California Institute of Technology

Report of the Visiting Committee for the Division of Geological and Planetary Sciences

November 5-7, 2017

Contents

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Executive Summary

Caltech's Division of Geological and Planetary Sciences continues to be preeminent in the fields in which it works, on the basis of the continuing series of major awards and recognition accorded its faculty, the caliber of its students and postdoctoral scientists, and its sustained, innovative intellectual contributions. Recent faculty hires have effectively addressed long-term strategic objectives. GPS faculty contribute to a well-crafted multi-divisional strength in the science of extrasolar planets, and a new GPS-led initiative on climate modeling with an ambitious and novel focus on cloud physics holds promise for a distinctive contribution by Caltech to a problem of compelling societal importance. The Institute's program in Global Environmental Science is intellectually vital and exploits well the complementary capabilities of the Jet Propulsion Laboratory, but in the key area of atmospheric chemistry the seniority of the faculty and the current disinclination on the part of the Division of Chemistry and Chemical Engineering to hire new faculty in this area may mean that GPS will have sole responsibility for rebuilding the program in this critical discipline in the near future. The educational programs in GPS are outstanding at all levels; the one area that can be strengthened is the provision of advice to its students and postdoctoral scientists on career opportunities outside of academia. The gender mix among students in GPS is good, and the fraction of female faculty in GPS is improving, but concerted efforts should be made to recruit underrepresented people of color to both the student population and the faculty. GPS hosts several innovative and broadly utilized facilities of high impact, but securing long-term support for key staff scientists and for the maintenance and timely replacement of instrumentation and software remains a challenge of high priority. At the same time that the Division's computer cluster, critical to several GPS options, has aged beyond its nominal lifetime, the Institute is launching a new campus-wide central facility for high-performance computing. The decision by GPS to support the central facility while maintaining the existing divisional cluster as feasible makes sense until a full assessment of the central facility for meeting GPS needs can be made. The Division has made good progress on a new Strategic Plan, including the identification of disciplinary areas of particular promise for their scientific importance and potential for the crafting of multiple intellectual bridges with current faculty members. A component of divisional strategic planning rendered urgent by the recent announcement that one of the Division's lynchpin young faculty members in seismology will be taking a long-term leave of absence is the future of the Seismo Lab, for which hiring goals and the role of the Southern California Seismic Network in the research priorities of its faculty are important issues that will benefit from dedicated strategic introspection.

Section I:
Introduction

The Visiting Committee for the Division of Geological and Planetary Sciences met at Caltech on November 5-7, 2017. Prior to the meeting the Visiting Committee received a written charge from President Thomas Rosenbaum, a report on the Division from Chair John Grotzinger, the Division's most recent strategic plan led by Prof. Kenneth Farley, the report of the 2010 Visiting Committee, and information on the Division's academic programs, finances, demographics, and faculty.

On Sunday, November 5th, the Visiting Committee met first with President Rosenbaum, Provost David Tirrell, and Prof. Grotzinger to hear the administration's view of the Division and an overview of the Division's accomplishments and issues from the Chair. Visiting Committee members then joined the Division faculty for cocktails and dinner.

The Visiting Committee began Monday, November 6, in a breakfast meeting with postdoctoral scientists from the Division. The Visiting Committee met next in Arms Laboratory for presentations on the state of the Planetary Science, Geology, Geochemistry, and Geophysics options by Profs. Bethany Ehlmann, Paul Asimow, John Eiler, and Jennifer Jackson, respectively. The Visiting Committee joined selected Division graduate students and undergraduate majors for lunch in the Millikan Board Room. That afternoon, in the Seeley G. Mudd Building, the Visiting Committee heard presentations on the state of the Geobiology and Environmental Science and Engineering options by Profs. Alex Sessions and Andrew Thompson, respectively, as well as special presentations on planetary astronomy and exoplanets by Prof. Heather Knutson, Division academic affairs by Prof. Robert Clayton, and a new initiative on climate modeling by Prof. Tapio Schneider.

Following a working dinner on November 6 and a working breakfast on November 7, the Visiting Committee met on the morning of November 7 with President Rosenbaum, Provost Tirrell, and Chair Grotzinger for a briefing on the committee's findings and recommendations.

Section II.
Committee's Response to the Questions in the President's Charge

1. **How well is the division implementing its strategic plans? In the past few years the division has identified a number of new research foci and initiatives that are ramping up. Do these constitute viable new directions for the division to pursue, and do its existing programs provide a solid foundation to exploit future opportunities as they emerge?**

   With the hiring of Francois Tissot in Geochemistry, the Division has completed its last strategic plan laid out 7 years ago. It has embarked on two major initiatives, one on exoplanets and one in climate modeling.

   The exoplanet initiative – started as an opportunistic hire of Prof. Heather Knutson seven years ago – has blossomed into a particularly successful research community, one that has deep interactions between groups in GPS, led by Profs. Knutson and Konstantin Batygin, and PMA, led by Profs. Andrew Howard and Dimitri Mawet. As we understand it, all incoming graduate students this year in Planetary Science expressed the wish to pursue research in exoplanets.

This preference speaks to the vibrancy of this scientific area and to the Caltech strength of organically based collaboration across divisional boundaries. We applaud the exoplanet initiative.

The climate modeling initiative – with an initial focus on addressing the role of clouds by integrating high-resolution simulations of cloud formation with global climate models, observations, and machine learning – was launched by the return of Prof. Tapio Schneider a little over a year ago. This effort now involves collaboration with Prof. Andrew Stuart in computer science and Joao Teixeira at JPL. Prof Schneider's inclusive approach involves convening a series of international workshops to recruit participants from Caltech, JPL, and the broader climate modeling community. The project to transform Earth systems modeling is audacious and not without substantial risk. Its success will depend not only on engaging the enthusiastic support of faculty across the Division and close collaboration with JPL climate scientists, but also on engagement by key segments of the climate science community. Caltech's willingness to support this effort with private philanthropy will be critical. It is difficult to see how the Division can do this and maintain peak strength in each of its disciplines without some relief on a faculty cap of 40 (see also response to question #2). The Division may also have to face the real challenge of cutting back in some area that has been an historical strength. Nonetheless, the Visiting Committee agrees that Caltech, with its close connection to JPL, has the potential for doing something very important and so strongly supports this initiative.

Apart from these new initiatives, the plan going forward, as detailed in the Strategic Plan circulated to the Visiting Committee (also called the Farley report) and the presentation of Chair Grotzinger, seems to emphasize building on current strengths. The Division was still in the process of arriving at a consensus on hiring priorities at the time of our meeting. The fact that this prioritization is being done at a divisional level rather than through the individual options speaks to a distinctively strong and positive divisional culture given the Division's intellectual breadth.

A long-articulated hiring goal – since the departure of Prof. Barclay Kamb – remains unfulfilled in glaciology. An appointment is this area would likely provide interdisciplinary strength to Geology, Geophysics, and Environmental Science and Engineering and would come at a time when the fate of ice on our planet is of great societal concern.

2. **The program in Global Environmental Science has now matured significantly, with emphasis on climate science given two recent hires. We would appreciate receiving the visiting committee's overall assessment of Caltech's global environmental science program with particular emphasis on the contribution of all three divisions (GPS, CCE, and EAS) to its growth and development. Is the program taking advantage of opportunities to collaborate with JPL?**

The collaboration between JPL and GPS is strong across the Division, from Planetary Science to Geophysics, Geology, and Global Environmental Science. In GES, the recent hires of Profs. Christian Frankenberg and Jörn Callies should strengthen those ties further. The GPS-JPL partnership is particularly vital to the new initiative on cloud physics and climate modeling.

The Visiting Committee was provided with no information, however, about the plans of the Division of Chemistry and Chemical Engineering (CCE) or the Division of Engineering and

Applied Science (EAS) to replace faculty now active in the GES program upon their retirement. The Committee recommends that, in the absence of commitments from the other Divisions in this area, GPS should assume responsibility for staffing in key areas when these retirements occur, particularly in the area of atmospheric chemistry (see below).

3. The quality and effectiveness of the educational program and interactions between faculty and students (both undergraduate and graduate) are critical to Caltech's success. Is the GPS teaching program of uniformly high quality, or are there areas that could be improved?

The Visiting Committee gained an appreciation of the quality and effectiveness of the Division's educational programs in several ways. The committee received information on the programs ahead of our meeting as well as through the presentations by individual faculty members. Committee members also benefited from conversations with groups of undergraduates, graduate students, and postdoctoral scientists.

In general, the quality of the educational programs continues to be high across all levels. In particular, the data regarding the high enrollment numbers in Ge 1 are quite impressive. The marked increase in enrollment in Ge 1 is viewed in large part to have been the result of efforts by Prof. Paul Asimow to engage the students and prepare lucid course materials. The Committee recognizes that the increased enrollment in Ge 1 has been mirrored by an increase in enrollment in Ge 10. Overall, not only do these efforts enhance the exposure of the Caltech undergraduate population to geological and planetary sciences, but they have also led to greater interest in undergraduates pursuing majors within the Division.

Overall, the sentiments of the students with whom the Committee met were generally positive, and a sense of satisfaction was apparent across all student levels. In particular, the graduate students were quite happy with access to state-of-the-art instrumentation and the analytical capabilities available to them. Additionally, numerous opportunities for cross-disciplinary research were seen to be available. At the postdoctoral level, the prize fellowships represent an excellent opportunity to attract a pool of outstanding candidates into the Division.

Although the Division has been successful in preparing graduate students and postdocs for academic careers, as evidenced by the positions now held by alumni of those programs, career advising across all areas of the educational program (undergraduate to postdoctoral) was viewed by the Visiting Committee as an area where additional effort would enhance the overall experience for students. This perspective was informed by several factors, including input from postdocs, graduate students, and undergraduates, as well as the experiences of Visiting Committee members at their home institutions.

In particular, from discussions during our visit, the Visiting Committee learned that strong interest exists among the students in learning about career options outside of academia. A widely held view among postdocs and graduate students, however, is that some stigma is associated with the pursuit of a non-academic career path, and this attitude constitutes a barrier to discussion of the topic. The Visiting Committee recommends that the Division implement mechanisms to increase the exposure of its students to non-academic career paths, to provide a broad perspective on career opportunities available to them and to remove the perception that careers outside of academia are viewed negatively. The Division should

experiment with different approaches to learn which are most effective, but one route we recommend is that the Division involve students in the selection of a more career-diverse set of speakers for the Division-level seminar series. Involving students in selecting seminar speakers at the Division level could also serve to expand the number of women and underrepresented professionals in that series (see also response to question #4).

4. **Increasing diversity in the student, postdoc, and faculty populations is a significant goal at Caltech. Is the division making progress in diversifying these populations? Are the climate of the division and the efforts of the faculty appropriate in this regard?**

   The gender mix among students in GPS is good, and the number of women on the GPS faculty has grown from 7 to 9 since the last Visiting Committee meeting in 2010, although the female fraction of the faculty remains lower than at several peer institutions. Underrepresented students of color continue to be only a small fraction of the student population (a national issue for the geosciences), and the one underrepresented faculty member of color in GPS will soon be taking an extended leave of absence from Caltech.

   The Committee suggests a sustained process for recruiting a more diverse group of faculty. With the retirements anticipated over the next several years, a continuing priority on diversity should allow GPS to make progress on faculty diversity, whether the faculty are regularly searching for new talent across all fields of the Division or elect more targeted searches to fill strategic objectives.

   We applaud the efforts of Prof. Grotzinger to expand the number of underrepresented people of color among the Division's postdoctoral scientists and to support their career development. We recommend that the Division seek opportunities for parallel programs at the graduate-student level. We expect that the broad issue of diversity is campus-wide and should be addressed at that level to help all divisions succeed.

   It is the sense of the Visiting Committee, after our brief visit, that the working climate for women in GPS, including that for working mothers, is healthy and supportive. Several of the women in GPS are outstanding role models, and their experiences should be highlighted to undergraduates and graduate students. We were not able to acquire information on the climate for students and staff from underrepresented people of color.

5. **How do the Center for Microanalysis, Analytical Facility, and the new Murray Laboratory for Planetary Imaging meet the needs of the division? Are they succeeding as multi-user facilities that meet a diversity of scientific objectives?**

   The Division's multi-user facilities are heavily used both inside GPS and by a large number of researchers across the campus. The new Murray Laboratory for Planetary Imaging has added an exciting resource in the Division that enables new research capabilities in planetary science and other fields (e.g., Geology, Geobiology). The investment in data manipulation, analysis, and visualization has been wise and will substantially increase the impact of large and diverse planetary and terrestrial datasets.

   These facilities are successful because of the talented staff scientists who manage to keep them going with support levels that are not sustainable. Loss of any one of these individuals would be

truly problematic, because they provide substantial value to the research programs on which they work. Typically, equipment once purchased is rarely upgraded, and the same can be said for analysis software. This research support problem may be a common one across the Institute, and it is often addressed by the creation of a new center. When the Linde Center was established, for instance, it was envisioned as a source of such support. Because of the timing of the Linde gift relative to the economic downturn of the last decade, however, the Committee understands that there has been no money available from the endowment for this purpose. If nothing else, Caltech's current fundraising campaign should add to the Linde Center endowment to maximize its research potential. The alternative model for shared facilities is a fee-for-service structure, but such fees rarely cover the full cost of maintenance and upgrades. More importantly, large fees inhibit exploratory research, cross-campus access, and new collaborations in novel directions. The GPS faculty argued strongly and persuasively for a funding structure that enables support for the staff scientists and ready access to the facilities.

Section III.
Other Division-wide Topics

Division Leadership

As Chair of the GPS Division, John Grotzinger is doing an excellent job. The breadth and depth of his understanding of the strengths and challenges faced by each GPS option is outstanding. His ability to articulate each option's multi-faceted dimensions epitomizes his efforts to dig deeply into the current research portfolio, the dynamics within and between options, and the issues that GPS faces overall. He is a forceful and articulate advocate, and he is also a skilled listener and leader who quickly perceives problems and is adroit at seeking innovative, effective solutions. It is difficult to envision a more thoughtful and dedicated leader for GPS at this time.

Distribution of Faculty by Age

The GPS Division has an enviably broad distribution of faculty by age. When faculty ages are binned by decades, the mode of the population is the bin for 40–49 years in age, the number per bin falls off gracefully with increasing decade, and the bin for 30–39 years in age is well populated. These characteristics are in large measure the result of the laudable practice by the Division of hiring primarily junior faculty, nurturing those faculty members with sufficient resources for their professional careers to blossom early, and then providing a collegial and intellectually stimulating environment for all members of the faculty to continue to lead innovative research programs and recruit outstanding students and postdoctoral scientists.

Computation

High-performance computing is critical to the Division's research enterprise in Geophysics, Environmental Science and Engineering, and other disciplines. The Division's computer cluster has long been the workhorse system for such computing, but the system has aged beyond its nominal lifetime, and efforts to secure outside funding to replace and upgrade the capability have not been successful. In parallel, similar issues faced by other divisions at Caltech has led the Institute to launch a new campus-wide central computing facility, with an initial investment in hardware and a "substantial" user fee established to amortize the cost of future upgrades and

replacements. Division faculty are understandably uncertain if the central facility will offer sufficient computational capability at appropriate rates to be both efficient and cost-effective, but the decision to support the central facility, while maintaining the existing GPS cluster as well as is feasible, makes sense until a full assessment of the central facility for meeting GPS needs can be made after a suitable trial period.

On a more focused matter, it was noted by students that the lack of access to the Adobe Creative Suite of programs imposes a considerable financial burden on them. It is recommended that an institutional license be obtained to provide student access.

Section IV.
Reports on Individual Options

Environmental Science and Engineering (ESE) - Global Environmental Science (GES)

The Caltech-wide Environmental Science and Engineering (ESE) option covers a broad range of topics in the environmental sciences with faculty from GPS and the Division of Biology, CCE, and EAS. Here we focus primarily on Global Environmental Science (GES), which has grown to be a major presence in ESE and GPS. The Visiting Committee did not review the environmental engineering part of ESE.

The Committee commends Caltech for growing and developing a world-class climate program within GES. With the return of Prof. Schneider, the tenure promotions of Profs. Thompson and Simona Bordoni, and the hiring of Profs. Callies and Frankenberg, GES has completed the vision laid out 20 years ago to build a broad program with expertise in the chemistry and dynamics of both the atmosphere and the oceans. This young and vibrant group is making strides on all aspects of climate science. The GES faculty have developed a comprehensive curriculum that introduces students to the fundamentals of climate science. This program sets an example for educational programs in other academic institutions, most of which are still conceived within traditional disciplinary boundaries instead of embracing the interdisciplinary nature of climate science.

The future is bright for ESE. The committee fully endorses Prof. Schneider's proposal to spearhead an initiative to move climate modeling forward. The vision to develop new mathematical tools and train numerical models with available observations could prove transformative for climate science. Caltech, with its expertise in the Earth sciences and the computational and mathematical sciences, and JPL, with its expertise in the Earth sciences and in observing systems, are uniquely positioned to lead in this area. Beyond its scientific appeal, the initiative would benefit ESE by providing scientific focus to the group and fostering closer collaborations among faculty.

The ESE faculty are taking full advantage of the Caltech collaborative environment with strong research activities in paleoclimate, biogeochemistry, microbiology, landscape evolution, and underwater navigation technology. The connection to JPL, a concern in the past, is now very strong, with active research collaborations between the two research institutions (in particular through Profs. Callies, Frankenberg, Schneider, Thompson, Paul Wennberg, and Yuk Yung.)

Although ESE is in excellent shape at the moment, a few challenges loom on the horizon. First and foremost, the atmospheric chemistry program, arguably one of the strongest components of ESE (with Profs. Geoffrey Blake, Richard Flagan, Michael Hoffmann, Mitchio Okumura, John Seinfeld, Wennberg, and Yung), is in jeopardy. Most of the faculty members in this area are quite senior, and the primary affiliation for four of them is with CCE. Although the Visiting Committee did not hear directly from CCE during our visit, we were informed that there have been strong indications that there is no current intention to hire new faculty members in environmental chemistry, with that Division instead moving more toward a focus on biomedical and analytical chemistry. Atmospheric chemistry is at the core of climate science. It is imperative that Caltech maintain a strong expertise in atmospheric chemistry if it is to continue its climate program.

A similar situation (although without the participation of CCE) has developed in the field of planetary atmospheres, a field arguably created by pioneers at Caltech and JPL. Some impending retirements raise the question of how best to continue Caltech's leadership. ESE, and GES in particular, ought to be involved in this discussion, because talent in this field may be found in atmospheric programs, as well as in planetary science programs.

The committee agrees with the ESE and GPS faculty that glaciology is a key research area presently missing in their climate program. However, this field is somewhat limited and is one in which several top-tier academic institutions are trying to recruit new faculty. The best way forward to achieve this long-standing hiring goal may be to search more aggressively and globally for talent.

Geobiology

When the GPS Visiting Committee met in 2005, Geobiology was a fledgling option with an uncertain future. Today, the option is vibrant and fully mature – a leader in the global geobiology community. Each of the six faculty members with a primary Geobiology affiliation is highly regarded, and the option has been successful in attracting and training outstanding students. Each faculty member pursues his or her own research agenda, but some creative collaborations have developed between option faculty, especially in harnessing the analytical capabilities of Caltech geochemists to address microbiological questions. There is perhaps less intellectual flow from biology toward Earth science, but the potential is certainly there for further innovative partnerships. Option faculty and students have also collaborated creatively with geologists, geochemists, and planetary scientists in the Division.

Although stable and healthy, the option has thought about its future, presenting a number of possibilities for future growth to the Visiting Committee. Several of these speak to institutional opportunities in microbiology without necessarily enhancing the "geo" in geobiology. The Visiting Committee hopes that the option will develop more fully articulated opportunities for its future; in particular, we hope that the microbiology-heavy faculty will consider investing in a colleague who focuses on complex multicellular life. There are several reasons to consider such an expansion. To date, faculty who study Earth history have focused on the long Archean and Proterozoic eons. Whereas these together represent ninety percent of Earth history, the more recent Phanerozoic record encompasses ninety percent of available data on our biological and environmental past. Particularly in light of the Division's growing investment in climate and environmental science; the programs of faculty such as Prof. Jess Adkins, who studies

geochemical records encrypted in invertebrate animal skeletons; and the recent appointment of an evolutionary biologist at the Institute, a GPS faculty member who researches marine life on a scale of millions rather than billions of years could build excellence in new directions.

In closing, we note that the Caltech Center for Environmental Microbial Interactions (CEMI) has a great potential to bring together disparate faculty who study microorganisms. The Visiting Committee strongly endorses this innovative program, but echoes concerns of some Division faculty that administrative fundraising efforts may inadvertently subsume all of geobiology under the CEMI umbrella. While CEMI will benefit some option faculty a great deal and all faculty somewhat, the more geological aspects of geobiology remain in need of focused support.

Geochemistry

Starting in the 1950s, Caltech was without peer in the field of isotope geochemistry, with Profs. Clare Patterson (age of the Earth, provenance of lead in the environment), Jerry Wasserburg (age of the Moon, among many other firsts), Sam Epstein (stable isotopic studies), and Lee Silver (geochronology), to name a few of the most dominant figures of their generation. They all came to Caltech at about at the same time, and they all retired from active research at more or less the same time. That following the departures of all of these eminent leaders Caltech was able to develop comparable dominance in some of the most important new developments in isotope geochemistry (e.g., Prof. Kenneth Farley developing helium thermochronometry, Prof. John Eiler developing novel methods and applications of clumped-isotope geochemistry) is truly remarkable. The other faculty members in geochemistry, Profs. George Rossman (mineralogy), Geoffrey Blake (spectroscopic characterization of molecules of astrophysical interest), and Jess Adkins (geochemical oceanography), are also significant leaders in their respective fields. The appointment of Francois Tissot to the faculty is the culmination of a 20-year effort to broaden the scope of geochemistry at Caltech by adding the capability to study heavy-element radionuclides and their application to both terrestrial and cosmochemical problems. Given these developments, there seems to be no urgent need for an additional appointment in geochemistry at this time.

An important attribute of the geochemistry program is exceptional instrumentation, both in individual labs and in shared facilities. The GPS Analytical Facility and the Center for Microanalysis have become major resources for research across the entire Division that enable highly innovative new research that crosses disciplinary boundaries. A good example is the submicron-scale imaging of isotopic labels in bacterial communities, which was certainly not anticipated at the time the Center for Microanalysis was originally proposed and funded. Also noteworthy are the efforts to develop new analytical instrumentation. These efforts include a collaboration with Thermo-Fisher to further develop mass spectrometers for isotopologue studies, geochemical instrumentation for in situ planetary exploration, bench-top ^{14}C analyses, and terahertz time-domain spectroscopy for astrochemistry. A good measure of the distinctiveness of the instrumentation initiatives is that 11 patents have been filed or awarded over the last several years.

The geochemistry group serves the entire GPS community by running the GPS Analytical Facility and the Center for Microanalysis. The latter was established with funds provided by the Moore gift, and it has greatly exceeded expectations both in terms of how it has affected research across the entire division and in the development of novel and unanticipated

applications. Because of this successful history, a very good claim for some level of continuing institutional funds to support its operation can be made. To demand that these two facilities be funded entirely by user fees would be shortsighted and damaging, in that doing so would reduce access to the facilities and make it less likely that they would be utilized to explore risky, but potentially highly rewarding, applications.

Geology

Two "events" have dominated the Geology option over the past 7 years. Following the landing of the Curiosity rover on Mars in 2012, its successful exploration of Gale Crater has greatly expanded Geology's high-profile contribution to planetary science, with major contributions coming in the areas of geomorphology, sedimentology, and petrology. These efforts promise to continue and will undoubtedly be further augmented by the Mars 2020 rover mission. In contrast, as funds for the Tectonics Observatory were expended, significant adjustments were necessitated within both the Geology and Geophysics options.

Since the 2010 Visiting Committee report, the addition of Prof. Claire Bucholz has expanded the igneous petrology program in the Geology option, and the return of Prof. Jean-Philippe Avouac after a brief absence has served to renew the strength in integrated tectonics within the option. With Prof. Jason Saleeby's retirement, the option has lost a skilled field and regional geologist.

Although the 2010 report on the Geology option recommended an "ice dynamics hire sometime over the next five years," this unfulfilled goal has persisted now for more than a decade, indeed since the retirement of Prof. Barclay Kamb 20 years ago. Both the ESE and Geophysics options have also expressed the desire to hire in glaciology. Even though several GPS faculty members in Geophysics (Profs. Mark Simons, Victor Tsai, Zhongwen Zhan), ESE (Prof. Thompson) and Planetary Science (Prof. David Stevenson) work on aspects of the cryosphere or icy satellites, a full-time glaciologist with a strong field component to his or her research would knit those efforts into a much more visible and coherent program. Given the importance of ice-sheet dynamics to the topics of climate change and sea-level rise, recruitment efforts in this area appear warranted.

Although no retirements appear imminent, the Geology option has articulated, but not prioritized, hiring goals that extend beyond glaciology to fault and rock mechanics, mineral sciences (in the form of a "card-carrying" mineralogist), and geochronology with a possible emphasis on dating the matrices of sedimentary rocks. Mechanics would build bridges to Geophysics and particularly seismology, whereas sedimentary geochronology would likely become a significant contributor to the upcoming Mars rover mission or any future mission that returned samples from Mars.

In an era when specialization is increasing and remote-sensing and instrumental approaches are burgeoning, it will be important within the Geology option not to lose its historical emphasis on field geology. Correct interpretation of the explicit context from which samples were collected forms the necessary prerequisite to proper interpretation of their significance. Hence, mapping and field courses for both undergraduate and graduate students should be sustained.

GPS's reputation for excellent (but short) field courses has led to augmented enrollment over the past several years. Ge 1 now serves 120–140 students per year and is apparently the largest

elective class on campus. Ge 10, a field-based research seminar, has more than tripled in size. We heard from some graduate students that they didn't take the weeklong field courses that were offered during the term because such participation would force them to miss lectures in other courses. Unfortunately, it is just such courses extending over multiple days that provide the opportunity to learn from mistakes and cement best practices. Perhaps some effort could be made to coordinate such weeklong field courses more effectively with other classes.

Geophysics

The last GPS Visiting Committee in 2010 raised several issues for the Geophysics option: (1) the imperative to hire an observational seismologist, repeated from an earlier Visiting Committee recommendation but rendered more urgent by the then-recent retirement of Prof. Hiroo Kanamori, the departure of Prof. Jeroen Tromp, and the fact that the research foci of the then-most-recent additions to the seismology faculty (Profs. Jean-Paul Ampuero and Victor Tsai) were primarily theoretical or computational, (2) the need to preserve the most fruitful activities of the Tectonics Observatory following the anticipated ending of Moore Foundation funding, (3) the importance of identifying research priorities in seismology that exploit data from the remarkable attributes of the Caltech-USGS Southern California Seismic Network, and (4) the need to renew computational resources, given the lifetime of hardware in the Beowulf computer cluster then in place. All of these issues remain, albeit some in modified form.

The hiring of Prof. Zhongwen Zhan in 2015 addressed the longstanding recommendation to add an observational seismologist with wide scientific interests. Nonetheless, the Visiting Committee learned only during our visit of the long-term leave of absence planned by Prof. Jean-Paul Ampuero. Coming closely after the retirement of Prof. Don Helmberger, and notwithstanding the success of the Division at luring back to Caltech several other faculty who left in recent years, the departure of Prof. Ampuero along with the uncertain time of his return is of concern to the carefully conceived plan to rebuild the Seismological Laboratory with the targeted hiring of outstanding young seismologists. As part of the ongoing strategic planning process now underway in the Division, we recommend that particular attention be paid to the future of the Seismo Lab. For nearly a century, the Seismo Lab has been an international leader in earthquake seismology and global Earth structure, known across the world as a powerhouse in the field. Caltech would be wise to preserve the best features of that institution, including the brand name, but given recent changes to both faculty membership and the discipline, a broadly thoughtful and introspective analysis of priorities for the future would be a particularly good investment at this time.

Although the end of Moore Foundation funding for the Tectonics Observatory was long anticipated, efforts ahead of that event to secure funding from other sources were not sufficiently successful, and the Observatory was terminated in 2014. The activities of that project that brought geologists, geophysicists, and climate scientists across the Division together regularly to address common problems in the geology of actively deforming areas, as well as the education of a number of students and early-career scientists in multidisciplinary approaches to tectonic studies, are deeply missed. Some effort should be made to revive the cross-GPS interactions that were one of the most fruitful products of the Tectonics Observatory.

The Community Seismic Network, led by Prof. Robert Clayton in GPS and developed jointly with EAS, constitutes an innovative approach to large, dense, and low-cost seismic networks for real-

time analysis of ground motion and damage for first responders following a large local earthquake. A partnership with the Los Angeles Unified School District offers a special opportunity for education and community engagement on top of public safety and science. The Visiting Committee was intrigued, too, by reports of new efforts by Prof. Zhan to develop "dark" portions of fiber optic cables into extremely high-density networks of strainmeters. Balanced against these opportunities is the continuing need to manage, operate, and maintain the Southern California Seismic Network (SCSN), the current backbone of the seismic monitoring system for southern California earthquakes. Although the Visiting Committee heard brief statements about ideas for integrating all of the geophysical networks into an efficient whole, we heard substantially more about the challenges to securing funding and personnel, particularly once Research Professor Egill Hauksson retires, to keep all of the networks running effectively. The importance of the SCSN and other local networks to the Division is in proportion to the number of scientific priorities of GPS faculty that are being and will be met by data from those networks. The role of Caltech in managing existing networks and developing new networks should be a key element of the strategic planning process for the Seismo Lab.

The need to renew computational resources for the Geophysics option is once again paramount, and recent efforts to secure federal funding to upgrade the Division's computer cluster were not successful. As addressed at greater length in the body of the main Visiting Committee report, a new campus-wide central computing facility may offer capabilities now met by the Division's cluster, but the latter should be maintained to the extent feasible while the ability of the new central facility to meet the needs of the option is carefully assessed.

Planetary Science

The faculty members in the Planetary Science option are world leaders in both solar system science and exoplanets (the latter with PMA). Future leaders in the science of exoplanets will benefit from strong training in solar system science, so with its cross-divisional expertise in exoplanet research Caltech is well positioned to continue a dominant role in this field.

As identified in the Farley report, the approaching retirement of three faculty members who have had broad research programs in core disciplines of Planetary Science will significantly change the landscape of solar system studies in GPS. Future hiring in planetary science should maintain essential strengths in solar system science and exploration while reshaping the disciplinary emphasis to anticipate the coming decades of planetary discovery. The tradition of hiring young scientists who take advantage of the opportunities enabled by collaboration with JPL is a good model for future searches, because the field of Planetary Science continues to be driven by exploration and discovery.

As noted in the 2010 Visiting Committee report, faculty members in Planetary Science have historically pursued independent research programs. Since the last Visiting Committee, the newest faculty have fostered more informal interactions within the Planetary Science option, including new research collaborations. The recent initiative on exoplanets has been particularly successful at building a strong research community, one with deep interactions between groups in GPS, led by Profs. Heather Knutson and Konstantin Batygin, and PMA, led by Profs. Andrew Howard and Dimitri Mawet. A wider variety of multidisciplinary bonds are encouraged, particularly those that arise organically. For example, targeted topical reading seminars provide broad training for students and postdocs while creating opportunity space for collaborations.

The joint appointment of Prof. Bethany Ehlmann in GPS and at JPL provided unique and productive early-career opportunities for her involvement in spacecraft missions and payload instrument development. The Division's mentorship of young faculty in such positions should include guidance and feedback on issues related to funding new initiatives between the campus and JPL.

Caltech's strengths in geobiology, sedimentary geology, and geochronology have enabled the Institute to take a leadership role in innovative investigations of the Martian surface through the Mars Exploration Rovers and the Curiosity rover. These cross-disciplinary collaborations, some of which arose from the Keck Institute for Space Science, should continue to be supported.

Strength in Planetary Science is intimately tied to strength in geoscience. The faculty in Planetary Science should call upon their colleagues' expertise in education related to foundational geoscience areas, in addition to drawing their colleagues into planetary research and spacecraft operations.

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