HIRSCH GRANT APPLICATION, F2016
Grosfils, Geology Department

1. INTRODUCTION

Large calderas—volcanic depressions up to tens of kilometers in diameter (**Figure 1**)—form when crustal material subsides in response to the release of magma from a subsurface reservoir. As common components of volcanic systems, and areas where complex magmatic activity can persist for considerable lengths of time, calderas are important sites where geothermal energy, vigorous groundwater circulation and mineral resource deposition can be found. These characteristics are clearly advantageous to nearby populations, but large caldera-forming eruptions themselves can have highly adverse regional and global consequences, matched only in immediacy and the scale of societal devastation by a large asteroid impact. Fortunately, such eruptions are rare, but they occur repeatedly over time spans of tens of thousands to millions of years in regions of high thermal activity. In order to understand both their potential benefits and hazards, it is critical to gain as much insight as possible into the factors controlling the formation and subsequent evolution of large caldera systems—topics that remain poorly understood.

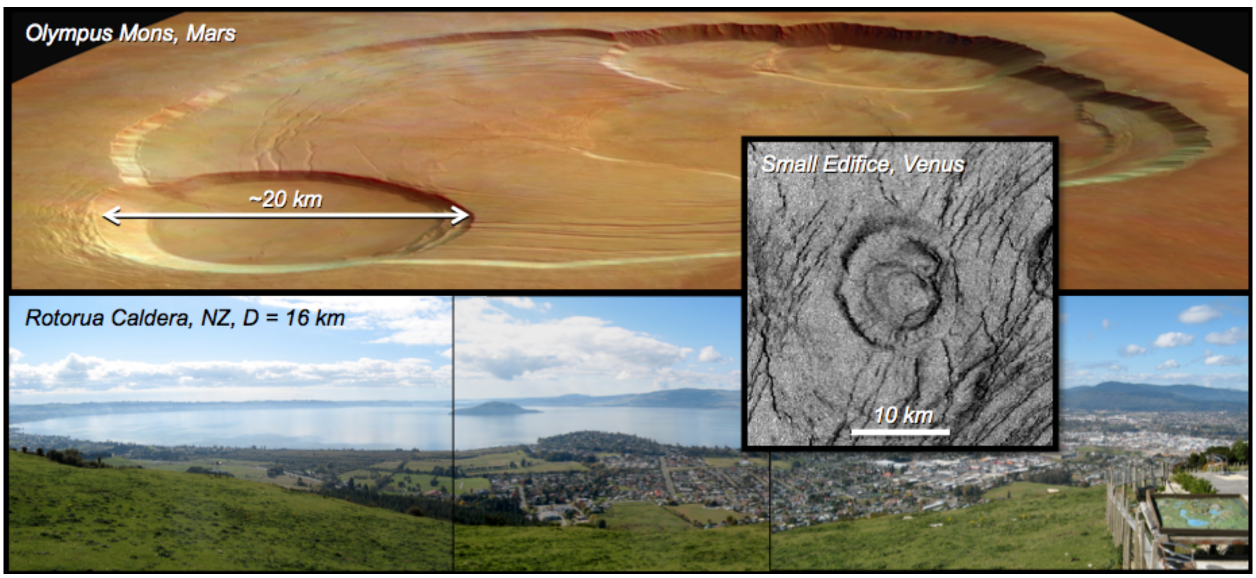

__Figure 1__. *Examples of calderas at different scales on Earth (Rotorua caldera lake photograph by Grosfils), Venus (Magellan, inverted left-looking data, NASA) and Mars (Mars Express, ESA/DLR/FU Berlin)*

While the link between the eruption of substantial volumes of magma and caldera formation has been recognized for some time, deciphering the details of the process from the geological record in order to gain insights that are useful for understanding the behavior of modern, active caldera systems (e.g. Taupo in New Zealand, Campi Flegrei in Italy, Long Valley and Yellowstone in the United States) is considerably more difficult. Over the past several decades experimental, field-based and numerical research efforts have focused on examining such factors as: the link between magma reservoir size and geometry and caldera characteristics; the role of magma pressure variations during eruption phases; the different effects expected when the topographic load from a volcano is added at the surface; the variations introduced by pre-existing regional and/or circumferential faults and rift systems; the complex interplay between surface deformation and hydrothermal circulation; and, geologic mapping and related analyses that constrain the timing and physical processes associated with past caldera-forming eruptions, plus study of detection methodologies and sensitivity for modern events. This list represents only a small subset of the recent work that has been performed, underscoring the importance geoscientists place upon understanding the characteristics of this major societal hazard.

One of the key things we don't understand, and which I have recently begun with collaborators to address, is how the mechanics of caldera formation works. Exploring this question ultimately requires development and application of complex numerical models that can be constrained using field data and geophysical observations. Since calderas form when magma escapes from subsurface reservoirs, my primary objective has been to understand the interplay between magma reservoir activity and accompanying crustal stresses: what conditions prime a magma system so that circular, throughgoing faults (ring faults), ones that permit magma escape and associated caldera subsidence, are likely to form? Critically, what geological factors control this process? Developing simple models that yield initial insights has been a central part of my research activities with students for the past several years, but we have reached the limits of what we can learn from the models we have constructed. Guided by our results and their shortcomings I now intend to try something totally new. If proof-of-concept testing is successful, results will feed into submission of a multi-year NASA grant, sharply enhancing (past experience suggests) the likelihood of funding.

2. MY PREVIOUS WORK

My investigations of caldera mechanics have followed two main paths. Each is described briefly below. The insights gained have been substantial, but a key take-away is that I cannot proceed further without testing and ultimately I hope implementing what is, in effect, a brand new technique for investigating how ring faults form (see Section 3)—a completely untried new path.

PAST PATH 1: ELASTIC MODELS OF RING FAULT FORMATION.

I began my investigations of caldera mechanics in 2009 when I traveled for a semester, as a Fulbright U.S. Senior Scholar, to New Zealand, where some of the most recent large caldera eruptions have occurred (e.g., Taupo caldera; the most recent eruption here ~20,000 years ago devastated the North island, currently home to in excess of 3 million people). This Fulbright semester allowed me to test and develop the basic elements of a 2D (axisymmetric) elastic model that explored where rock failure near a magma reservoir would occur in response to an inflation event and how potential fault planes would be aligned; this approach represented a significant advance over the state-of-the-art in the field at the time. From 2012-2016, funded by a grant from NASA's Planetary Geology & Geophysics program[1], I worked to translate these 2D models into a fully three-dimensional framework. The translation to 3D enabled me to incorporate factors such as volcano loading and complex regional tectonic stresses, additions that permit application of the models to specific test cases on Earth and elsewhere in the solar system. Multiple students were closely involved in these efforts (cf. Figure 2), many extended them via

1 *The acceptance rate for "new start" grants in 2011 for NASA PG&G was ~10%. My proposal succeeded in part because of the proof-of-concept test results I had obtained looking at the 2D cases.*

senior thesis efforts, and all but one of those who have graduated to date have gone on (one via a Fulbright) to top graduate programs in physical volcanology and geophysics.

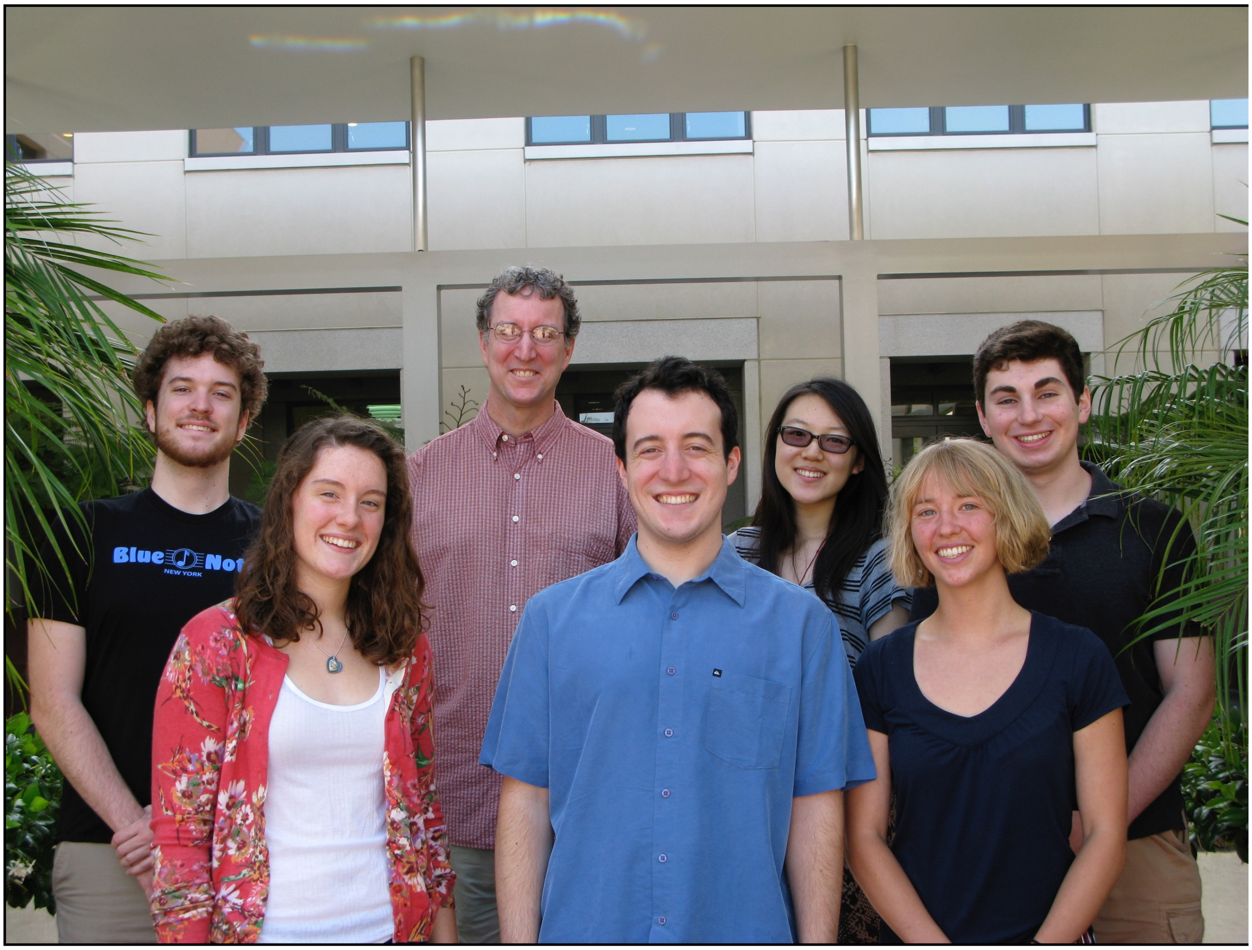

Figure 2: *Undergraduate students engaged in PG&G funded magma reservoir numerical modeling research with PI Grosfils during the summer of 2014. Robby Goldman ('15) in the middle front, and Jack Albright ('16) at left in the back, contributed significantly to the research supported by the caldera grant and are now pursuing related research via a Fulbright and graduate study; Shelley Chestler ('12), not pictured, also participated in the caldera formation modeling and subsequently pursued graduate work in geophysics. Of the other four students pictured, who were involved in a different numerical modeling project, three were first year students ('17) and one was a second year student ('16), demonstrating how quantitative volcanology research can be a powerful and accessible way to engage a diverse array of students early in their academic career.*

Specifically, via the NASA grant, I: a) developed and calibrated a 3D half-space model using an idealized spherical reservoir, developing innovative new ways to visualize the stresses and fault plane orientations, and then assessed how regional tectonic stresses affect the process of caldera formation; b) added small volcanic edifice loads to the surface, altering the stress state beneath the volcano, to explore how calderas form at the crest of such edifices with and without tectonic stresses; and, c) added large volcanic edifices to the surface, inducing flexure (bending) of the underlying crust, to assess how this impacts caldera formation. A complete summary of the results from the grant, prepared for the NASA program officer late this past summer, is available upon request.

Via these studies I gained exciting new insights into the conditions that permit calderas to form. A fundamental limitation of my elastic modeling approach, however, is that it can only examine whether or not the crust is primed for ring fault formation as it responds to an inflation event and other loading conditions; it can't track the changes that occur once faulting initiates. Put another way, the models are by definition static, not dynamic. In addition, while half-space elastic models neatly match many large caldera characteristics, it has been exceedingly difficult to identify plausible conditions whereby calderas can form at the crest of either a large or small edifice. Since edifice-topping calderas are commonly observed, this is a fundamental shortcoming that our models are unable to address: some process involved in the formation of these calderas has not been captured by the approaches used to date.

PAST PATH 2: TEMPERATURE-DEPENDENT VISCOELASTIC CALDERA FORMATION.

Working in collaboration with Dr. Patricia Gregg during her postdoc at Oregon State University and tenure track appointment at the University of Illinois Urbana Champaign, I have explored how time- and temperature-dependent viscoelasticity affects (and does not affect) the process of caldera formation. A viscoelastic material responds in two ways to an applied stress, akin to the way the arm on a screen door controls how it closes: when the door is wide open and you let it go, it swings partly shut fast (the elastic, instantaneous response), then it slows and gradually eases shut the rest of the way (the viscous, time-evolving response). As temperatures elevate, reducing viscosity (think thick honey when cold vs runny honey when hot!), a viscoelastic material will respond differently to applied stresses. Since a magma reservoir is filled with hot material, it elevates the temperature in the surrounding crust, affecting its viscosity, and hence how it responds to stress: there is an instantaneous (elastic) element when an inflation event occurs as well as a time-dependent (viscous) element that accommodates the stress over the longer term.

The results from these studies indicate that only the very largest magma bodies (>100 km^3 size) produce enough temperature change for the viscous response to change the outcome relative to a purely elastic simulation. This means two things. First, temperature and host rock response must be included when studying the largest caldera systems; without this, the results will be in error. Second, it means that temperature dependence alone is insufficient to explain why our elastic models can't explain how smaller calderas form at the crest of many volcanoes! The latter is worrying, because it indicates that we are missing some key element(s) in our underlying approaches to date. These same elements could conceivably affect the outcomes of our models examining larger systems as well. I need to try something totally new in an effort to identify them.

3. THE CHALLENGES – WHY IS THERE NEED TO EXPLORE SOMETHING COMPLETELY DIFFERENT?

My previous investigative paths improved our insight into caldera mechanics, yet as noted above their shortcomings also call into question whether the models are capturing the right factors. That in itself is not unusual—simple solutions and insights help scientists frame more complex questions to improve their understanding—but given the extremely hazardous nature of large caldera-forming eruptions and the potential for them to have significant adverse societal impact it is critical to try and identify what we are missing in our efforts to decipher their formation.

In addition, I face a different pair of challenges that stem from my position at a teaching-focused liberal arts college. First, in the past half decade the new modeling approaches I have developed have revolutionized how many volcanologists study magma reservoir inflation and failure. However, as my approaches are disseminated and become more mainstream, they are adopted by research groups at many centers around the world, and these groups—cored by research-focused faculty with pools of graduate students—are now advancing research using these methods far more rapidly than I can. In essence, in some ways I have become a victim of my own success! I have made an impact on the field, but now it would be wise to move on and seek new research paths other groups haven't yet begun to consider… and I think I have found one, which I describe below. Second, whatever I do, I want to ensure that the work remains tractable to my undergraduate students so that there are persistent opportunities for them to be involved in the research. I have decided that I can't simply move to ever more complex models that simply enhance those I have already developed the way my "R1" colleagues can. If I do, there is little chance that an undergraduate will be able to absorb this complexity and take meaningful ownership of a new investigation in the time they have available. As things stand at present the mathematics, and the physical situations being explored, are increasingly out of students' reach.

4. THE SOLUTION – A THIRD PATH (AND MY PROPOSED HIRSCH GRANT PROJECT DETAILS)

Magma reservoirs are dynamic systems. As new magma injections inflate an existing reservoir they stress the surrounding crust, then those stresses gradually ease with time. In addition, hot magma gradually cools, resulting in volume changes that can also affect the surrounding material. As injections of magma continue to occur—a cyclical phenomenon documented at many active and long-dead systems around the world—magma reservoir systems thus seem to "breathe": they inflate a bit, then deflate, inflate, and deflate, and so on. This means that, over time, the surrounding rock is pushed and stressed, then relaxed, stressed again, then relaxed. *I hypothesize that this repeated loading and unloading of the crust during repeated magma injection cycles may introduce time-dependent fatigue effects that cause the rock to weaken and, eventually, rupture in ways no existing models have attempted to incorporate.* Conceptually, this process is akin to bending a paperclip: bend it hard once and nothing happens, but bend it back and forth repeatedly, just a bit each time, and it eventually weakens, then cracks and breaks because a little damage occurs with every small bend. It is the accumulation of small amounts of damage that causes the eventual failure.

What if the host rock surrounding a magma reservoir does the same thing in response to the cyclical inflation events we observe? It is reasonable to suppose that ring faults are (at least in part) a product of long-lived evolution of the magma reservoir system, a response to natural cyclicity in the loading that goes on, but is this cyclic loading process an *important* contributor? If so, it in turn may be controlled by very different factors than the ones we have investigated to date. For instance, is failure dependent upon the magnitude of the inflation events? We have constraints on magnitude from surface uplift at many volcanoes. What about the frequency of the inflation events (similarly constrained)? As faults begin to nucleate, will they reach a stage at which they shift from "subcritical" to "critical" growth, meaning that they transition from weakening the rock to the stage when formation of a major throughgoing fault occurs? How sensitive might this be to the depth of the magma reservoir, its size, the temperature of the magma, or the mechanical properties of the host rock within which the magma reservoir resides?

There is an abundance of literature examining subcritical weakening and the jump to critical failure from a materials science perspective, but to my knowledge this approach has never been used to examine the process of ring fault nucleation and growth. A compelling reason to remedy this situation is that, if fatigue accumulation helps prime a system for ring fault formation, it would imply that caldera-forming events could result after a prolonged history of mild magma injections, rather than requiring a single high-intensity and –volume magma injection event that drives the system directly to the point of catastrophic rupture "in one go." This, in turn, would mean that the probability for a caldera-forming event could potentially be much greater than we currently realize. Until the fatigue hypothesis is tested, we won't know how vital a role it has the potential to play.

DETAILED HIRSCH PROJECT DESCRIPTION & TENTATIVE SCHEDULE

During the proposed proof-of-concept test project I intend to explore the process of subcritical rock weakening and ascertain whether this mechanism has the potential to alter our understanding of ring fault nucleation mechanics and caldera formation in meaningful ways.

While the project idea clearly stems from my recent interest in caldera mechanics, this research task is otherwise a *completely new research path*, requiring me to explore and develop new mathematical methods and to understand the strengths and weaknesses inherent to a totally new numerical modeling approach. Without this exploration, and what I hope will be promising proof-of-concept results, there is little chance that I will be able to land external funding that would enable me to assess the mechanism and its role in full detail.

During my Spring 2017 sabbatical, if Hirsch grant funds are available to help offset the costs of the necessary software acquisition, I will strive to perform the following sequence of steps:

1) Refresh my somewhat-rusty recollection of subcritical weakening physics and mathematics, which I first began studying during Applied Engineering courses in graduate school at Brown University, and search more broadly for geological examples (e.g., in the field of earthquake mechanics) where similar techniques may have been used. This background effort will help prepare me to dive into the details of the numerical modeling software I will need to understand during performance of the study. <u>Schedule</u>: I anticipate this taking several weeks.
2) After acquiring the necessary software model extensions for COMSOL Multiphysics, the finite element modeling software I have used extensively for previous projects and with students, I will run through all pertinent tutorials, and seek clarification from the company's technical support staff concerning any questions I have. <u>Schedule</u>: I anticipate this taking 1-2 weeks.
3) Once I am comfortable with the basic operation of the software, I will test my abilities by striving to duplicate one or more analytically-constrained benchmark solutions in the literature. For example, solutions exist for cyclical fatigue accumulation around a hole in a repeatedly bent or heated steel beam, and if I can duplicate these solutions then I will have confidence that the software is operating properly and that I am using it correctly. [This sort of calibration is something I do at every step of a new modeling project. I tend to be

mistrustful of others' claims that model elements work as expected, and I don't like black boxes!]. Schedule: I anticipate this taking several weeks.

4) Finally, using a simple axisymmetric model with an appropriate (likely elasto-plastic) mechanical behavior appropriate for rock fatigue, I will build a reservoir model that permits me to cyclically inflate and deflate a simple reservoir in a half-space. It is difficult to know how long this will take until I get further into the project (my best guess is several months at least), but ultimately to have results I can feed into a proposal will require that I:

    a. Use a realistic rate of inflation and deflation, which I plan to constrain using cycles of rapid inflation and then gradual deflation observed at Kilauea caldera in Hawaii;

    b. Take into account temperature effects which, on their own and via poroelastic coupling, may independently help regulate the magnitude of the inflation and deflation events;

    c. Assess the accumulation of subcritical damage and the geometry of any critical crack growth that occurs, evaluating whether or not the results are consistent with known ring fault geometries; and finally,

    d. Use the model to systematically explore how different parameters (faster cycling, greater cycling magnitude, reservoir geometry and placement, host rock material characteristics, etc.) affect the eventual rupture of the rock—assuming of course that such rupture proves plausible! This stage of the project will, I think, prove to be the most student accessible, and I may seek to fold a SURP student (or two) into the modeling process in the Summer 2017 window.

If the proof-of-concept 2D testing described above is successful, and demonstrates that cycling-derived fatigue can indeed promote ring fault-like failure in the host rock surrounding a magma reservoir using a simple axisymmetric configuration (which is likely to yield a publication), then I will begin to prepare a new NASA proposal to pursue this work in greater detail, with a Stage 1 proposal deadline of October 2017 and (if encouraged for submission) a Stage 2 deadline in the late Spring of 2018. I target NASA for funding because my expertise deciphering the mechanics of volcanic and tectonic processes draws upon the geological record preserved on multiple planets (esp. Mars and Venus). The desired goal of the proposal, leveraging the test-run insights and my previous research results, will be to develop fully 3D models that examine the question of caldera formation from a time-dependent fatigue perspective; the exact focus, of course, will depend upon what my proof-of-concept results reveal about the processes involved and their sensitivity to different factors.

DETAILED HIRSCH PROJECT BUDGET

I am requesting funds to acquire three new computational modules for COMSOL Multiphysics, complementing others that are required for the new project direction that I already have in hand. The "Heat Transfer Module" ($895) will permit me to fold thermal effects into the experiment; thermal effects, as noted above, contribute to expansion and contraction of the host rock as hot magma is injected and subsequently cools, and I anticipate that this effect will play a significant role during fatigue accumulation based on engineering studies of other materials. The

“Subsurface Flow Module” ($795) will enable me to incorporate poroelastic effects; the amount of fatigue that occurs will depend upon how much pore space exists in the host rock, and the elasto-plastic response of the host will in turn depend upon the composition, quantity and temperature of the largely incompressible pore fluids circulating in these spaces. This again could sharply affect the amount of strain (damage) accumulated during each cycle of inflation and deflation. Finally, I am requesting funds for the “CFD Module” ($1695) which will enable me to consider dynamic fluid dynamic effects when simulating an injection. Rather than treat the reservoir contents as an idealized fluid (like water), which permits me to simulate the inflation process via an applied boundary condition (pushing outward on the reservoir wall), use of the fluid dynamic module may enable me to perform an actual injection into the chamber, with thick viscous fluid circulation then controlling the stresses applied to the wall rocks and the temperature distribution that results. The benefits of using this approach are not known; however, I would like to have the option to fold in this effect, though I would not do so until the other two module contributions and effects are fully explored.

Cost for all 3 Modules: $3385.00

Cost without CFD Module: $1690.00

As an additional comment to contextualize this funding request, my modeling for the past several years has been performed using a 2010 Mac Pro workstation. At a ripe old age (for computers!) of six years, this has become a limiting factor, and so for some time I have been saving funds from various sources to permit acquisition of a new computer in 2017, either a PC workstation or, if one is released in the near term and the specs are competitive, a new Mac Pro. [Note: one can’t request funds from federal agencies for desktop computers, so keeping my research computer and software up to snuff is always an interesting challenge!]. The expected workstation cost, initially, will exceed $10k, and my maintenance fees for the COMSOL software are another ~$2k per year. I share this information not because I am requesting assistance with these costs, but simply to communicate that I work hard to meet the expenses associated with my research, and do not request the software acquisition funds above lightly.

5. CONCLUSION

I have had considerable success in recent years acquiring funding from federal agencies, largely NASA, to perform my volcanology-focused research. A typical NASA grant for me covers a three-year window of time for ~$150k, and since I can acquire neither software nor computers for my work via these grants they focus primarily on salary and conference-related expenses for me and for the students with whom I work. Roughly one-fourth of the students who do advanced senior thesis work with me generate first-authored, peer reviewed journal articles published in top venues for my field, and most of these have focused on numerical modeling of volcanic processes.

If I was doing “more of the same” – i.e. simply adding more complexity to existing models as I try to identify the circumstances that trigger caldera-forming eruptions – I would not be requesting Hirsch funds, for I could pursue support for such an endeavor based on my proven track record. The complexity of my research at present however, as noted, is such that it has become difficult to fold in even talented undergraduate students, and for this reason plus the others arcticulated I hope to investigate a totally new process that may be involved in caldera formation, one that could address existing limitations. I won't know until I try whether fatigue effects will be important or not relative to other factors, so pursuing an external grant to support this work would be pointless as things now stand, but if proof-of-concept testing is successful past experience suggests the results will sharply enhance subsequent proposal competitiveness.

Thank you for your time and consideration! If I can answer any questions, or clarify any of the information provided above, please don't hesitate to let me know!