I am a planetary geoscientist who studies the evolution of rocky and icy planets. Planets with solid surfaces 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. For planets with solid surfaces – with emphasis on Mars, icy moons, and rocky exoplanets – I use models and geologic data analysis to solve problems relevant to long-term environmental evolution. My research program combines geologic data analysis with basic 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, discussed below, include the following milestones:

1. The first direct constraint on the paleoatmospheric pressure of Mars at the time the rivers were flowing. (Kite et al. Nature Geoscience 2014).
2. New models for wet climates on Mars. (e.g., Kite et al. Nature Geoscience 2017).
3. The first model to explain sustained cryovolcanism. (Kite & Rubin PNAS 2016).
4. The first direct retrieval of the multi-Gyr obliquity history of any planet. (Holo*, Kite, et al., EPSL 2018).
5. The first time series of paleohydrology proxy data (runoff production) for another planet. (Kite et al. Science Advances 2019).
6. The first complete analysis of the build-up and destruction of sedimentary-rock mountains on Mars. (Five papers starting with Kite et al. Geology 2013).
7. The first physical+chemical models for hot rocky exoplanets (Kite et al. ApJ 2016), and for deep-ocean rocky exoplanets (Kite & Ford ApJ 2018).

(* = *student or post-doctoral researcher working under my supervision.*)

Over the past decade, evidence for habitable environments beyond Earth has become unequivocal. Regardless of whether or not life established itself in these environments, their apparent complexity poses a grand challenge for geoscience: *Can we identify simple rules for planetary evolution? How do planets stay habitable? What are the modes of planetary surface-interior exchange? What does sedimentary-deposit accumulation on Mars record and how can we read that record?* Currently, more data is returned from Mars each year than from all other interplanetary missions in the past 50 years, combined. To advance these goals, I have established a planetary geoscience data analysis lab at the University of Chicago to distil this data into stratigraphically-coordinated geologic datasets that are needed to build time series of paleoclimate proxy data, alongside the modeling framework needed to relate these data to hypotheses about Early Mars wet climates. Ultimately I seek to understand Mars climate evolution as a benchmark for rocky exoplanets. This emphasis on planetary habitability (rather than geophysics or planetary origins) parallels a shift in NASA's science goals, marked by the upcoming launches of the flagships Mars 2020, JWST, & Europa Clipper.

Retrieval and modeling of Early Mars climate as recorded by geology.

Mars is the only planet known to record a major habitability transition in its sediments (from more-habitable to less-habitable). 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 dictated by the geology, with different runoff intensities and different characteristic timescales, strongly suggestive of multiple warming mechanisms. Recent spacecraft observations, for example from the CTX and HiRISE instruments, provide abundant data. The most challenging observations to explain – and so my focus – are the evidence for surface liquid water that persisted for >100 Myr (the major sedimentary-rock basins), and separately the evidence for river-forming climates that persisted for >3 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, 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 the sedimentary rocks was deep-sourced groundwater, my research showed that snowmelt-limited formation of sedimentary rocks 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 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.

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 have 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 by sediment accretion over time. This new idea 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 available rover data - to support each of the elements of my original hypothesis. These ideas 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 have shown that wind erosion can form Mars mounds from initially-flat infill (Steele*, Kite, et al., JGR 2018). Undergraduate lead author Leila Gabasova and I showed 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 ("duststone"), and also ranked locations with exhumation fast enough to favor the preservation of complex organic matter.

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, and intermittency of the wet events. An overview and synthesis of my contributions on this topic was recently published (Kite, Space Science Reviews 2019).

Preservation of river and stream deposits on Mars is often better than on Earth, allowing these parameters to be inferred from measurements of paleochannel width, meander wavelength, river-deposit volume, embedded craters, and the number of regionally correlatable fluvial packages. Retrieving these parameters from the geologic record requires equal meticulousness in data collection and in uncertainty analysis. Crater-counts and stratigraphic analyses 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). For meandering Martian floodplains preserved in inverted relief, DTMs allowed quantification of stratigraphic architecture including >100 Myr-long unconformities (Kite et al. Icarus 2015). A promising new method is the analysis of channel branching angles (Seybold, Kite, et al., Science Advances 2018). Paleodischarge directly constrains past climate, because peak runoff production depends on atmospheric pressure, greenhouse forcing, and the phase of precipitation – rain or snow. I showed that river-deposit dimensions record a paleodischarge decrease in Aeolis Dorsa (Kite et al. EPSL 2015). I have extended this method to a globally-distributed set of Mars paleochannels. My analysis shows that (for a given drainage area) Mars rivers were wider than Earth rivers, consistent with extreme runoff production (Kite et al., Science Advances 2019). Many of the river channels on Mars are preserved in inverted relief. Therefore, I led fieldwork to Utah's terrestrial-analog inverted channels to assess channel-width preservation fidelity.

Models for river-forming climates on Mars.
Example paper: Kite et al. Nature Geoscience 2017.

New lower limits on the lifetime of individual Mars lakes (e.g. Gale crater) 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 is particularly attractive because it reconciles proxy data that show intense physical erosion, but modest chemical weathering, for early Mars. I have also shown that atmospheric collapse and reinflation triggers clathrate release (Kite et al., arXiv:1709.08302). This is counterintuitive, because atmospheric collapse cools the planet. However, because CO_2 collapse occurs on a faster timescale than H_2O-ice migration, a collapse-and-reinflation loop will destabilize clathrate that is initially stable beneath H_2O-ice sheets. The resulting warm pulse explains Mars' valley networks and associated weathering.

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. We applied this model to test the hypothesis that lake storms sourced from chasms in the Valles Marineris are the cause of opaline 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 around Eberswalde Crater (Mangold, Kite, et al., Icarus 2012). Although transient localized precipitation cannot account for all Early Mars data, these methods can offer insights into impact-induced precipitation that has probably occurred throughout Mars history.

Ongoing work on global Mars warming as an explanation for river-forming climate focuses on testing the water-ice cloud greenhouse hypothesis.

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. Both accidents have evolved into research programs.

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 idea into action (Kite et al. Nature Geoscience 2014), obtaining an upper limit of 0.9 ± 0.1 bar. This is low enough to rule out many warm/wet greenhouse proposals. I have found three additional ancient-crater lagerstätten. Next I plan to model them with an improved model, to obtain a time series of early Mars atmospheric pressure, stratigraphically coordinated to the great drying. This research is timely because the MAVEN spacecraft is currently constraining atmospheric loss processes.

Second, I discovered anisotropies in the distribution of the orientations of the long axes of elliptical craters on Mars. These anisotropies record the convolution of past obliquity, past True Polar Wander (TPW), and the past relative-velocity vectors of objects that bombard Mars. 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 Gyr (Holo*, Kite et al., EPSL 2018). For this period I have previously shown that TPW is small (Kite et al. EPSL 2009). We found that the mean obliquity was close to the central expectation from a $\sim 10^3$-solar-system probabilistic ensemble (Kite et al. Icarus 2015), and ruled out higher mean obliquities. Next, I plan to analyse 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). Preliminary work shows that the numerous claims of large-amplitude net TPW on Mars are incorrect. The possibility of constraining 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 in Early Mars work is whether warm 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 Cl column densities bracket the expected Cl content for 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.

Long-term planetary climate evolution.
Example papers: Kite & Ford ApJ 2018; Kite et al. ApJ 2011.

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

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 have shown that the weathering-rate feedback that stabilizes Earth's climate can change sign, and destabilize climate (Kite et al. ApJ 2011). This new 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_2 loss, extrapolated over 3 Ga, are consistent with geologic constraints on snowmelt intermittency and duration - a surprise, because of the simplicity of the model. The data-model agreement indicates that if Mars' atmosphere has decayed due to escape to space, then most of the net O_2 loss must come from CO_2 (not H_2O), and this can be tested by future MAVEN measurements.

Review papers and textbooks assert that without a climate-regulating feedback, long-term planetary habitability is unlikely. To the contrary, I have found, in the first physics+chemistry model for rocky planets with deep oceans, that multi-Gyr habitability will often 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 sufficiently close to neutral to set atmospheric CO_2 at levels that permit long-term habitability. This is the first paper in a research arc that will constrain atmospheric evolution on small-radius exoplanets in general.

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 the 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 may be sustained on Myr timescales, and the ice flow aspect of this work linked back to my undergraduate 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 ocean material, like Enceladus' tiger stripes, but only Enceladus' volcanism has been observed up close (Spencer & 7 others including Kite, accepted). Therefore, Enceladus is likely 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.

Rocky exoplanets. 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 idealized models with a uniform mantle to test whether plate tectonics and Earthlike volcanic degassing would be possible on massive rocky planets (Kite et al. ApJ 2009). I 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 (Sramek, 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 detect and 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 ocean. 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_2O and resulting formation of volatile-but-dense FeO. High FeO abundance may allow a buoyant, stable lag to form - a compositionally evolved surface - with potentially observable consequences. This links close-in planet observables to the planet formation era and to the nebula water-ice line.

I stay current with exoplanet data in part via collaborating with observers. 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 Fomalhaut b – identifying and fixing an erroneous orbital calculation – with major implications for the interpretation of the photometry. For the follow-up study (Chiang, Kite et al., ApJ 2009), my primary contribution was to using N-body models to obtain an upper limit on Fomalhaut b's mass using the distribution of dust in Fomalhaut's debris belt. I was part of the team for the first-observed disintegrating planet (Rappaport & 10 others including Kite, ApJ 2012), and am currently working with (new MIT professor) Katherine de Kleer on the interpretation of a Keck time series of spatially resolved Io magmatic activity (de Kleer, Nimmo, & Kite, submitted).

Solar system and exoplanet habitability - a research agenda

My long term research plan is to seek the equivalent of a Hertzsprung-Russell diagram for long-term planetary habitability. Environmental 'snapshots' for rocky exoplanets will allow for ensemble statistics. These 'snapshots' are complemented by Solar System geologic records, which constrain environmental stability over timescales much longer than the telescopic-observations baseline. Key constraints will be provided by the CASSIS, NOMAD, PIXL, SAM, and EIS instruments (for Mars and Europa), JWST and GMT (for exoplanets), and numerical experiments. For Mars, by tying together paleohydrological investigations of past watersheds of different ages, together with basin analysis of key areas and paleopressure constraints from exhumed craters, I plan to reconstruct the the history of the atmospheric greenhouse effect. The availability of topographic data at a variety of scales will allow simultaneous characterization of watersheds and fine-scale channels within those watersheds. Seperately, I will model warming mechanism to include H_2-production blooms triggered by mantle plumes, and the cirrus-cloud greenhouse. Although my research emphasis over the next 5-10 years will remain on Early Mars, I will continue to direct these studies with the goal of understanding planets in general.