river parameters requires equal meticulousness in data collection and in uncertainty analysis, as well as high-quality, high-resolution Digital Terrain Models; the availability of DTMs is the limiting factor for these measurements. (My lab has produced  $\sim 300$  DTMs and shared them with the community.) Using  $\sim 100$  of our DTMs, I extended this method to a globally-distributed set of Mars paleochannels. My analysis showed that (for a given drainage area) Mars rivers were wider than Earth rivers, consistent with extreme runoff production (Kite et al. Science Advances 2019). Remarkably, though the spatial pervasiveness of river erosion waned over time during Mars' era of river-forming climates, peak runoff production did not. Intrigued by this, I used proxies such as lake-deposit extent and fan-toe elevation to survey the aridity index of all large relatively young closed-basin impact craters on Mars (results are included in the paper described in the next paragraph). I found that aridity increased over time in southern midlatitudes, but wetter climates (semiarid to arid) persisted elsewhere. A promising new method, analysis of channel branching angles (Seybold, Kite, et al., Science Advances 2018), independently suggests arid climate. These paleoclimatic trends in space and time constrain both paleoclimate and climate evolution, painting a picture of arid, but essentially Earth-like, lake-forming climates persisting remarkably late in Mars history.

What was the nature of the atmosphere that supported these climates? The Habitable Zone (HZ) concept has been interpreted to give a clear prediction: habitable climates near the cold edge of the HZ should have  $\gtrsim 1$  bar  $p\text{CO}_2$ . Recently, I led a team that used detectability-corrected Mars paleoriver distributions to test and reject this hypothesis. I found changes over time in the spatial distribution of rivers - a decline in the preferred elevation for rivers, and a shift from early-stage elevation control to late-stage latitude control. I used models (Mars GCMs) to confirm that both changes are well-explained by a reduction in the total strength of the atmospheric greenhouse effect, with a decline in average  $p\text{CO}_2$  from  $\gg 10^2$  mbar for early river-forming climates, to  $\lesssim 10^2$  mbar for later river-forming climates (Kite et al. in revision). Our finding that Early Mars (near the cold edge of the HZ) had river-forming climates at low average  $p\text{CO}_2$  complements my work on the ancient-crater paleobarometer and raises the likelihood of false negatives in the search for habitable exoplanets. With graduate student Bowen Fan, I am currently using GCMs to determine the theoretical basis for these  $p\text{CO}_2$ -driven shifts.

## (ii) How do planets stay habitable?

### **Models for river-forming climates on Mars.**

**Example papers: Kite et al. Nature Geoscience 2017; Kite et al. PNAS 2021.**

Mars' geology is usually interpreted in terms of global climate change, but could instead be a palimpsest of localized, transient events. To test this, I modeled the mesoscale response of Mars' atmosphere to transient surface liquid water (Kite et al. JGR 2011a). As a consequence of Mars' low atmospheric density, model output showed that strong storms and localized precipitation occur even for lakes at the freezing point. I applied this model to test the hypothesis that lake storms sourced from chasms in the Valles Marineris are the cause of mineralized layered deposits just downwind of the chasms (Kite et al. JGR 2011b). The results support the hypothesis. I wrote the cratering, ablation, and runoff-production code for an analysis of localized impact-triggered runoff ~3.5 Gya in Margaritifer Terra (Mangold, Kite, et al., Icarus 2012). Although transient localized runoff cannot account for all Early Mars data (e.g. large alluvial fans; Kite et al. GRL 2017), these methods can offer insights into impact-induced runoff that has probably occurred throughout Mars history.

Lower limits on the lifetime of some Mars lakes exclude impact- or volcano-triggered wet climates. Instead, I have shown that lake flooding on Mars can be both orbitally-triggered and somewhat self-sustaining, because clathrates below inundated seafloor will outgas methane, a greenhouse gas (Kite et al. Nature Geoscience 2017). This climate scenario reconciles proxy data that show intense physical erosion, yet modest chemical weathering, for early Mars.

My work, and that of people working under my supervision, on ancient river deposits has underlined that precipitation-fed runoff production was globally distributed, was intense, and persisted intermittently over a time span of >1 Ga. Very few mechanisms have the potential to explain these data: one is intermittent greenhouse warming from water ice clouds. However, previous 3D GCM work on the water ice cloud greenhouse warming mechanism did not consistently find the 290 K surface temperatures permitted by 1D models of the cloud greenhouse. This is in part because extensive surface water ice drives the formation of low clouds which cool the planet. For the past three years, I have pursued this problem. With postdoctoral researcher Liam Steele, I found that in 3D GCMs strong water ice cloud warming can indeed arise, but only if the climate is arid (Kite et al. PNAS 2021). Stable warm arid climates involve surface ice (and low clouds) only at locations much colder than the average surface temperature. At locations horizontally distant from these surface cold traps, clouds are found only at high altitudes, which maximizes warming. Unexpectedly, partial drying-out of Mars' surface may have been the pre-requisite for warm climates on Early Mars. For the first time, our warm cloud greenhouse scenario achieves steady state both with respect to the atmosphere and with respect to surface ice reservoirs. The success of this idea has uncorked two near-future research programs, one to anatomize the high-cloud feedback with idealized 3D models, and the other to test the hypothesis against Mars' geologic record.

### **Long-term planetary climate evolution.**

**Example papers: Kite et al. ApJ 2011, Kite & Ford ApJ 2018.**

I have built models to study long-term climate evolution on exoplanets and Mars.

Review papers and textbooks assert that without a climate-regulating feedback, long-term planetary surface habitability is unlikely. To the contrary, I showed, in the first physics+chemistry model for climate evolution on rocky exoplanets with deep oceans, that multi-Gyr habitability can arise through chance variation of initial conditions, without geochemical cycling (Kite & Ford ApJ 2018). This is because the cosmochemically-reasonable initial range of atmosphere+ocean inorganic C inventories overlaps the geophysically-reasonable range of positive charges leached from the planetary crust by water-rock interactions. As a result, ocean pH is often within a range that sets atmospheric CO<sub>2</sub> to levels that permit long-term habitability. This work also led to the accidental discovery of a new kind of climate instability (runaway exsolution at high DIC concentration). This is the first

paper in a research arc that will constrain atmospheric evolution on small-radius exoplanets in general.

Requirements for a climate-stabilizing weathering feedback include a positive dependence of planet-averaged weathering rate on atmospheric greenhouse-gas concentration. If day-night surface temperature contrast is large (as observed on Mars and expected for tidally locked planets), and the principal greenhouse gas is also the dominant constituent of the atmosphere, I showed for the first time that the weathering-rate feedback that stabilizes Earth's climate can change sign, and destabilize climate (Kite et al. ApJ 2011). This climate instability will be most severe for tidally locked rocky planets; Mars may also have passed through this climate instability in the past.

With graduate student Megan Mansfield, I modeled the long-term evolution of the potential for snowmelt on Mars, taking into account the evolution of solar luminosity, atmospheric pressure, and chaotic orbital forcing (Mansfield\*, Kite, et al., JGR 2018). We showed that MAVEN measurements of modern O loss, extrapolated over 3.5 Ga, are consistent with geologic constraints on snowmelt intermittency and duration, but only if most of the net O loss came from CO<sub>2</sub> (not H<sub>2</sub>O). Linking CO<sub>2</sub> loss mechanisms to Early Mars geochemistry, I quantified the 'carbon penalty' and isotopic predictions associated with the global deep-groundwater circulation hypothesis (Kite & Melwani Daswani EPSL 2019). Subsequently, with graduate student Andy Heard, I used D/H data and MAVEN results to break the degeneracy between CO<sub>2</sub> and H<sub>2</sub>O loss and show that little CO<sub>2</sub> can have escaped Mars' atmosphere to space since 3.5 Ga (Heard\* & Kite EPSL 2020). Either Mars' atmosphere went into the ground, or climate models are greatly overstating the amount of CO<sub>2</sub> that is needed to make Mars warm enough for habitability (consistent with indications from our river-distribution paleobarometer, p. 4).

### (iii) What are the controls on planetary atmosphere-interior exchange?

#### **Volcano-tectonic coupling on icy moons. Key paper: Kite & Rubin PNAS 2016.**

Eruptions on the ice moon Enceladus provide access to materials from Enceladus' ocean, but the mechanism that drives and sustains the eruptions has been unclear. I showed (with assistance from Allan Rubin) that a simple model in which the erupting fissures are underlain by slots that connect the surface to the ocean can explain the observations. In my new model, the slots are mostly filled with water, and Saturn tides drive turbulent water flow in the slots whose dissipation produces enough heat to keep slots open. In turn, long-lived water filled slots drive a negative feedback that adjusts the flux of ice consumed by melt-back into slots near the base of the shell to balance the flux of subsiding ice. This feedback buffers the rate of volcanism to approximately the observed value. Our results suggest that the ocean-surface connection on Enceladus is sustained on Myr timescales, and the ice flow aspect of this work linked back to earlier work on planetary applications of a thermo-mechanically coupled ice-sheet model (Kite & Hindmarsh GRL 2007). Our Enceladus study inferred a new mode of planetary tectonics from spacecraft data. The next step is clear: new Hubble data strongly suggest that Europa is also cryovolcanically active. Europa's double ridges are conduits for salty ocean material, like Enceladus' tiger stripes, but only Enceladus' volcanism has been observed up close (Spencer & 7 others including Kite, 2018). Therefore, Enceladus is plausibly the key to Europa tectonics. The importance of Europa is shown by its selection as the target for NASA's next flagship-class orbiter, Europa Clipper. In addition to investigating Europa tectonics, my future icy-moons work will examine other heat-generating mechanisms, such as shear heating from libration of partly-grounded ice shells.

#### **Super-Earths. Key papers: Kite et al. ApJ 2009, 2016.**

Requirements for a rocky planet's climate to be regulated by a weathering feedback include a supply of greenhouse gases from volcanism. I used parameterized models with a uniform mantle to test whether plate tectonics and Earthlike volcanic degassing would be possible on massive rocky planets - 'super-Earths.' Volcanism shuts down after  $\lesssim 7$  Gyr in stagnant lid mode, so volcanism on an old super-Earth would be evidence for plate tectonics (Kite et al. ApJ 2009). I also found that planet mass can strongly affect the mode of mantle convection. This

work led to an interest in whether Earth’s thermal history is strongly dependent on mantle structure, which can only be resolved by geoneutrinos. I have determined the optimal siting of neutrino detectors for this purpose; this work was subsequently combined with work done independently by a different team (Šrámek, McDonough, Kite, et al., EPSL 2013).

>100 rocky planets are hot enough to have permanent magma pools. Because magma planets are at close orbital distance, they are – and will remain – intrinsically easier to characterize than true Earth analogs. In the first physical+chemical study of these worlds (Kite et al. ApJ 2016), I combined a vertically-averaged model of the evaporation wind with chemical evolution of the magma pool. I showed that surface-interior exchange on hot rocky exoplanets is regulated by near-surface contrasts in melt density. In turn, these density effects are set by the relative vigor of evaporation and ocean circulation, and also by exposure of the planet’s building-blocks to oxidants such as H<sub>2</sub>O and resulting formation of volatile-but-dense FeO. This links close-in planet observables to the planet formation era and to the nebula water-ice line.

I collaborate with observers on the interpretation of exoplanet data. For the discovery paper for the first directly-imaged exoplanet candidate (Kalas & 8 others including Kite, Science, 2008; Science #2 Breakthrough of the Year), I calculated the correct orbit for the planet candidate – identifying and fixing an erroneous orbital calculation – with major implications for the interpretation of the photometry. I was second author on the follow-up dynamics study (Chiang, Kite et al., ApJ 2009), was part of the team for the first-observed disintegrating planet (Rappaport & 10 others including Kite, ApJ 2012), and worked on the interpretation of a Keck time series of spatially resolved Io magmatic activity (de Kleer, Nimmo, & Kite, GRL 2019). With graduate student Megan Mansfield, I showed that surprisingly thin exoplanet atmospheres interior to the habitable zone can be detected if they have extensive cloud cover, like Venus (\*Mansfield, Kite et al., ApJ 2019). This and our related studies have had an immediate impact on JWST planning, and I currently collaborate with several exoplanet observer teams, both inside and outside the University of Chicago (e.g., Koll & 6 others including Kite, 2019). As a result I am a team member for multiple selected proposals for JWST Cycle 1. Now that the era of small-radius exoplanet geoscience data has finally arrived, exoplanet work will form an increasing proportion of my research, with an example being the research arc described next.

## **Exoplanet sub-Neptunes: size, chemistry, and legacy for super-Earths.**

**Key papers: Kite et al. ApJL 2019; Kite & Schaefer ApJL 2021; Kite & Barnett PNAS 2020.**

Worlds in hot orbits with  $2 R_{\oplus} < R < 3 R_{\oplus}$  appear to be the most intrinsically abundant type of planet in the Universe. Strong indirect evidence implies that these ‘sub-Neptune’-sized exoplanets have massive magma oceans blanketed by thick hydrogen-dominated atmospheres. It is plausible that most of the known super-Earths were born as sub-Neptunes, but sub-Neptunes have no solar system analog. Therefore, I led a research program to apply basic physics and chemistry to understand sub-Neptunes’ size, chemistry, and legacy. For the first time, my research program focused on the chemical interaction between the multi-Earth-mass magma ocean and the hydrogen-dominated atmosphere. This led to the unplanned and unexpected discovery (Kite et al. ApJL 2019) that dissolution of the atmosphere into the magma explains the drop-off in exoplanet abundance at  $3\times$  Earth’s radius. This drop-off is one of the major features in the exoplanet radius distribution, and has been a puzzle for almost a decade. Magma-atmosphere interaction naturally reproduces the radius cliff and is robust to initial conditions, in contrast to previous explanations that require tuning of core masses and/or accretion time to reproduce the radius cliff. Moreover, magma-atmosphere redox reactions turn out to be key to both the size and the H<sub>2</sub>O abundance of sub-Neptune atmospheres, based on a detailed thermodynamics-plus-mass-balance model (Kite et al. ApJ 2020). Our model predicts that small sub-Neptunes will have O/H  $>500\times$  solar, which is imminently testable. I found that magma-atmosphere interactions, in combination with non-fractionating atmospheric loss, may endow large super-Earths with nearly-pure H<sub>2</sub>O atmospheres (Kite & Schaefer 2021); this is testable with JWST. Capping this research arc, with assistance from graduate student Megan Barnett, I used my new model of atmosphere evolution (including atmosphere loss to space, magma ocean crystallization, and volcanic

outgassing) to analyze for the first time the transition over time from sub-Neptune atmospheres to super-Earth atmospheres. This allowed us to find the (narrow) range of conditions under which super-Earths will have secondary atmospheres Gyr after primary-atmosphere loss (Kite & \*Barnett PNAS 2020). This research arc has unlocked numerous new questions for follow-up: most urgently, quantifying the effect of magma-atmosphere interaction on the mass-radius diagram for the exoplanet ensemble. I am currently collaborating with astrophysicists and material scientists to answer these questions.

## **Solar system and exoplanet habitability — a research agenda**

Earth's long-term climate stability is remarkable. We want to understand all the ways in which a planet's long-term climate stability can break down and all of the ways (not just Earth's way) that it can be maintained. This quest defines the new field of comparative planetary habitability.

*Can we identify simple rules for planetary evolution? Are the processes that generate planetary habitability common or rare?* Answering these questions by observing Earth-analog exoplanets (Earth-sized exoplanets in the Habitable Zone) poses an enormous challenge, and the signal/noise will be marginal even with next generation telescopes. We can make faster progress on closing the loop between models and observations using 'Earth cousins' - small-radius exoplanets that lack Solar System analogs, but are a little bigger or a little hotter and so are more observationally accessible (Kite, Kreidberg et al., in press). The ensemble of 'snapshots' from Earth cousins is complemented by Solar System geologic records, which constrain environmental stability over timescales much longer than is possible for telescopic observations of exoplanets. New constraints will be provided by the CASSIS, PIXL, SAM, and EIS instruments (for the Solar System), and JWST, ARIEL, PLATO, and GMT (for exoplanets). Parsing these data to extract process insights will continue to require a hierarchy of numerical models, from box models and N-body models up through GCMs. For Mars, I will continue to use geologic data to reconstruct the history of the atmospheric greenhouse effect. Separately, I will model warming mechanisms to include H<sub>2</sub>-production blooms triggered by mantle plumes and the high-altitude-water-ice-cloud greenhouse, increasingly emphasizing GCM-data comparison. My research emphasis over the next 3-5 years will remain on Mars; Mars' record of planetary habitability greatly ameliorates the survivorship bias that inherently limits using Earth as an analog to understand the habitability of exoplanets. Moreover, Mars is the only currently accessible geologic record that can provide an independent test of Earth-derived models of planetary habitability. Therefore, I will continue to direct these studies with the goal of understanding planets in general.