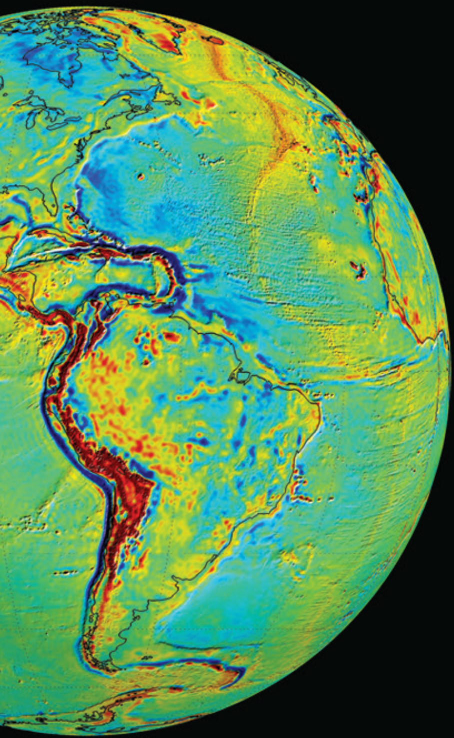
National Aeronautics and
Space Administration

Report from the NASA Earth Surface and Interior (ESI)
Focus Area Workshop, November 2–3, 2015, Arlington, Virginia



CHALLENGES AND OPPORTUNITIES FOR RESEARCH IN ESI (CORE)

COVER: THE GRACE INTERMEDIATE FIELD 48 (GIF48) MODEL IS AN IMPROVED MEAN GRAVITY FIELD THAT COMBINES GRACE OBSERVATIONS AND TERRESTRIAL GRAVITY INFORMATION FROM THE DTU10 GLOBAL GRAVITY FIELD. SHOWN HERE ARE THE SO-CALLED FREE AIR GRAVITY DEVIATIONS FROM AN IDEAL ELLIPSOIDAL EARTH MODEL. WARM COLORS DEPICT AREAS WHERE THE ACTUAL GRAVITY FIELD IS LARGER THAN THE FEATURE-LESS-EARTH MODEL PREDICTS. COOL COLORS INDICATE PLACES WHERE THE GRAVITY FIELD IS LESS THAN THIS MODEL. SHADING CORRESPONDS TO ACTUAL TOPOGRAPHY/BATHYMETRY.

FIGURES COURTESY OF F. LANDERER, JPL, BASED ON GIF48 FROM UT-CSR.

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Initial drafts of this report were publicly available, and additional comments by members of the scientific community improved the text.

The committee thanks B. R. Phillips for his guidance and vision.

NOTES

Preferred citation: Davis, J. L., L. H. Kellogg, J. R. Arrowsmith, B. A. Buffett, C. G. Constable, A. Donnellan, E. R. Ivins, G. S. Mattioli, S. E. Owen, M. E. Pritchard, M. E. Purucker, D. T. Sandwell, and J. Sauber (2016), Challenges and Opportunities for Research in ESI (CORE): Report from the NASA Earth Surface and Interior (ESI) Focus Area Workshop, November 2–3, 2015, Arlington, Virginia, 88 pp.

Note on acronyms: Many acronyms, especially names of satellite missions, observing systems, techniques, projects, and organizations, are not defined in the text. Appendix D contains a complete list of acronyms used throughout the report.

Note on figure citations: Figure citations appear before Appendix A.

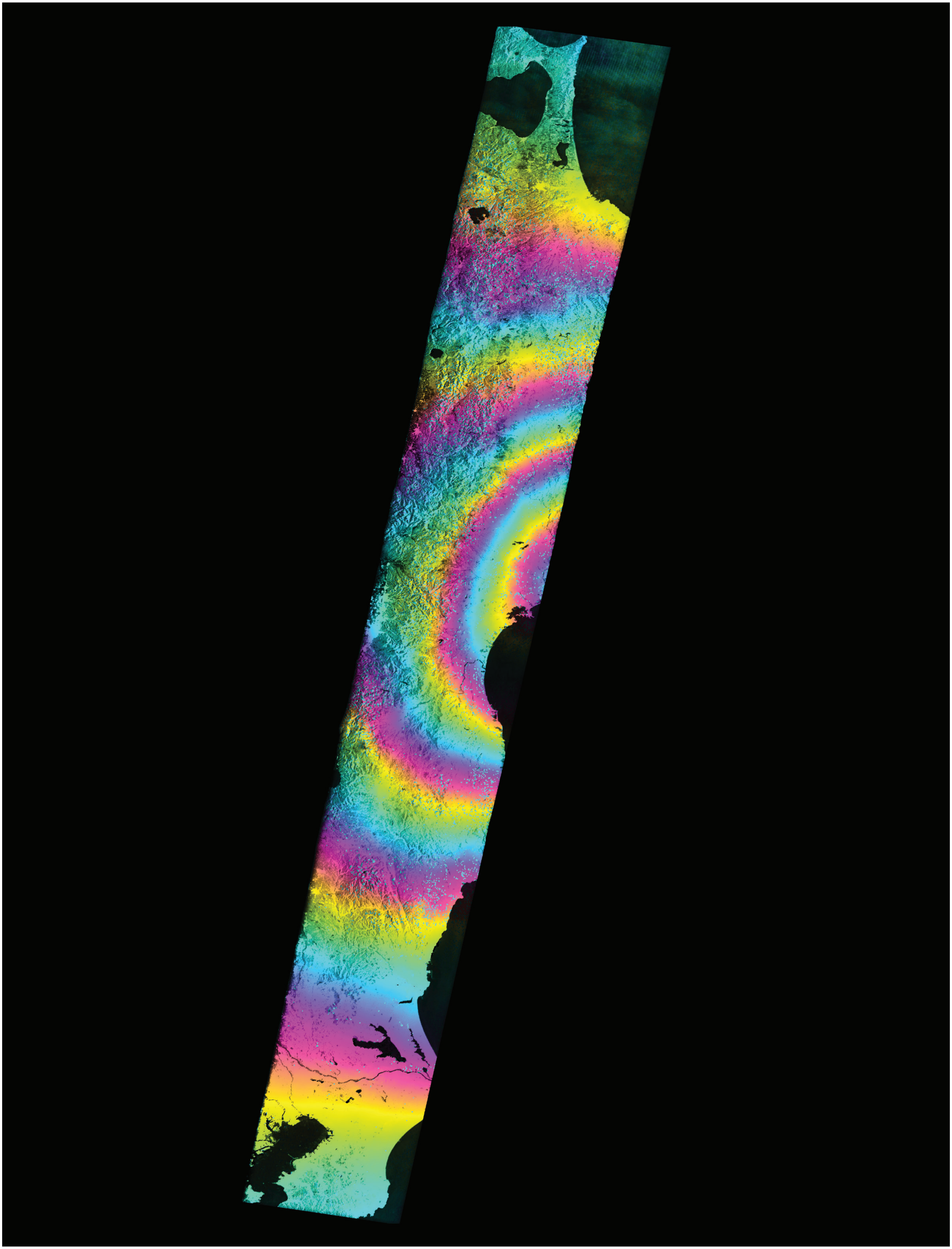
CHALLENGES AND OPPORTUNITIES FOR RESEARCH IN ESI (CORE)

This report is based on discussion and submitted white papers for the NASA Challenges and Opportunities for Research in ESI (CORE) Workshop, held on November 2–3, 2015, in Arlington, Virginia.

Financial support for the CORE workshop and publication of this report was provided by the National Aeronautics and Space Administration, Earth Science Division, Earth Surface and Interior Focus Area.

TABLE OF CONTENTS

LEFT: SEAWIFS IMAGE OF THE PACIFIC NORTHWEST.



CHAPTER 1

EXECUTIVE SUMMARY

The purpose of the NASA Earth Surface and Interior (ESI) Focus Area Workshop, Challenges and Opportunities for Research in ESI (CORE), held on November 2–3, 2015 in Arlington, Virginia, was to engage a broad representation of the solid-Earth science community in discussion, revisiting and updating the 2002 Solid Earth Science Working Group report "Living on a Restless Planet" (the SESWG Report). The SESWG Report presented a 25-year vision for the NASA solid-Earth science program. The goal of the current report is to synthesize the workshop discussion and assess scientific progress on the questions that form the core of the vision articulated in the SESWG Report, to evaluate the impacts of changes in technology and operational systems, and to revisit challenges and opportunities for NASA solid-Earth science in light of scientific progress and new capabilities realized over the past decade.

By and large, the SESWG Report remains a vital and scientifically significant document. In discussions on the progress in solid-Earth science over this last decade, however, several overarching themes emerged for taking the science forward:

1. Earth science continues to become more interdisciplinary; new approaches to problems in solid-Earth science often require understanding of multiple Earth systems and observations and models that connect interacting components.
2. Advances in technology, particularly growing availability of data and advances in computational and communication capabilities, have transformed our experimental approach, placed new requirements on data analysis and modeling, and expanded the frontiers of observation.
3. We better understand that humans fundamentally interact with, and are influenced by, the processes that shape the solid Earth; understanding the impact of human activities and their interaction with natural Earth systems can both benefit society and provide avenues for innovative research.

These changes in scientific viewpoint and better understanding of the connections between complex interacting systems prompted us to revise and update the six primary science challenges, posed as questions in the SESWG Report (see below). A new challenge also emerged, directly addressing how humans interact with the solid Earth.

LEFT: CO-SEISMIC INTERFEROGRAM DEPICTING GROUND DISPLACEMENT RESULTING FROM THE 2011 TOHOKU EARTHQUAKE.

REVISED PRIMARY SCIENCE CHALLENGES EMERGING FROM THE NASA CORE WORKSHOP

1. What is the nature of deformation associated with plate boundaries and what are the implications for earthquakes, tsunamis, and other related natural hazards?
2. How do tectonic processes and climate variability interact to shape Earth's surface and create natural hazards?
3. How does the solid Earth respond to climate-driven exchange of water among Earth systems and what are the implications for sea-level change?
4. How do magmatic systems evolve, under what conditions do volcanoes erupt, and how do eruptions and volcano hazards develop?
5. What are the dynamics of Earth's deep interior and how does Earth's surface respond?
6. What are the dynamics of Earth's magnetic field and its interactions with the rest of Earth's systems?
7. How do human activities impact and interact with Earth's surface and interior?

The white papers, talks, and in-person discussion at the workshop provided examples of major scientific accomplishments of the last decade related to the NASA solid-Earth science program. Chapter 2 of this report highlights these and other scientific accomplishments. These should be seen as representative examples, and not a comprehensive review of noteworthy accomplishments in solid-Earth science since the SESWG Report. Chapter 2 also outlines a number of scientific opportunities for the next decade. These represent both new questions emerging from the past decade of scientific research, and research opportunities that build on new technologies, initiatives, and computational and observational capabilities.

The past decade has seen profound advances in solid-Earth science, and has opened new avenues of research. The workshop revealed key opportunities that will greatly benefit from continued investments in mission science and modeling efforts, new observational systems, and advances in modeling and analysis. These are discussed in Chapter 3 and summarized in Table 1. In addition, Chapter 3 discusses utilization of new science-enabling technology, and consideration of strategies for interdisciplinary collaboration across disciplines, programs, agencies, and nations.

TABLE 1: ACCOMPLISHMENTS, ONGOING EFFORTS, AND FUTURE OPPORTUNITIES IN OBSERVATIONAL STRATEGIES FOR ADVANCING NASA SOLID-EARTH SCIENCE GOALS. THE FOCUS OF THIS TABLE IS ON NASA ESI PROJECTS AND MISSIONS HIGHLIGHTED WITHIN THE REPORT, AND IT IS NOT MEANT TO BE REPRESENTATIVE OF THE WIDER EARTH SCIENCES IN GENERAL.

Observational strategies	Last 10 years	In progress/under study	Next 10 years and longer	Plate Boundaries	Land Surface Change	Climate Interactions	Magmatic Processes	Mantle Dynamics	Magnetic Field	Human Activities
Earth rotation and terrestrial reference frame (TRF)	**Space Geodesy Project** • Development of next-gen systems for VLBI and SLR • Goal of 1 mm, 0.1 mm/yr • International services	**Space Geodesy Project** • Deployment and testing of next-gen systems • Deployment of multi-technique geodetic stations • Improved temporal resolution: <1 year **Collocation in space**	**Long-term continuous operation of up to 11 NASA sites** **Improved temporal resolution of global geodesy: ~1 day**	■	■	■	■	■	■	■
Surface deformation	**Dedicated US InSAR satellite delayed but now in pipeline** **UAVSAR** **Terrestrial-based GNSS** • Increased use of high-rate, low-latency raw data streams • Improved accuracy of "GPS Seismology" • Measurements of elastic and viscoelastic loading (GIA) • Collocation with tide gauges and sea surface altimetry control/calibration locations	**NISAR (2020)** • L-& S-band repeat-pass polarimetric InSAR **Terrestrial-based GNSS** • Improved accuracy at high frequencies • Improved understanding of long-term systematic errors	**InSAR Constellation** • Improved temporal resolution, spatial coverage, accuracy **Terrestrial-based** • Improved access to seafloor geodesy • Near-real-time global access • Improved spatial coverage	■	■	■	■	■		■
High-resolution topography	**STRM** • 2002: 90 m resolution • 2015: 30 m **GDEM** **ICESat (2003-10)** • cm-level vertical profiles	**STRM** • Reprocessing 2016–17 **ICESat-2 (2017)** • cm-level multibeam profiles **Cryosat-2 (bathymetry 2010-17)** **LVIS facility** **Airborne Swath laser** • cm vertical accuracy	**SWOT bathymetry (2020)** **Satellite global land surface mapping** • 5 m horizontal, decimeter vertical • Vertical structure and "bald" Earth topography	■	■	■				■
Variability of Earth's magnetic field	**SWARM (ESA): 2013–** **Orsted (DK-US): 1999–** **CHAMP (Ger-US): 2000–10** **SAC-C (multinational): 2000–05** **ST-5 (US): 2006** • Development of modularized instrument package to facilitate missions of opportunity	**SWARM, ongoing** **Mesospheric magnetic fields from ground-based observatories** • Guidestar laser system • Miniaturization of helium scalar-vector magnetometer	**12-satellite constellation** **CubeSat** **Suborbital**					■	■	■
Variability of Earth's gravity field	**GRACE (2002–present)** • Present-day surface mass changes up to degree/order 60 • SLR constrains lowest-order terms in geopotential	**GRACE-FO (2017)** • Demonstrate laser interferometry ranging system • Calibrate existing de-aliasing models with GRACE • Examine spaceborne gravity gradiometer technologies	**GRACE-II (2020?)** • Multiple satellite-to-satellite tracking capabilities	■		■	■	■		■
Imaging spectroscopy of Earth's changing surface	**Airborne VSWIR: AVIRIS** **Airborne TIR: HyTES** **Spaceborne VSWIR: Hyperion** **Spaceborne VNIR: HICO**	**Spaceborne VSWIR** **HyspIRI (US)** **EnMAP (Germany)** **HSIU (Japan)** **PRISMA (Italy)**	**HyspIRI (2023)** **Imaging airborne spectrometers spanning multiple wavelength regions**		■	■	■			■

CHAPTER 1

INTRODUCTION

In 2002, the NASA Solid Earth Science Working Group (SESWG) set down a strategic plan for the NASA solid-Earth science program. That document, "Living on a Restless Planet" (hereafter the SESWG Report), has provided core guidance for program development and a scientific rationale for NASA missions with a solid-Earth science component. In summer 2015, a working group with broad expertise and positions within and outside of NASA was formed with the purpose of organizing a workshop whose participants would review scientific and technological progress since the SESWG Report, review and update the scientific drivers, and outline opportunities for the solid-Earth science program going forward.

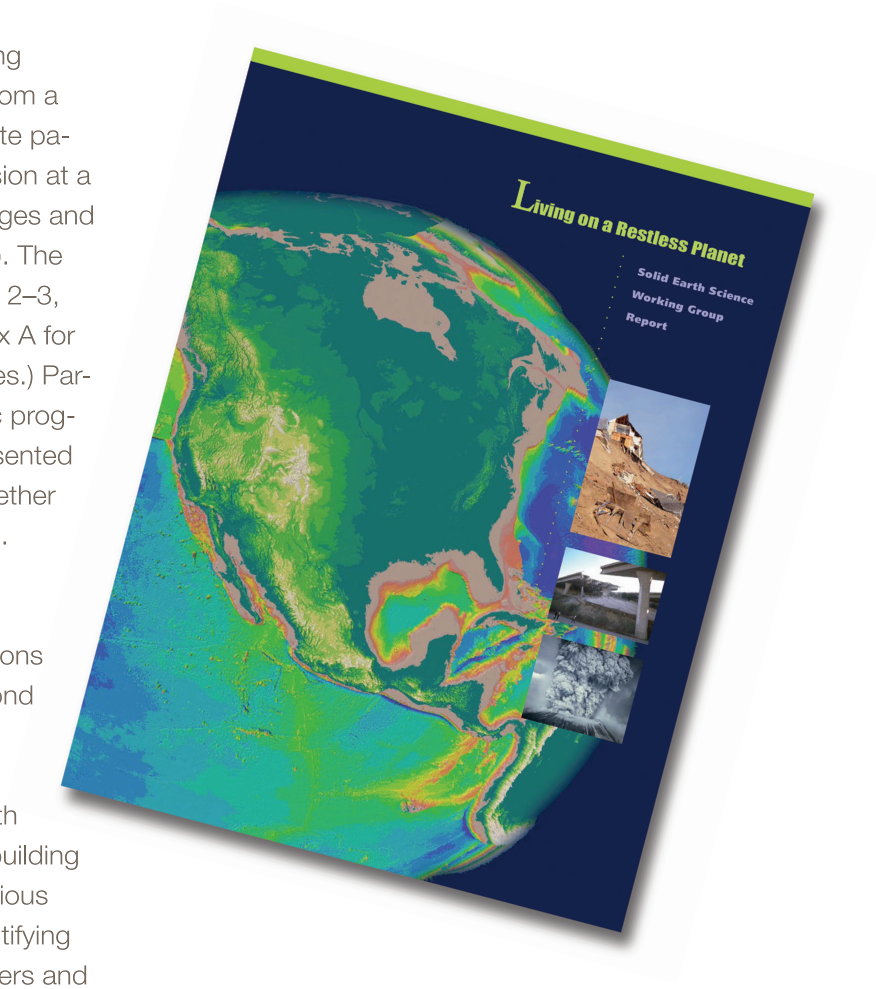
LEFT: MODIS ON TERRA CAPTURED DATA USED TO CREATE THE SPECTACULAR "BLUE MARBLE" IMAGES OF EARTH.

In revising the SESWG Report, the working group obtained contributions and input from a broad community of Earth scientists. White papers were solicited to help inform discussion at a planned two-day workshop titled Challenges and Opportunities for Research in ESI (CORE). The CORE Workshop was held on November 2–3, 2015, in Arlington, Virginia. (See Appendix A for the workshop agenda and list of attendees.) Participants were asked to evaluate scientific progress on the six "Science Challenges" presented in the SESWG Report and to discuss whether the list of challenges requires any revision.

On the first day, attendees of the CORE Workshop participated in break-out sessions defined by these challenges. On the second day, attendees were divided into twelve groups that participated in roundtable discussions on twelve different topics, with each round of discussion (after the first) building on discussions held on that topic by previous groups. The topics were selected by identifying themes that emerged from the white papers and by reviewing the discussion of the first day.

The themes were presented for discussion at a Town Hall at the 2015 Fall Meeting of the American Geophysical Union. The working group reconvened in February 2016 to complete a draft report. The draft report was made available for public comment and was formally reviewed by a panel of experts (see the inside front cover). The final report includes changes based on both the public comments and the formal reviews.

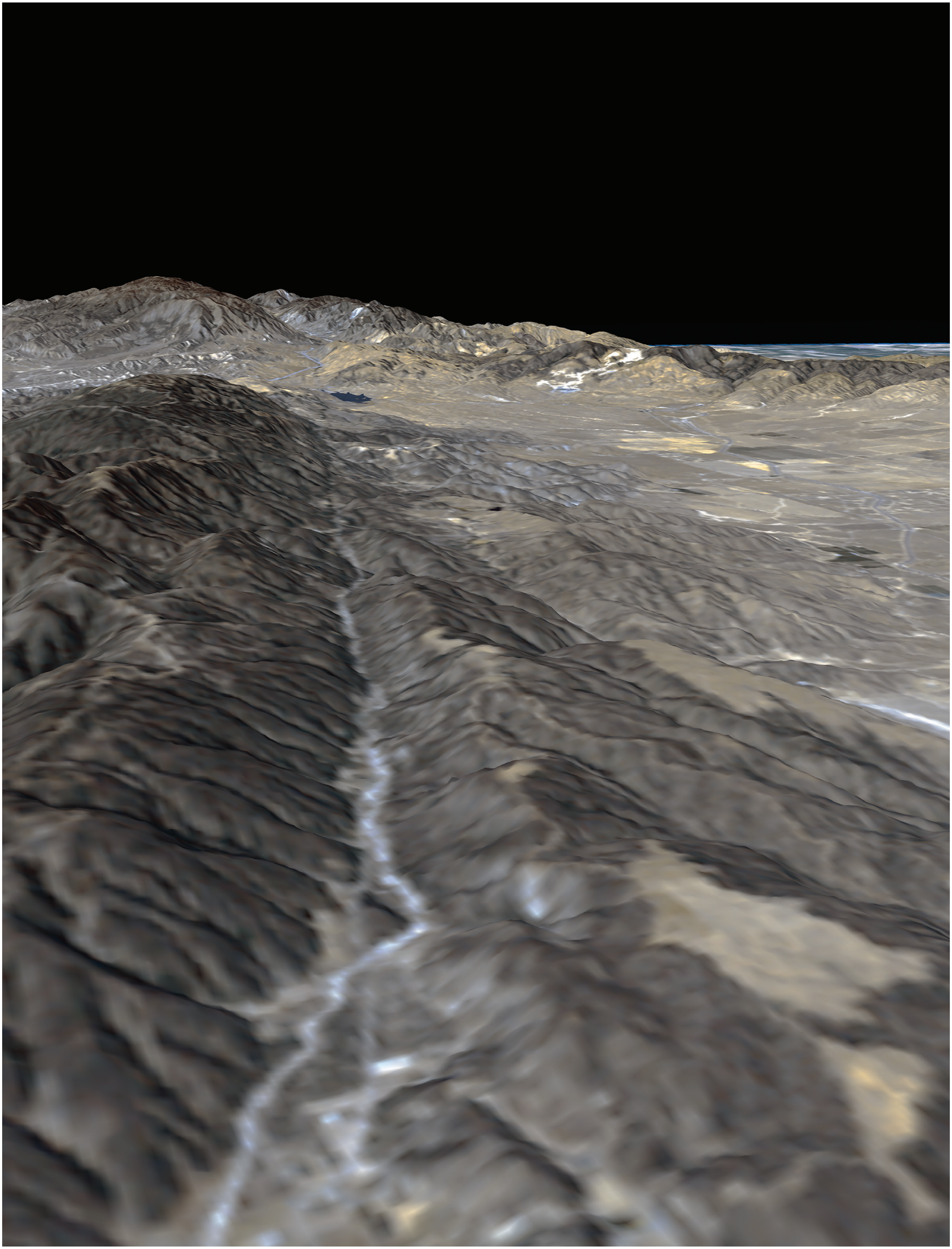
The past decade has produced remarkable insight into the interconnected processes driving change of Earth's surface and interior on human to geologic time scales, accompanied by rapid technological and societal changes that provide a deeper perspective on the human impact of the solid Earth's systems. Since 2002, geological events including numerous great earthquakes and large tsunamis have had enormous impact, as have smaller geologic events with disproportionate human impact such as the 2010 M7.0 Haiti earthquake and the 2010 Eyjafjallajökull volcanic eruption in Iceland. These events highlight both the increased risk to humans from Earth's hazards



IN 2002, THE NASA SOLID EARTH SCIENCE WORKING GROUP (SESWG) SET DOWN A STRATEGIC PLAN FOR THE NASA SOLID-EARTH SCIENCE PROGRAM. THAT DOCUMENT, "LIVING ON A RESTLESS PLANET," HAS PROVIDED CORE GUIDANCE FOR PROGRAM DEVELOPMENT AND A SCIENTIFIC RATIONALE FOR NASA MISSIONS WITH A SOLID-EARTH SCIENCE COMPONENT.

and the need for scientific data and models to enhance resilience. Space-based observations and the associated modeling fueled the scientific and human response to these events and enabled scientific discoveries about the underlying processes. New technological capabilities make it possible to collect and model large data sets, and to carry out large computer simulations; near-real-time access to data has enabled rapid response to geologic events, and has become an expectation of both scientists and the general public. Nevertheless, infrastructure challenges remain, such as how to maintain a robust geodetic network. Looking beyond our own planet, planetary missions to Mars, Mercury, and beyond, and the discovery of thousands of planets external to our solar system, provide an additional appreciation for and perspective on Earth's surface and interior.

The purpose of this report differs in several respects from that of the SESWG Report. First, this report takes extensive advantage of the existence of the SESWG Report, which lays out a detailed long-range plan for the solid-Earth science program. Many of the major scientific questions posed by the SESWG Report remain valid, and this report does not therefore need to restate the earlier content. In addition, it was felt that this report should adhere to the overall structure of the SESWG Report. Significant major science advances have stemmed from ESI science since the SESWG Report, and one of the goals of the workshop was to identify these updates. A number of areas were also identified, however, in which our thinking had evolved significantly regarding interaction among Earth systems, the boundaries between different subfields within Earth science, technological approaches, and new avenues of scientific inquiry. Thus, this report fills the dual purpose of looking back over the last decade to summarize the evolution of the science, while also looking forward to appropriately reframe solid-Earth science program goals for the coming decade, and identify opportunities and observational approaches not evident or available at the time of the SESWG Report.



CHAPTER 2

SCIENTIFIC CHALLENGES FOR NASA'S SOLID-EARTH SCIENCE PROGRAM

2.1

What is the nature of deformation associated with plate boundaries and what are the implications for earthquakes, tsunamis, and other related natural hazards?

GOALS

Measure spatio-temporal deformation at plate boundaries to determine how mantle and lithospheric processes couple to crustal faulting

Better define material properties along and around faults

Determine material properties and mechanisms of deformation in Earth's crust and on faults to understand evolution of stress and failure in earthquakes or aseismic deformation

Improve integration of surface displacement fields, hypocenters, and mapped faults with known or inferred material properties with physics-based models for elastic and anelastic strain accumulation and release prior to, during, and after all seismic events M > 5

LEFT: A PERSPECTIVE VIEW OF THE SAN ANDREAS FAULT CREATED WITH SRTM DATA.

Significant progress on understanding the nature of plate boundary deformation has occurred since the SESWG Report, particularly in space geodetic measurement, on a wide range of scales from local and regional to global, of relative plate motion and intraplate deformation; the focus on temporal variability of deformation (see below) has also expanded greatly. (Note that while this section focuses on plate boundary deformation, nearly all of the science challenges include a component of surface deformation.) The exact processes that drive tectonic plates are still not fully understood. Plates may be driven from their edges, or from their base. Measurement of the distribution of strain across plates and at plate boundaries may provide a means of understanding the relative importance of various plate driving forces.

Transient deformation has emerged as a new research area for improving understanding of fault zone constituent properties and forcing mechanisms. Non-steady ground motion has been measured across a number of different plate boundary settings, suggesting more complicated processes than simple elastic strain accumulation and release. Episodic tremor and slip (ETS), initially observed for Cascadia and known at the time of the SESWG Report, has been recognized at other subduction zones and also at major continental transcurrent plate boundaries. Assessing the prevalence of transient motions, and understanding how transients relate to large and infrequent seismic events is a natural focus for the solid-Earth science program.

The advent of large terrestrial space-geodetic networks, such as the Plate Boundary Observatory (PBO) continuous GPS network, provides excellent constraints on deformation associated with plate boundaries. In particular, they provide broad scale distribution of crustal deformation as well as better understanding of the partitioning of strain across plate boundary fault systems. They also provide excellent temporal sampling, which has been particularly important for identifying transient deformation processes such as fault after-slip and fault creep. The spatial density of the ground networks is generally not sufficient to resolve important physical properties of earthquake ruptures, such as how slip is distributed on the rupture plane or whether multiple ruptures were involved. One of the continuing challenges has been the need for a dedicated U.S. InSAR mission focused on scientific research to provide

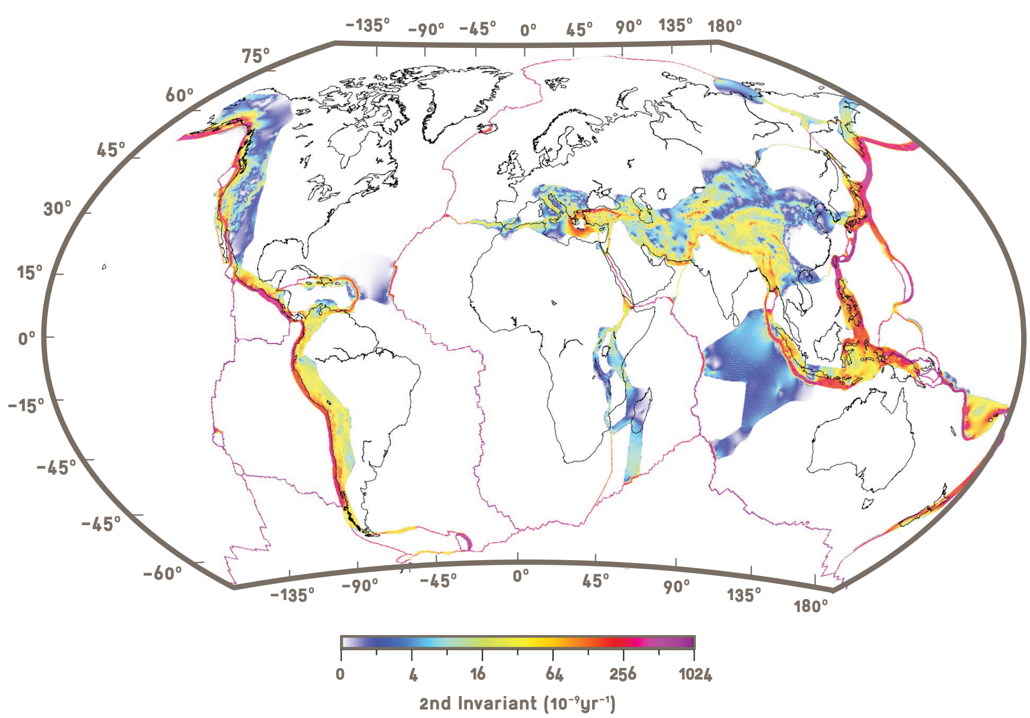


FIGURE 2.1: WORLDWIDE GNSS MEASUREMENTS SUPPLEMENTED BY GEOLOGIC SLIP RATES HAVE BEEN USED TO HELP US UNDERSTAND THE NATURE OF DEFORMATION AT PLATE BOUNDARIES. HERE, THE 2ND INVARIANT OF STRAIN RATE IS A MEASURE OF THE ONGOING DEFORMATION WITHIN THE CRUST ATTRIBUTABLE MAINLY TO PLATE TECTONICS. AREAS IN WHITE ARE ASSUMED TO BEHAVE RIGIDLY.

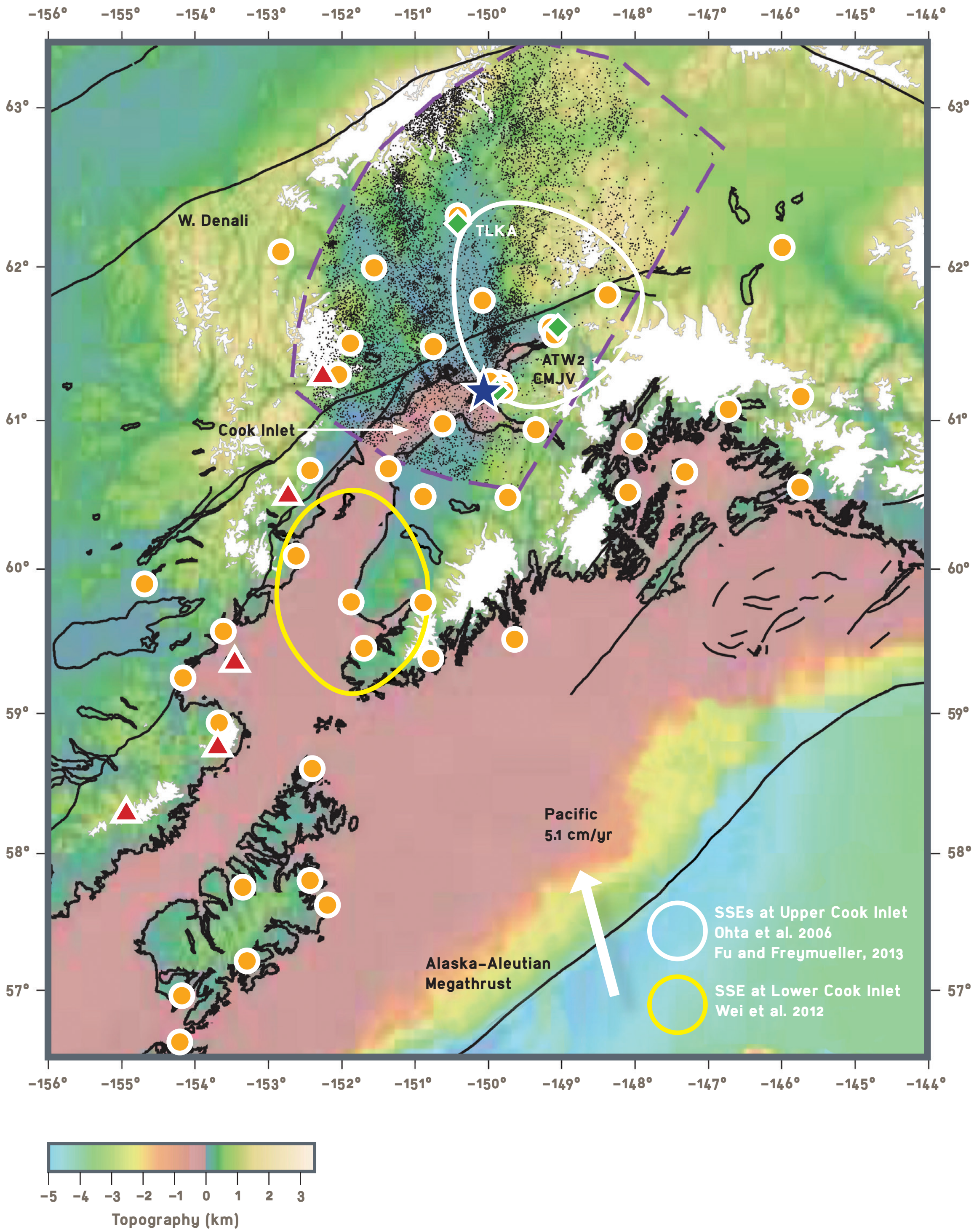
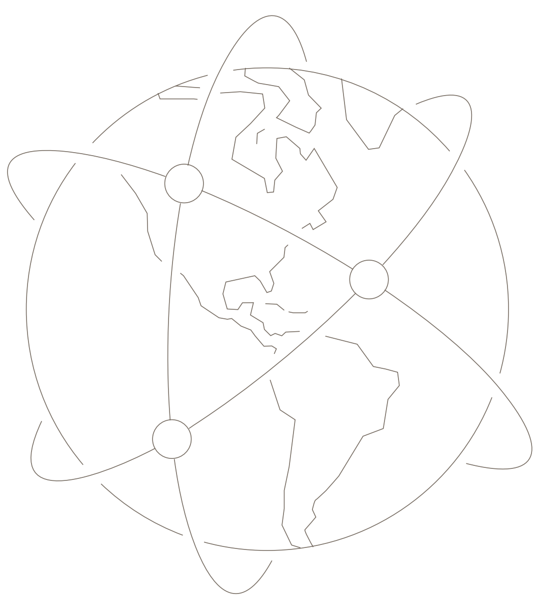


FIGURE 2.2: ALASKA PROVIDES A NATURAL LABORATORY FOR MEASURING CRUSTAL DEFORMATION ASSOCIATED WITH LARGE EARTHQUAKES AND TRANSIENT SLOW-SLIP EVENTS, AS WELL AS WITH INTERACTION WITH STRESSES CAUSED BY MELTING GLACIERS. HERE, A GNSS NETWORK (ORANGE CIRCLES) IS USED TO MEASURE DEFORMATION IN SOUTHERN ALASKA.

The advent of large terrestrial space-geodetic networks, such as the Plate Boundary Observatory (PBO) continuous GPS network, provides excellent constraints on deformation associated with plate boundaries. In particular, they provide broadscale distribution of crustal deformation as well as better understanding of the partitioning of strain across plate boundary fault systems.



coverage and temporal sampling needed to advance our understanding of earthquakes. Such a mission was given high priority in the SESWG Report, the 2007 NAS report "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" (hereafter Decadal Survey), the 2012 community report on Grand Challenges in Geodesy, and by the CORE Workshop attendees. The NISAR mission, a dual-frequency (L- and S-bands) repeat-pass polarimetric InSAR, will fill this gap. NISAR's systematic measurements will provide spatially detailed measurement of interseismic strain accumulation, co-seismic slip, postseismic deformation, and damage maps following earthquakes. The measurements are necessary to understand how earthquake fault systems evolve over time and how faults fail in earthquakes.

Six of the fifteen largest earthquakes since 1900 occurred after publication of the SESWG Report in 2002, including two devastating tsunamigenic earthquakes: the 2004 M9.1 Sumatra-Andaman Indian Ocean and the 2011 M9.0 Tohoku-Oki interplate megathrust events. Comprehensive analysis of ocean surface wave heights, ocean bottom displacements, and onshore high-rate displacements from GPS, long-wavelength gravity change, coupled with elastic wave energy measured with seismometers for the Tohoku-Oki event illuminated clearly how deformation on convergent plate boundaries must be observed across the terrestrial–marine interface to capture the full kinematics and inform the detailed dynamics during rupture. Such integrated approaches hold great promise for early characterization of earthquake rupture dynamics, magnitudes, associated strong ground shaking, and the generation of tsunamis when earthquakes occur offshore and cause significant displacement of the seafloor.

RIGHT: ARTIST'S CONCEPT OF THE NISAR SPACECRAFT.

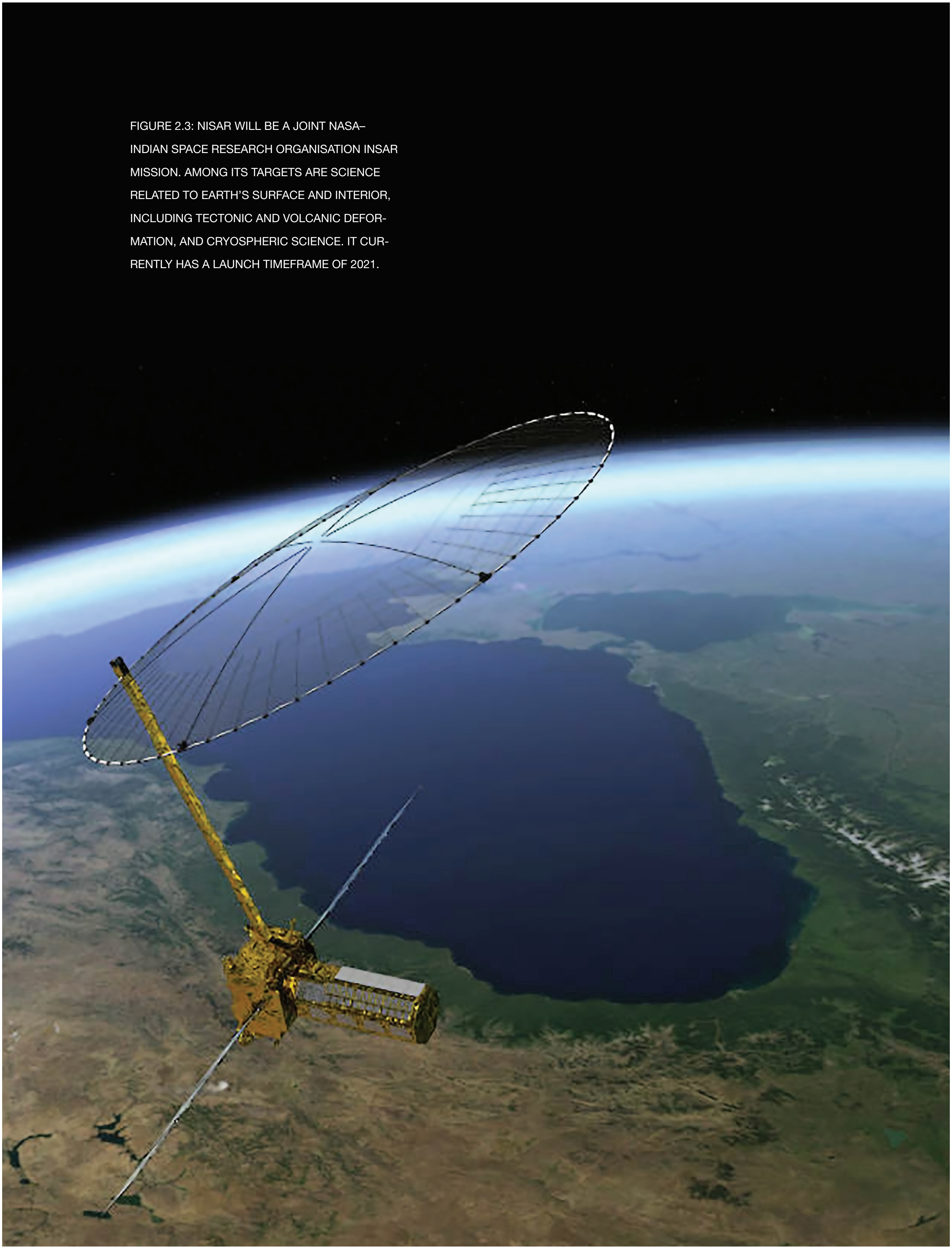


FIGURE 2.3: NISAR WILL BE A JOINT NASA–INDIAN SPACE RESEARCH ORGANISATION INSAR MISSION. AMONG ITS TARGETS ARE SCIENCE RELATED TO EARTH'S SURFACE AND INTERIOR, INCLUDING TECTONIC AND VOLCANIC DEFORMATION, AND CRYOSPHERIC SCIENCE. IT CURRENTLY HAS A LAUNCH TIMEFRAME OF 2021.

2.2

How do tectonic processes and climate variability interact to shape Earth’s surface and create natural hazards?

GOALS

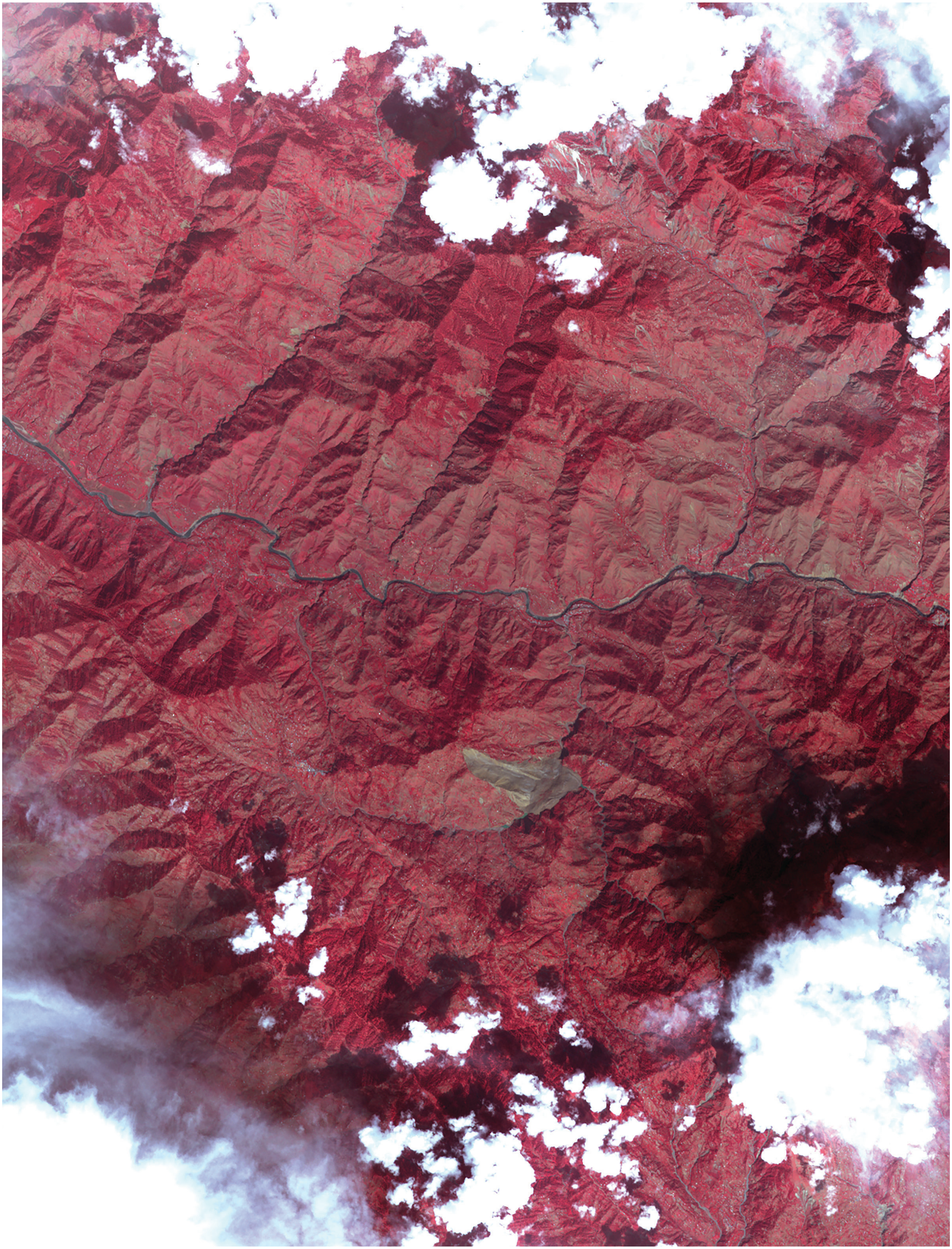
Improve understanding of the impact of climate change on the landscape and seascape

Explore under what conditions sedimentation and erosion rates vary smoothly or abruptly with time

Advance topographic/bathymetric data and imaging techniques to provide geomorphic metrics and to study tectonic process models

Develop technologies and methodologies needed to provide complete compositional mapping of Earth’s land surface and ocean bottom

RIGHT: AN ASTER IMAGE SHOWS A LANDSLIDE (BROWN) RESULTING FROM THE 2005 PAKISTAN EARTHQUAKE.



The SESWG Report presented a three-fold challenge regarding Earth's land surface: "to unravel the record of past interactions embedded in this surface, to determine the relative roles of natural and human-induced change, and to understand processes that act on this surface in order to predict and mitigate natural hazards." These challenges persist.

A process-based understanding of Earth's dynamic surface is evolving. Progress has been made in understanding laws governing instantaneous geomorphic transport. The need to go beyond steady, time independent process rules, as the SESWG Report recognized, still exists. Coupling detailed surface process models with global Earth system models is an important challenge for the solid-Earth science program.

The processes in the solid Earth that build and influence topography are an important topic of research; efforts to reconstruct the history of subduction, basin formation, and orogeny, coupled with models of the dynamics of the mantle that drives plate tectonics, contribute to understanding the origins of dynamic topography. Connecting these models of Earth's interior to surface models of geomorphic transport is challenging because of interacting processes on wide ranging spatio-temporal scales.

Research is needed on the application of the study of surface processes to managing water and soil resources, both of increasing concern in the face of changing climate and growing population (see Section 2.7). Scientific studies that characterize, understand, and predict phenomena at Earth's surface can thus have a role in lessening the impact of hazards and in improving our ability to manage these resources. The solid-Earth science program can thus facilitate studies that seek to link the science of surface processes to the understanding of natural hazards.

Many Earth processes can be understood only by studying bathymetry and tectonics in the deep oceans. NASA missions have produced phenomenally detailed maps of the surfaces of other planets, moons, and asteroids, contributing greatly to our knowledge of planetary processes, but in comparison our knowledge of Earth's seafloor topography remains rather limited. Shipboard surveys offer the only means for high-resolution seafloor mapping, but useful maps of moderate accuracy and resolution can be achieved by mapping the permanent sea surface topography, which reflects the topography of the seafloor. The SWOT mission could improve the marine geoid accuracy by perhaps an order of magnitude and also improve spatial resolution on the shallow continental margins.

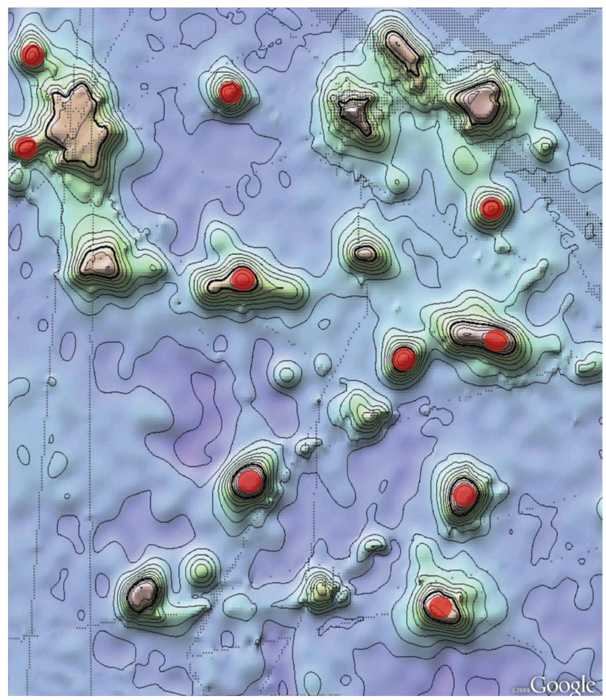


FIGURE 2.4: A NUMBER OF LARGE SEAMOUNTS IN THE WESTERN PACIFIC (RED DOTS) EXTENDING MORE THAN 3000 M ABOVE THE ABYSSAL PLAIN ARE STILL UNSURVEYED BY SHIPS. APPROXIMATELY 100,000 SEAMOUNTS MORE THAN 1000 M TALL ARE UNSURVEYED. THE SWOT ALTIMETER WILL PROVIDE SPACE-BASED MEASUREMENTS FOR PREVIOUSLY UNSURVEYED FEATURES TALLER THAN 1000 M.

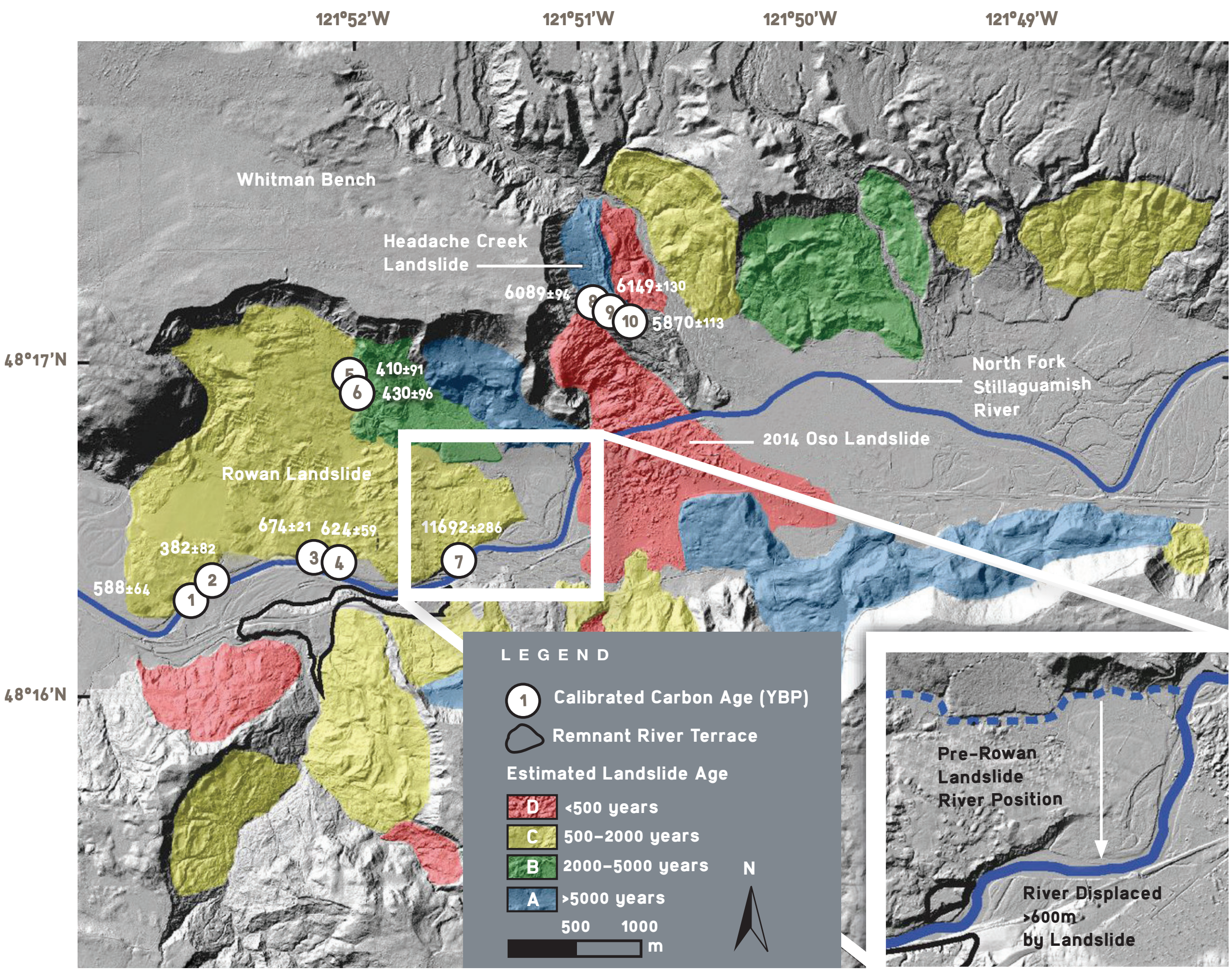


FIGURE 2.5: LIDAR REVEALS ANCIENT AND HISTORIC LANDSLIDES AND TOPOGRAPHIC ROUGHNESS AROUND THE 2014 OSO LANDSLIDE IN WASHINGTON STATE. RESEARCH ON THE HISTORY OF LANDSLIDES HELPS US UNDERSTAND THE EVOLUTION OF EARTH'S SURFACE IN THESE AREAS AND CAN BE USED TO ASSESS FUTURE RISK.

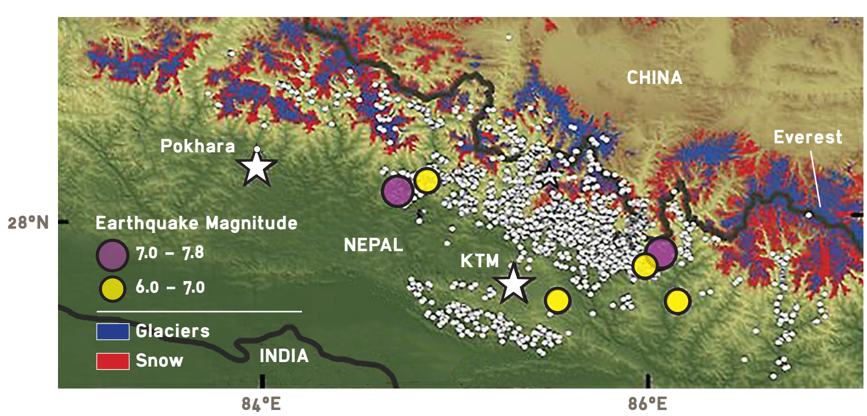


FIGURE 2.6: HOW DO CLIMATE, TOPOGRAPHY, GEOLOGY, AND PLATE TECTONICS INTERACT TO PRODUCE SEISMIC AND LANDSLIDE HAZARDS? HERE, SAR IMAGERY OF TOPOGRAPHY, SNOWFIELDS (RED), AND GLACIERS (BLUE) IN NEPAL ARE SHOWN. SRTM IS USED TO CORRELATE LANDSLIDES (WHITE DOTS) WITH TOPOGRAPHIC SLOPE, GEOLOGY, AND THE SEISMICITY, PEAK GROUND ACCELERATION, AND SURFACE DISPLACEMENTS IN THE AREA OF THE 2015 NEPAL EARTHQUAKE.

2.3

How does the solid Earth respond to climate-driven exchange of water among Earth systems and what are the implications for sea-level change?

GOALS

Obtain accurate continuous observation of, and improvement in models for, global water mass balance on seasonal to decadal timescales

Understand the role of the solid Earth in multidecadal projections of sea-level change, including ocean–ice feedback mechanisms

Obtain accurate estimates of solid-Earth contributions to regional and global sea-level change

Improve observations and models of processes that drive solid-Earth deformation related to regional sea level change

Develop the capability to combine observations with different spatial and temporal resolution to provide self-consistent models for sea-level change and solid-Earth deformation

Improve spatial and temporal resolution of global vertical deformation, gravity, and sea-surface fields

RIGHT: GROUND TRACKS FOR NASA SATELLITE AND AIRBORNE MISSIONS INDICATE WHERE DATA WERE ACQUIRED TO DETERMINE GREENLAND ICE FLOWS.

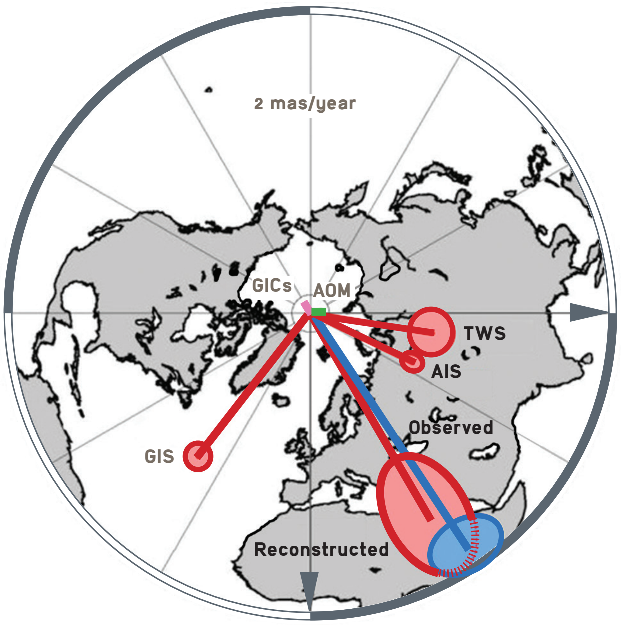


FIGURE 2.7: REDISTRIBUTION OF SURFACE MASS ASSOCIATED WITH CLIMATE CHANGE IMPACTS EARTH'S ROTATION. HERE, RECONSTRUCTION OF PLANETARY ROTATION-POLE MOTIONS FROM GRACE AND OTHER DATA AND MODELS INCLUDES REDISTRIBUTION OF EARTH'S SURFACE MASS ASSOCIATED WITH TERRESTRIAL WATER STORAGE (TWS), ATMOSPHERIC AND OCEANIC MASS (AOM), GREENLAND ICE SHEET (GIS), ANTARCTIC ICE SHEET (AIS), AND OTHER GLOBAL GLACIERS AND ICE CAPS (GIC).

Understanding the transport of water on seasonal time scales over the entire surface of Earth has only been possible during the past decade and a half. A major accomplishment since the SESWG Report, the GRACE mission has provided scientists with the first maps of global transport of surface water mass and, simultaneously, of the slow movements of the solid rock interior associated with glacial isostatic adjustment (GIA).

Interpretation of GRACE observations, and translating GRACE observations to changes in relative sea level at a location, depend on understanding Earth's response to surface mass loads on a large range of time scales, having a detailed picture of the mass loss, and on understanding processes that impact local subsidence. The new observational capabilities, coupled with advances in modeling and data analysis, have had a profound impact. We now have space-based observations in place that enable us to study the mass flux of the entire fluid envelope of Earth and of the response of the solid Earth to this changing surface load. The latter is of particular continued interest to the solid-Earth science program.

The ability to disentangle various gravity signals depends critically on improved models for several important processes, like surface hydrology and GIA. Indeed, uncertainty in GIA, a solid-Earth process, remains the dominant uncertainty in GRACE estimates of present-day mass change from surface ice and water (see Section 2.5).

Societal concern is focused on sea level at particular locations, primarily the dramatic economic and social consequences associated with coastal inundation, especially in urban centers. Reliable projections of sea-level change will depend on a range of observational systems and models as well as the capability of combining the observations and models and assessing the errors in prediction. Understanding the causes of current sea-level change and making predictions requires understanding all processes that affect sea-level rise locally, and the interaction among these processes, including contributions from the cryosphere, ocean dynamics, and the solid Earth. Many of the underlying observations are geodetic in nature, and the solid-Earth science program therefore has a vital role in this multidisciplinary research.

The new observational capabilities, coupled with advances in modeling and data analysis, have had a profound impact. We now have space-based observations in place that enable us to study the mass flux of the entire fluid envelope of Earth and of the response of the solid Earth to this changing surface load.

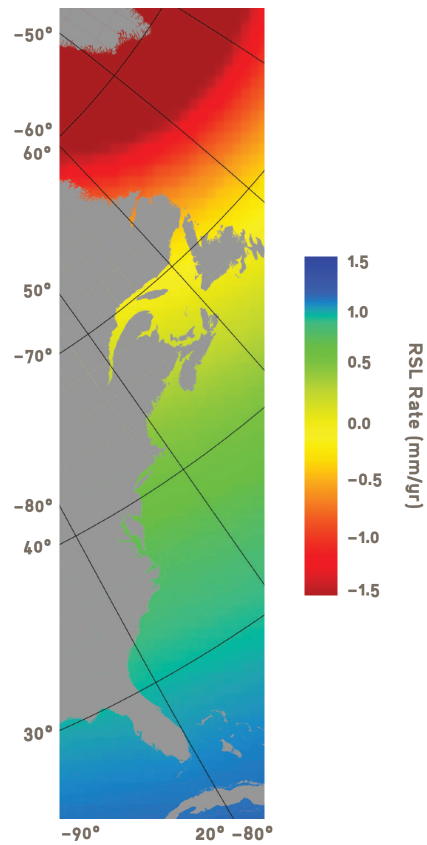
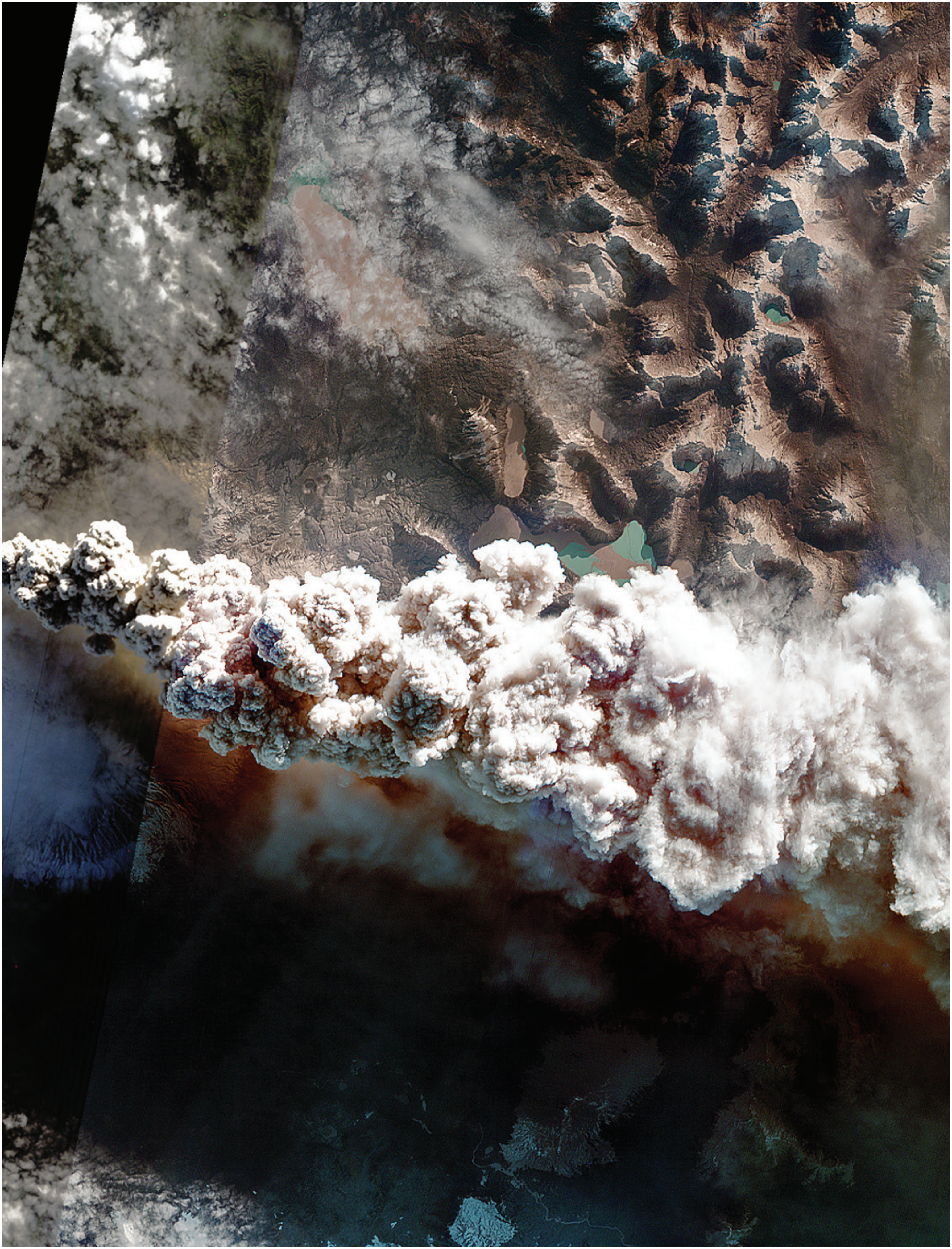


FIGURE 2.8: THE CHANGE IN RELATIVE SEA LEVEL (RSL) DUE TO ICE-MASS LOSS IN GREENLAND VARIES DRAMATICALLY DEPENDING ON LOCATION AND DEPENDS CRUCIALLY ON THE RESPONSE OF THE SOLID EARTH.



2.4

How do magmatic systems evolve, under what conditions do volcanoes erupt, and how do eruptions and volcano hazards develop?

GOALS

Identify and characterize Earth's active magmatic systems globally

Assess hazards of active and potentially active volcanoes

Improve the capability to forecast the start and end of an eruption

Understand the relationships between surface deformation, seismicity, thermal emissions, changes in gravity, emissions of gasses, and eruptions

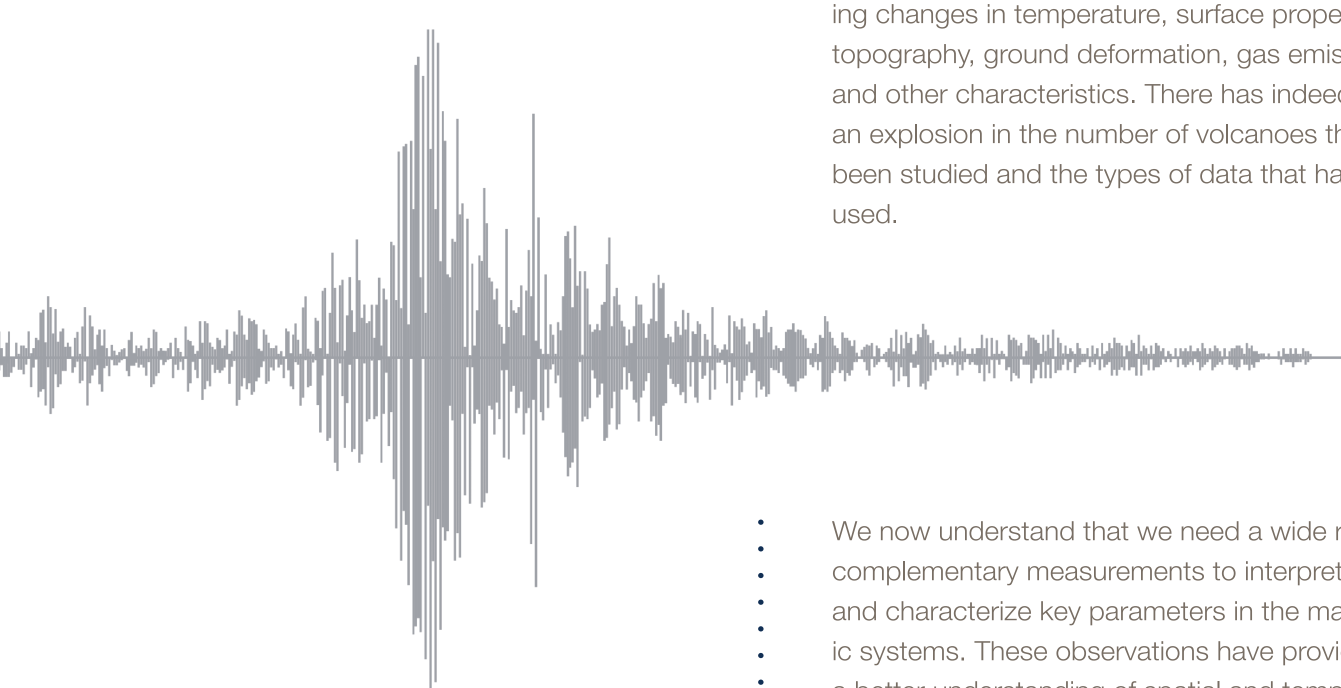
Improve the capability to forecast quantities and types of eruptive products and their distribution in space and time with application to the wide range of volcanic hazards

Investigate interactions among magmatic systems, earthquakes, and tectonics

Improve our understanding of the overall impact of volcanoes and their eruptions on the Earth system

LEFT: ERUPTION OF CHILE'S PUYEHUE-CORDON CAULLE VOLCANO IMAGED BY INSTRUMENTS ON BOARD NASA'S EO-1 SPACECRAFT.

Since the SESWG Report, there has been significant progress on several of the challenges and opportunities identified for magmatic systems. The report highlighted the need for a "globally comprehensive compilation of observations of all major land volcanoes" and we are approaching this goal with several near global databases that inventory active volcanoes and magmatic unrest including changes in temperature, surface properties, topography, ground deformation, gas emissions, and other characteristics. There has indeed been an explosion in the number of volcanoes that have been studied and the types of data that have been used.



We now understand that we need a wide range of complementary measurements to interpret unrest and characterize key parameters in the magmatic systems. These observations have provided a better understanding of spatial and temporal complexity of volcanic activity. In addition, remote sensing observations have saved thousands of lives. During the 2010 Merapi, Indonesia, eruption, for example, daily satellite SAR data provided critical information about the high rate of dome growth, which prompted evacuation.

As observational systems improve, both deterministic and probabilistic modeling capabilities must grow in step to take advantage of the new datasets and make progress towards forecasting of volcanic hazards.

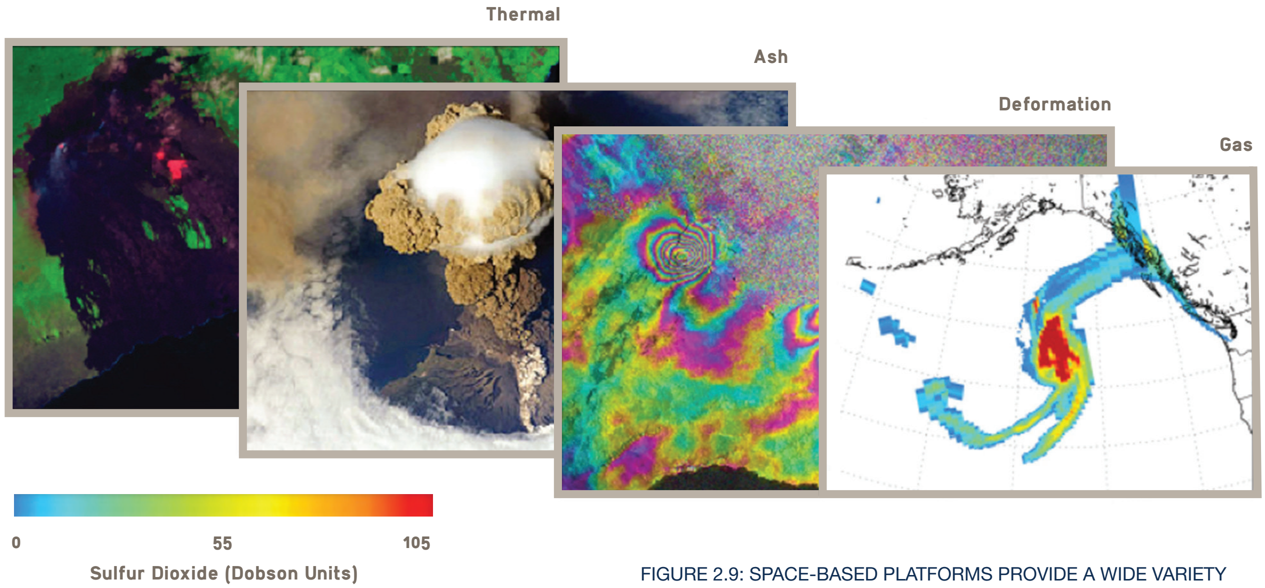


FIGURE 2.9: SPACE-BASED PLATFORMS PROVIDE A WIDE VARIETY OF INFORMATION WITH WHICH TO STUDY VOLCANIC PROCESSES.

There is a continued need for higher temporal, high spatial resolution, multi-sensor observations to understand volcanic processes. It is also clear that with the new observations available there is a spectrum of volcano behaviors that we are just beginning to decipher. NISAR will provide systematic global observations that will improve our ability to understand the changes in deformation that occur during different phases of volcanic unrest. Many volcanoes are monitored for ground motion using local GNSS networks. An innovative application of these data that enables detection of the volcanic plume, a possible indicator of activity independent from deformation, has recently emerged. Future airborne and spaceborne spectral instruments would also provide unique thermal and chemical information on active volcanoes. As observational systems improve, both deterministic and probabilistic modeling capabilities must grow in step to take advantage of the new datasets and make progress towards forecasting of volcanic hazards.

There have also been significant advances in modeling and laboratory work. Some examples include the use of physics-based models that can match the coupled subsurface magma reservoir and surface eruption flux. The solubility of volatiles in magmas have been better defined, over a whole range of pressures, from surface to mantle, and the role of these volatiles in magma compressibility and the interpretation of volcano deformation has been appreciated. We can now better estimate the atmospheric dispersion of tephras, with implications for ash hazards for aviation.

New developments since the SESWG Report have prompted some revisions to the overarching question and subquestions for magmatic systems. In particular, it has been clear that our scientific interest in a magmatic system does not end when an eruption begins; space measurements, and models constrained by them, inform forecasts for the distribution and type of eruptive products in space and time. Moreover, hazards do not end when the eruption ends; lahars and landslides, for example, remain hazards in volcanic areas even without ongoing eruptions. Furthermore, magmatic systems and eruptions are connected with the entire Earth system, linking the solid-Earth science program to other NASA programs like the atmospheric chemistry, cryospheric sciences, and applied sciences programs.

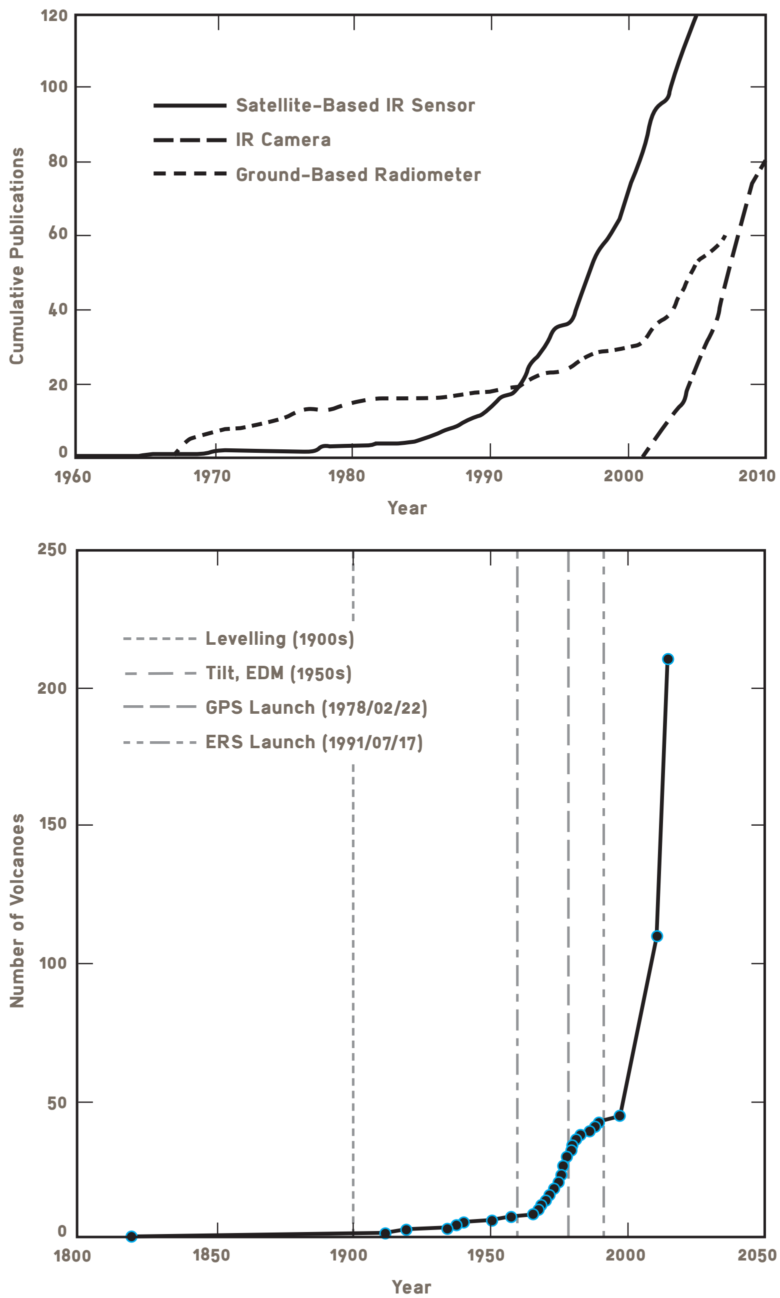
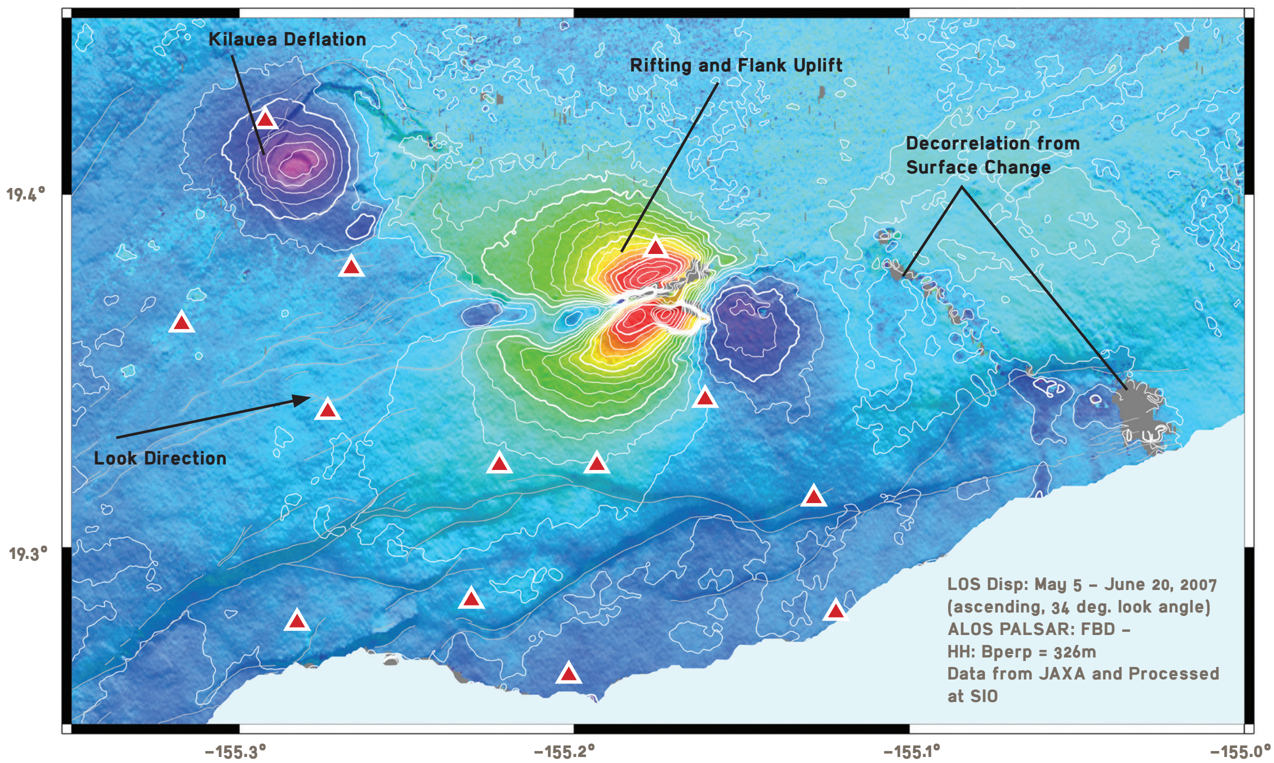
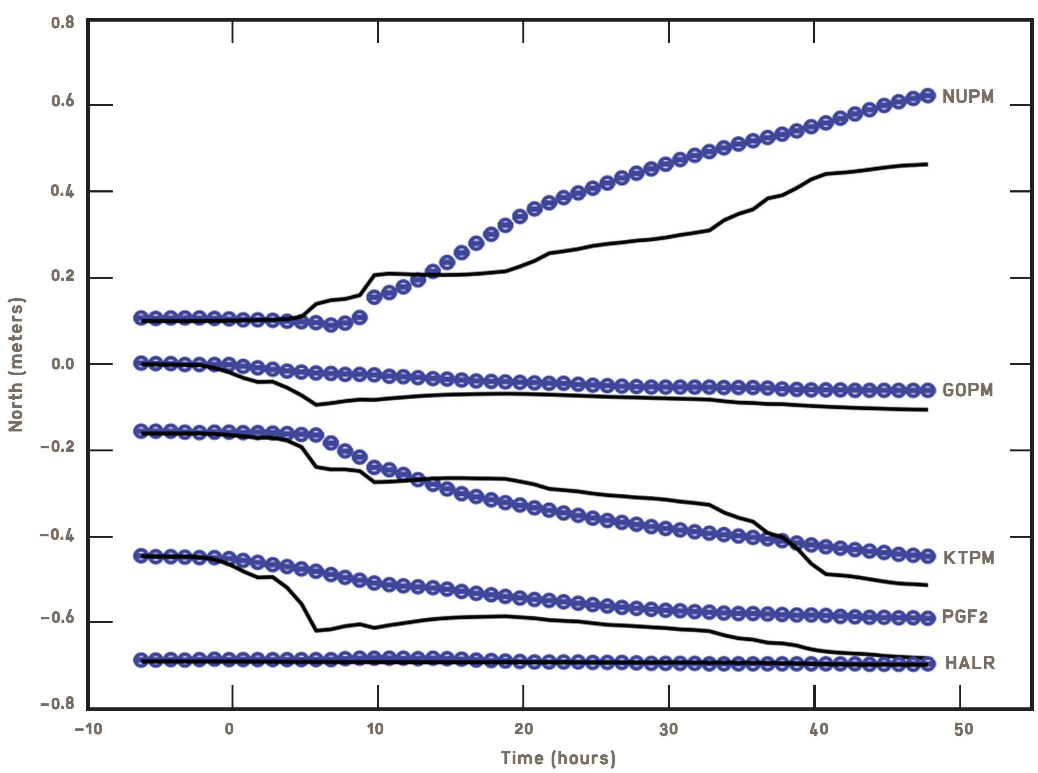


FIGURE 2.10: THE STUDY OF VOLCANOES HAS GROWN DRAMATICALLY WITH THE ADVENT OF (TOP) THERMAL AND (BOTTOM) SPACE GEODESY STUDIES.

OPPOSITE PAGE, FIGURE 2.11: INSAR AND GPS HAVE COMPLEMENTARY TEMPORAL AND SPATIAL RESOLUTIONS, AND THE COMBINATION IS USEFUL FOR STUDYING MAGMATIC EVENTS. TOP: ALOS INSAR IMAGED MULTIPLE SOURCES OF SURFACE DEFORMATION ASSOCIATED WITH THE “FATHER’S DAY” (JUNE 2007) RIFT EVENT ON KILAUEA VOLCANO (RED IS UP, BLUE IS DOWN). BOTTOM: GPS MEASUREMENTS (BLUE CIRCLES WITH ERROR BARS) REVEAL THE DETAILED TIME-DEPENDENCE OF CRUSTAL DEFORMATION AT SOME OF THE GPS SITES (RED TRIANGLES IN TOP FIGURE). THE EVENT OCCURS AT T = 0 HRS. A MODEL FOR TEMPORAL EVOLUTION OF DEFORMATION IS SHOWN IN BLACK.


Kilauea Deflation
Rifting and Flank Uplift
Decorrelation from Surface Change
Look Direction
19.4°
19.3°
LOS Disp: May 5 – June 20, 2007
(ascending, 34 deg. look angle)
ALOS PALSAR: FBD –
HH: Bperp = 326m
Data from JAXA and Processed
at SIO
–155.3°
–155.2°
–155.1°
–155.0°


North (meters)
Time (hours)
0.8
0.6
0.4
0.2
0.0
–0.2
–0.4
–0.6
–0.8
–10
0
10
20
30
40
50
NUPM
GOPM
KTPM
PGF2
HALR

2.5

What are the dynamics of Earth's deep interior and how does Earth's surface respond?

GOALS

Develop a comprehensive physical model of mantle convection and plate tectonics that permits the self-consistent evolution of plate geometries

Combine observations of the global gravity field, surface topography, and rates of change of topography to define an accurate snapshot of the present-day dynamical state of the mantle

Use measurements of glacial isostatic adjustment to refine mineral-physics models of mantle rheology

Quantify the role of mantle convection on the dynamics of the underlying core

Use observations of Earth orientation and rotation to quantify the origin of angular momentum exchanges between the core and the mantle

Detect evidence of persistent mantle-driven flow at the top of the core using observations of geomagnetic field variations

LEFT: AMSR-E DATA WERE USED TO CREATE THIS IMAGE OF HUDSON BAY AND SEA ICE.

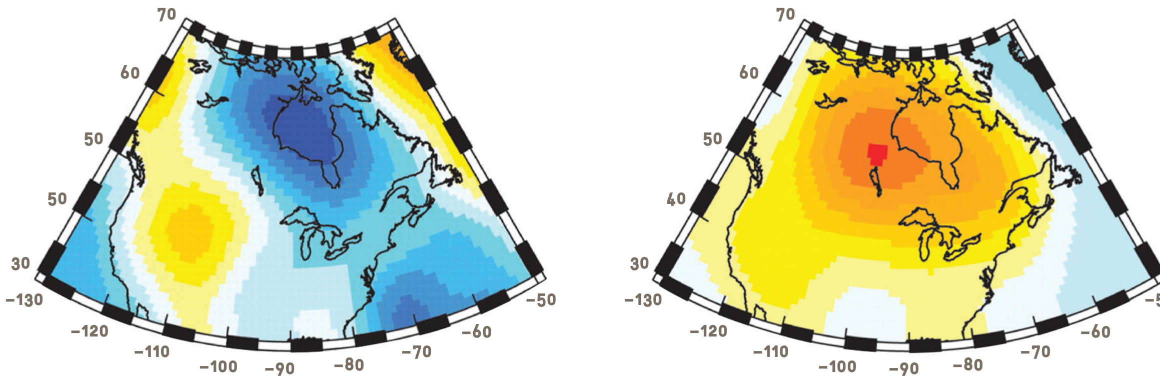
Details of how plate motion is linked to flow in the deep mantle remain obscure and this continues to pose an important scientific challenge. Defining the balance among forces that drive plate motion, however, represents only one part of the challenge. Determining how new plate boundaries are initiated as the plate geometry continually evolves with time is an important component of this problem. Indeed, conditions at the onset of plate tectonics on Earth are fiercely contested, as are the processes governing changes in plate configurations; we are still a long way from understanding the dynamics underlying plate tectonics. Understanding plate tectonics on Earth is an initial and necessary step towards characterizing the internal dynamics of other planetary bodies.

At the time of the SESWG Report, the first space geodetic measurements of three-dimensional crustal deformation associated with GIA were being used to infer mantle viscosity. Increasingly, models for GIA incorporate lateral variations in viscosity, and predictions are revealing consequences for the way we interpret present-day sea level change and assess the future stability of West Antarctic Ice Sheet and northeast Greenland Ice Sheet. Improved techniques for constraining mantle viscosity from GIA observations will lead to a more accurate picture of Earth's structure and interior dynamics, and improved inferences of sea-level and ice-mass change for which GIA is a source of error.

Geodetic nutation observations have long been used to constrain structure and interactions at the core–mantle boundary, the transition 2900 km below the surface where Earth's rocky mantle meets the metallic core. More recently, length-of-day (LOD) variations at a 5.9-year period have been shown to be strongly coherent with occurrence times of the sudden changes of the magnetic field known as geomagnetic jerks, thereby constraining electrical conductivity—and therefore composition and structure—of the lower mantle. Global, high-accuracy, geodetic observations of solid-Earth tides may provide some key observations in regard to determining the nature of large low shear velocity provinces (LLSVPs) at the base of the mantle.

There is growing consensus that the heterogeneity of the mantle inferred from seismic wave speed variations has both thermal and compositional contributions. The task of untangling these contributions is a major obstacle to defining a current snapshot of Earth's internal structure, composition, and dynamics. Outward expressions of this internal state can be observed in variations in the external gravity field and in the presence of dynamically supported surface topography, although the interpretation is far from unique. A quantitative description of the rheological properties of the mantle continues to be a key challenge for understanding large-scale dynamics. The development of innovative methodologies that enable space geodetic observations to address these problems is a potential opportunity for the solid-Earth science program.

FIGURE 2.12: UNDERSTANDING THE STRUCTURE AND DYNAMICS OF EARTH'S INTERIOR IS AN OVERARCHING GOAL OF EARTH SCIENCE. HERE, COMPARISON OF THE GRACE-DERIVED STATIC (LEFT) AND SECULAR (RIGHT) GRAVITY FIELDS OVER NORTH AMERICA ENABLES SEPARATION OF THE EFFECTS OF GIA, HAVING A TIMESCALE ON THE ORDER OF 10,000 YEARS, AND MANTLE CONVECTION THAT DRIVES PLATE TECTONICS, HAVING A TIMESCALE OF MILLIONS OF YEARS.



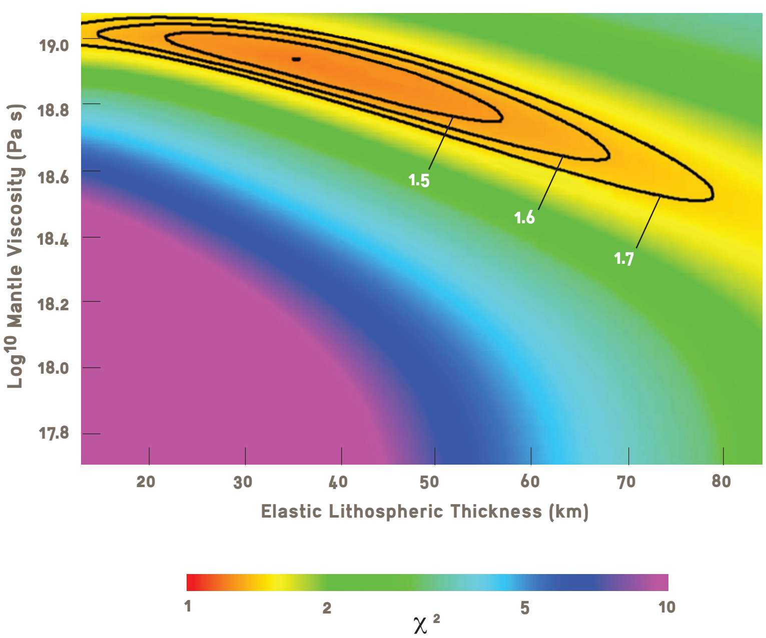


FIGURE 2.13: SPACE GEODETIC OBSERVATIONS OF GIA IN PATAGONIA CONSTRAIN THE VISCOSITY STRUCTURE OF THE SOLID EARTH. HERE, REGIONS OF LOWEST χ^2 FIT BETWEEN OBSERVATIONS AND MODEL SHOW PLAUSIBLE VALUES FOR THE THICKNESS OF THE LITHOSPHERE AND THE VISCOSITY OF THE UPPER MANTLE.

2.6

What are the dynamics of Earth's magnetic field and its interactions with the rest of Earth's systems?

GOALS

Quantify individual contributions of magnetic field sources on a wide range of temporal and spatial scales

Understand the internal structure and dynamics of the geodynamo in the context of Earth and other planets

Understand how the core interacts with the mantle and its impacts on Earth rotation

Improve forecasts of decadal-scale and shorter changes in the geomagnetic field

Map waves in the outer core and determine their physical origin on decadal and longer time scales

Determine the degree of stratification of flow in the outer core

Relate electrical conductivity of the mantle to thermal and compositional structure and understand the contribution of the core field to mantle induction

Understand the links between improved models of lithospheric magnetization and near-surface dynamics

RIGHT: AN ISS CREW MEMBER PHOTOGRAPHED THIS NIGHTTIME SCENE OF AURORAS OVER IRELAND AND THE UK IN 2012.

Since the time of the SESWG Report, there has been a stream of magnetic data from satellite missions led by other nations (with NASA partnerships), starting in 1999 with the individual, but decade-long temporally overlapping, Ørsted, CHAMP, and SAC-C missions, and followed in 2013 by the current ESA Swarm triplet of satellites. Swarm's gradient field configuration has allowed improved separation of more external and internal magnetic sources, including detection of some components of ocean circulation. Magnetic observatories have been enhanced in some areas to provide more rapid sampling along with ground truth and data collected below the ionosphere to complement satellite magnetometry. Seafloor magnetometers have been deployed, surviving for a year or more and demonstrating potential possibilities for submarine observatories. All of these efforts increasingly permit improved temporal and spatial separation of magnetic fields, although much more remains to be accomplished. Additional benefits would also accrue from a denser array of satellite and ground observations as research becomes more interdisciplinary, and the solid-Earth science program could seek to participate in such missions. At the same time, advances in theory, laboratory experiment, and computational modeling are making it possible to better understand the origins of the geodynamo and can inform strategies for observing the complex and changing nature of Earth's magnetic field.

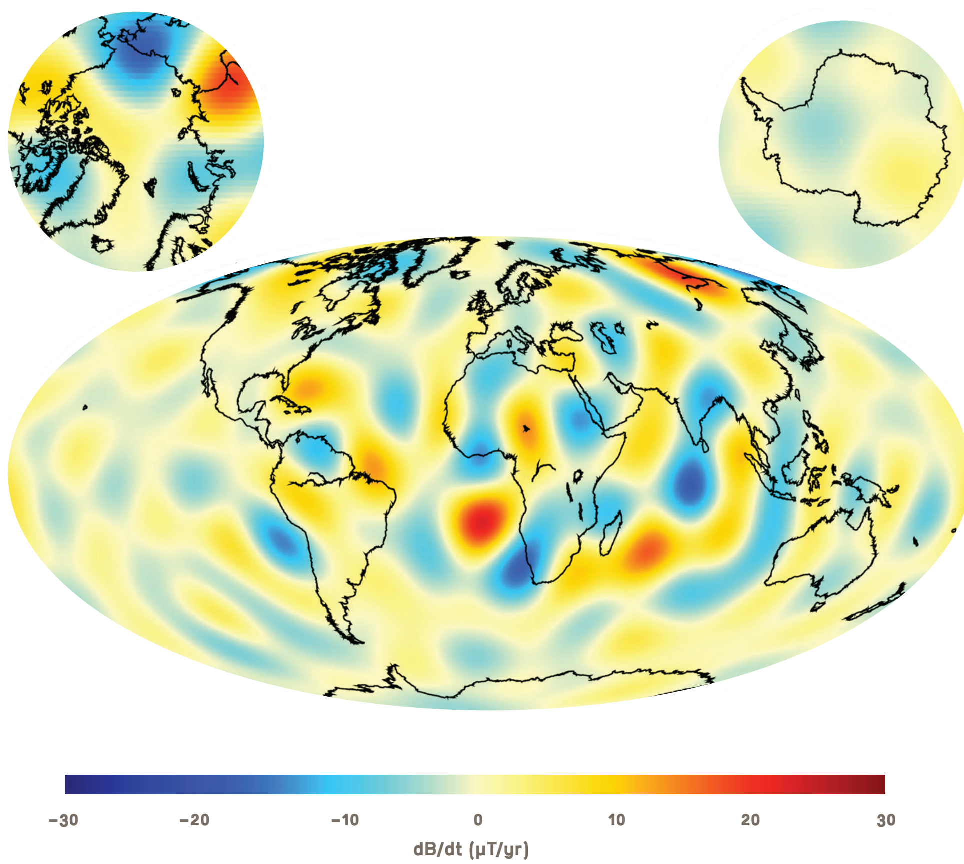


FIGURE 2.14: SATELLITE MEASUREMENTS OF EARTH'S MAGNETIC FIELD ARE LEADING TO IMPROVED MODELS FOR ITS TEMPORAL VARIABILITY. THE MODEL CM5 WAS DERIVED FROM CHAMP, ØRSTED, AND SAC-C SATELLITE DATA.

Satellite measurements have led to an improved understanding of complex processes contributing to geomagnetic signals varying on a wide range of timescales as depicted in aggregate on the so-called "Grand Spectrum" of variability of the magnetic field of Earth. At the same time, better source field separation has led to recognition of ever shorter (sub-annual) secular variation and acceleration signals originating in Earth's core, and improved knowledge of current systems in the ionosphere. Identification of rapid core field variations plays an important role in developing understanding of core-mantle coupling and geomagnetic expression related to variations in Earth's rotation (see Section 2.5). Continuing satellite measurements will enable us to characterize wave propagation in the outer core, suggesting entirely new ways of probing structure and dynamics of Earth's interior, a key component of the solid-Earth science program.

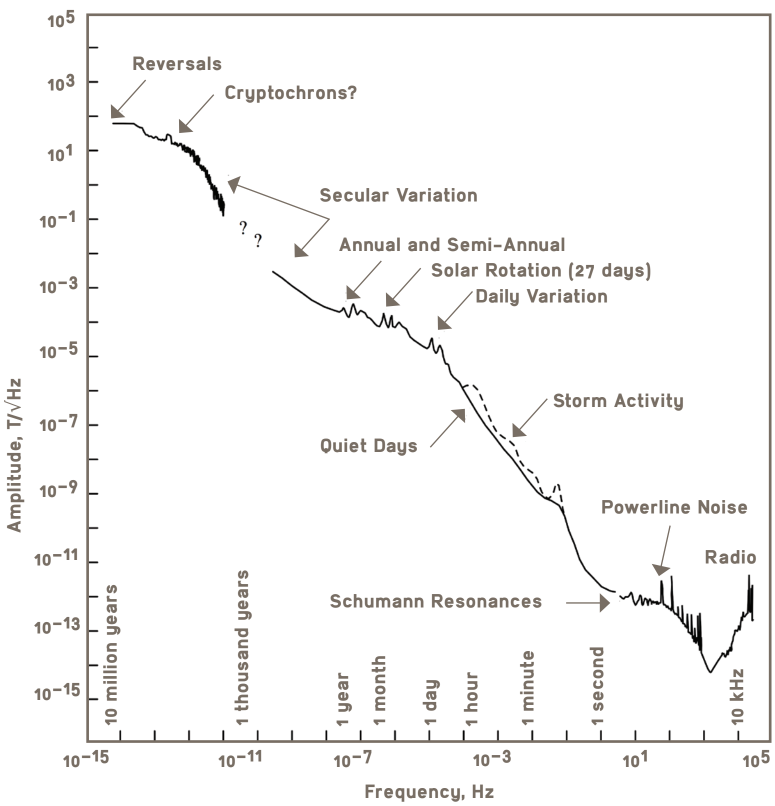


FIGURE 2.15: THE GEOMAGNETIC GRAND SPECTRUM SUMMARIZES PROCESSES THAT CONTRIBUTE TO THE EARTH'S MAGNETIC FIELD OPERATING ON WIDELY VARYING FREQUENCIES. GEOMAGNETIC STORMS ACTING OVER MINUTES, HOURS, OR DAYS CAN DISRUPT CRITICAL COMMUNICATIONS AND POWER SYSTEMS; SOLAR PROCESSES ALSO INFLUENCE EARTH'S MAGNETIC FIELD ON SCALES FROM MONTHS TO DECADES; WHILE SECULAR VARIATION OVER THOUSANDS TO TENS OF MILLIONS OF YEARS REVEALS THE DYNAMICS OF EARTH'S CORE.

2.7

How do human activities impact and interact with Earth's surface and interior?

GOALS

Leverage human-induced perturbations as experiments to understand solid-Earth processes

Understand feedback mechanisms between anthropogenic and solid-Earth processes

Characterize interactions between urbanization and other large-scale human activity and solid-Earth processes

Improve data analysis for hazard mitigation and societal benefit

LEFT: ASTER IMAGE OF THE THREE GORGES DAM ON THE YANGTZE RIVER IN EAST-CENTRAL CHINA.

The period since the SESWG Report has seen not only an increase in human activities that significantly impact natural Earth processes, but also increased understanding of these impacts and the complexity of the interactions within the Earth system. Human activities induce forces that interact with background lithospheric stresses to alter crustal behavior, either indirectly through climate change, or more directly through pumping of fluids or changing of loads. For instance, anthropogenic subsurface stress perturbations are known to induce small earthquakes, but much about this issue remains uncertain, including the interaction with large fault systems and implications for larger events. Anthropogenic impacts occur on a range of spatial scales: localized effects such as reservoir loading, mining, petroleum and geothermal production, and urbanization and land use change; regional-scale groundwater extraction, changes in surface and coastal processes and loading through increased erosion or river diversion; and global climate change (see Section 2.3).

Feedback between anthropogenic forcing and solid-Earth systems is nonlinear and complex. Many driving anthropogenic processes interact with Earth systems near cities and other large-scale infrastructures that are particularly vulnerable to unexpected changes and feedbacks to socio-economic systems. Geodetically observed surface displacements in and near metropolitan areas around the world are caused by groundwater production, fluid extraction, and injection associated with hydrocarbon and geothermal energy production, and coastal sedimentation and inundation. These perturbations can lead to changes in surface drainage, ground cracking and fissuring, and foundation damage. With the exponential increase in human population and attendant resource exploitation, these interactions are expected only to increase in scope and magnitude.

Human activities induce forces that interact with background lithospheric stresses to alter crustal behavior, either indirectly through climate change, or more directly through pumping of fluids or changing of loads.

Given the focus of the NASA solid-Earth science program on understanding the interaction between the solid Earth and other Earth systems, the feedback between anthropogenic forcing and the solid Earth is a natural focus having important scientific and societal benefits. (Also see Section 3.5.) Anthropogenic forcing, often accompanied by unique knowledge of the forcing terms (such as pumping histories), can yield unique scientific insights into solid-Earth structure and dynamics. These scientific problems represent a significant opportunity for study with observational systems having high spatial and temporal resolution and global coverage, such as many of those discussed in this report.

Understanding how human activities impact and interact with Earth's surface and interior was not a major focus in the SESWG Report. This new scientific challenge arose from an increased awareness over the last decade regarding the scientific significance of this area of research, and its role within the NASA solid-Earth science program has yet to be fully examined. Such research is inherently cross-disciplinary and could include social, ecological, engineering, and Earth science components. Investment in such research would be valuable not only for science, but also for decision-makers, businesses, and educators; and for understanding and assessing hazards.

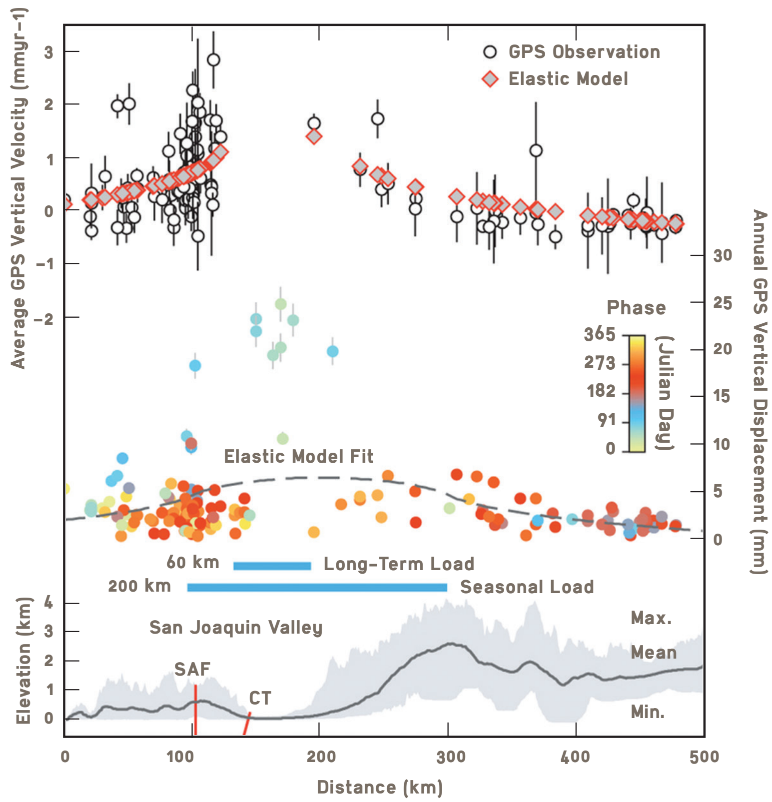


FIGURE 2.16: MODELS FOR DEFORMATION DUE TO GROUNDWATER WITHDRAWAL BY HUMANS HELP US UNDERSTAND THE IMPLICATIONS FOR CHANGING FAULT STRESS AND EARTHQUAKE HAZARD. HERE, GPS-DERIVED VERTICAL VELOCITY ESTIMATES CLOSELY MATCH PREDICTIONS MADE USING AN ELASTIC FLEXURAL MODEL BASED ON GROUNDWATER-WITHDRAWAL LOAD CHANGES, ON A PROFILE THROUGH THE SAN JOAQUIN VALLEY (CALIFORNIA) THAT INCLUDES THE SAN ANDREAS FAULT (SAF) AND THE COAST RANGE THRUST (CT).

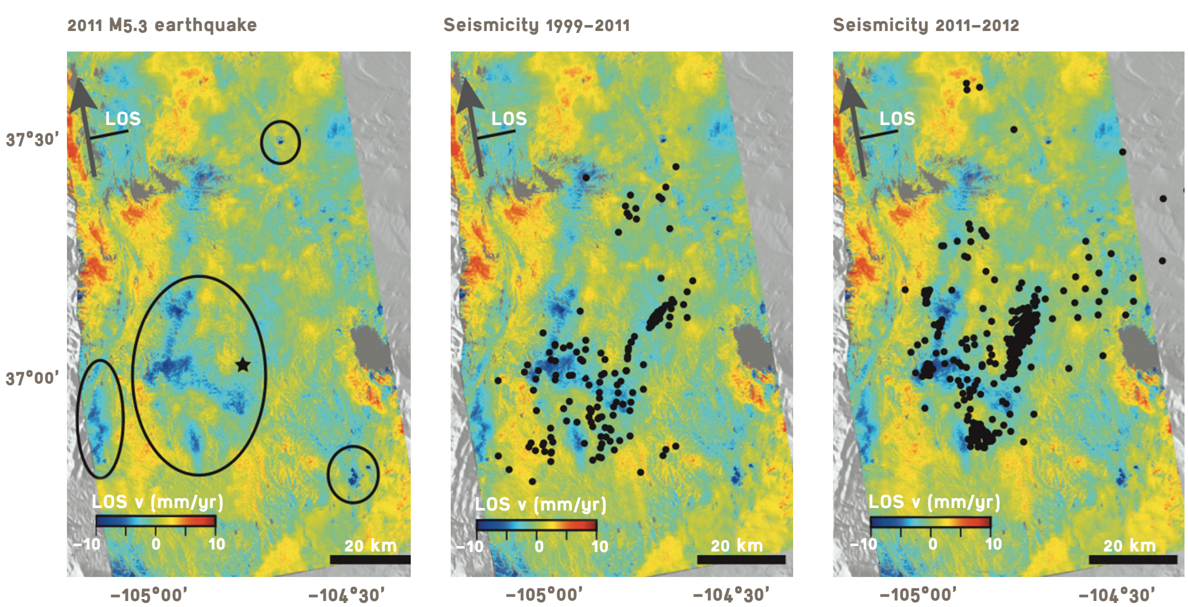
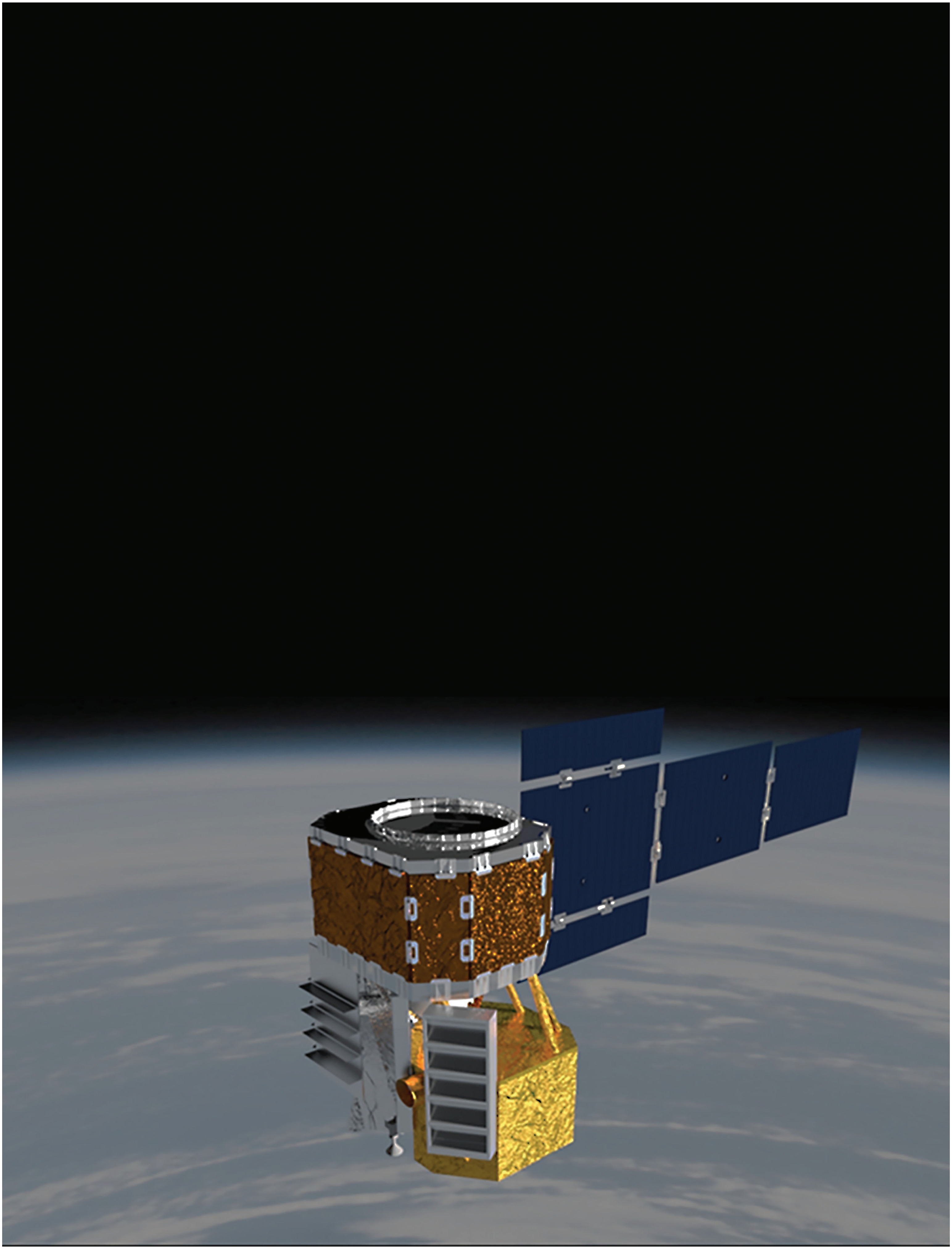


FIGURE 2.17: COMPLEX INTERACTIONS BETWEEN THE SOLID EARTH AND HUMAN ACTIVITIES YIELD INCREASED UNDERSTANDING OF THE BEHAVIOR OF EARTH UNDER CHANGING STRESSES. SINCE 2001, SEISMICITY HAS INCREASED IN THE RATON BASIN OF SOUTHERN COLORADO AND NORTHERN NEW MEXICO, THE LOCATION OF HYDROCARBON EXTRACTION STARTING IN 1999 (RIGHT TWO FRAMES). THE AUGUST 23, 2011, TRINIDAD, COLORADO MAGNITUDE 5.3 EARTHQUAKE (STAR IN LEFT FRAME) WAS THE LARGEST ALONG THE ROCKY MOUNTAIN FRONT RANGE SINCE THE 1966 ROCKY MOUNTAIN ARSENAL EARTHQUAKE THAT WAS INDUCED BY INJECTION OF FLUID WASTES. COLOR SHOWS INSAR VELOCITIES. INSAR MEASUREMENTS OF LOCALIZED SUBSIDENCE (CIRCLED BLUE AREAS IN LEFT FRAME) CONSTRAIN DEFORMATIONAL STRESSES IN AREAS OF GROUND WATER OR GAS WITHDRAWAL. ADDITIONAL INSAR MEASUREMENTS OF EARTHQUAKE DEFORMATION SHOW THAT IT STARTED WITHIN THE CRYSTALLINE BASEMENT IN THE VICINITY OF AN ACTIVE WASTEWATER DISPOSAL SITE.



CHAPTER 3

OBSERVATIONAL AND TECHNOLOGICAL OPPORTUNITIES

While the NASA Earth-science program supports many scientific investigations, it also has a unique and important role in the development of new space-based observational systems and in the continued improvement in accuracy of these systems. This role is a natural outgrowth of NASA's satellite-based technology as well as NASA's historical role in the development of space geodetic observing techniques. NASA's Space Geodesy Program supports research in modeling and analysis that not only advances solid-Earth science, but also a wide range of NASA missions that depend on accurate satellite positioning. This research is thus important to other federal scientific and operational agencies (including the military) and benefits civilian activities as well. At the same time, the solid-Earth science program benefits from a number of relevant NASA initiatives, such as the Instrument Incubator Program and CubeSats.

Advancing toward the science goals described in the previous chapter depends on what the SESWG Report refers to as a "fully realized" program. While the structure described in the SESWG Report remains relevant, a major theme evident from the CORE Workshop discussions and white papers was that the overall scientific and technological context in which Earth-science research takes place has evolved significantly. This is especially true for observing systems and computational infrastructure and capabilities.

The remainder of this chapter focuses not on technological requirements (as did the SESWG Report) but on identifying the major advances over the last decade. Ongoing efforts and scientific and technological opportunities and initiatives for the next decade are also identified. In many cases, these technological accomplishments and ongoing and future initiatives reflect targets discussed in the SESWG Report. In other cases, these are based on unforeseen advances that were nonetheless found relevant to the CORE Workshop attendees. However, no effort has been made to separate factors discussed in the SESWG Report from those that are newly identified.

LEFT: ARTIST'S CONCEPT OF THE HYPERSPECTRAL INFRARED IMAGER (HYSPIRI) SATELLITE IN LOW-EARTH ORBIT.

Picture credit Felipe Hall

3.1

Observational Strategies

REFERENCE FRAMES, EARTH ORIENTATION AND ROTATION

Critical to NASA's Earth science mission, as well as to a vast array of NASA missions and other scientific efforts, is the infrastructure that establishes the Terrestrial Reference Frame (TRF) and the Celestial Reference Frame (CRF). The reference frames are maintained by international organizations that use data acquired by global networks of space geodetic stations. The global geodetic infrastructure is of great societal benefit, for it supports a range of activities and missions of NASA and other agencies of the U.S. Government, as well as civilian and commercial applications. The SESWG Report stressed the importance of maintaining the global geodetic infrastructure, but the 2010 NAS report "Precise Geodetic Infrastructure: National Requirements for a Shared Resource" pointed out that the infrastructure was degrading due mainly to the aging of network hardware, and that the systems that were designed in the 1990s or earlier were not designed to deliver the accuracy required for the science problems of the 21st century.

Partly in response to Precise Geodetic Infrastructure, NASA created the Space Geodesy Project (SGP). SGP is overseeing development of NASA's next-generation observational systems, and is deploying them in a network of integrated "core" stations that also serve as NASA's contribution to the Global Geodetic Observing System.

Activities in this area include research on space data analysis techniques and model improvement; development and maintenance of technological and computational infrastructure; and participation in and leadership of international services that coordinate reference frame activities; in particular the IGS, IVS, ILRS. Support for these core infrastructure activities is unique to the NASA solid-Earth science program, and is required to realize maximum accuracy of the next-generation observational systems. At the same time, NASA supports research that utilizes these data to advance the solid-Earth sciences. Thus, NASA programs create a community of researchers involving science, reference frame infrastructure, and accuracy improvement activities.

ACCOMPLISHMENTS SINCE SESWG

- Establishment of SGP to direct and coordinate planning, development, testing, and initial build-out of next-generation space-geodetic observing systems and core network
- System reviews for next-generation VLBI (VGOS) and SLR (SGSLR) systems
- Regularly scheduled observing sessions for VGOS systems at Westford and GGAO

LEFT: THE PROTOTYPE VLBI STATION AT THE GODDARD GEOPHYSICAL AND ASTRONOMICAL OBSERVATORY IN MARYLAND FIRST DEMONSTRATED THE FEASIBILITY OF BROADBAND VLBI IN 2013.

- First light and first fringes at Koke‘e Park Geophysical Observatory (KPGO)
- Detection of seasonal hemispheric Earth surface deformation due to hemispheric water exchange and development of regional and global mass transport models
- Tests of general relativity using SLR and VLBI observations
- Continued improvement in terrestrial and celestial reference frames and reference gravity models
- Submission of first-ever NASA TRF solution to the IERS

ONGOING ACTIVITIES

- Continued build-out of next-generation SLR and VLBI systems
- Regularly scheduled observations with systems as they come on line
- Validation of combined next-generation geodetic systems using best geodetic analysis tools

FUTURE PLANS AND OPPORTUNITIES

- Periodically revisit requirements for reference frame and geodetic system accuracy vis-à-vis evolving science goals
- Develop means to improve geodetic reference frame accuracy through novel combinations of geodetic data types and by collocation of geodetic systems on Earth and in space

SURFACE DEFORMATION

Studying surface deformation places rigorous requirements on observational systems, because Earth's surface deforms over a wide range of length scales and time scales associated with tectonic, volcanic, hydrologic, human-induced, and other processes. Temporal scales of interest span seconds to millions of years (13 orders of magnitude), and spatial scales range from less than a few meters across fault zones to the motion of tectonic plates and the response of the entire Earth to changing loads (seven orders of magnitude). A variety of space-based approaches are therefore used, including GNSS surveying and geodetic imaging by laser or synthetic aperture radar. The TRF must be maintained to a high degree of accuracy to support all of these observation types.

In GNSS surveying, there has been significant progress in satellite systems, ground systems, sensor integration, and processing methods since the SESWG Report, along with a concomitant improvement in precision and accuracy. The main emphasis has been on improved temporal resolution, decreased data latency, and continued integration with collocated seismic systems and accelerometers. New analysis approaches have made possible accurate estimation of subdaily transient motion as well as longer-term transient motion associated with postseismic deformation and ETS. GNSS-based real-time warning applications have become possible. Groundwater variations have also been recognized as a major source of surface deformation.

Advances in InSAR have been important but incremental, and have been hampered to some extent by limited data availability. An InSAR mission dedicated to Earth-science research was given high priority in the SESWG Report, the 2007 Decadal Survey, and 2012 community report on Grand

FIGURE 3.1: FOUR SPACE-GEODETIC TECHNIQUES ARE USED TO DETERMINE THE TRF. CLOCKWISE, FROM TOP LEFT: DORIS BEACON AT GGAO; GNSS ANTENNA AT PALMER STATION, ANTARCTICA; VGOS SYSTEM AT KPGO; NGSLR SYSTEM AT GGAO. VLBI PROVIDES THE LINK BETWEEN THE TRF AND CRF.

Challenges in Geodesy. The CORE Workshop attendees felt that NISAR deserved high priority; the solid-Earth science program has the opportunity to support research that will optimize the success of that observational platform for innovation and discovery in the solid-Earth sciences. This mission will also provide a regularly collected, openly available InSAR data set. The benefit of such a dataset has been confirmed by the early results of the ESA Sentinel satellite.

Other recent advances in geodetic imaging include improved processing methods for measuring surface deformation: for example, the development of persistent scatterer InSAR, improved methods for InSAR time series with integrated atmospheric models, testing of new imaging modes like ScanSAR, SweepSAR, and spotlight, and use of optical and SAR pixel tracking. Continued advances in InSAR data analysis and modeling by the solid-Earth science program will have important benefits for NISAR. There is also a need for easy access to InSAR analyses by those not involved in InSAR data processing, such as is available for GNSS data products from the IGS and other sources. Routine production of InSAR time series would greatly enhance the use of InSAR data.

Seafloor geodesy was described as a "frontier" in the SESWG Report, and it has evolved slowly since then. The main technical challenge is the acoustic measurement needed to position a point on the seafloor from a measurement on the surface, which is well defined within the terrestrial reference frame. Because of the expense and time involved, there are only a handful of seafloor monuments offshore South America, Hawaii, Cascadia, and the Japanese trenches.

Despite the challenges to be overcome, increasing the accessibility of the seafloor geodesy technique could have tremendous payoff given the large number of scientific targets relevant to the NASA solid-Earth science program covered by Earth's oceans. Exploratory research to improve existing or develop new technologies could be valuable to solid-Earth science program objectives. Advancements in this area will likely require multidisciplinary approaches, and could benefit from interagency coordination.

ACCOMPLISHMENTS SINCE SESWG

- Increased use and availability of high-rate, low-latency GNSS data streams and products
- Integration of seismic and high-rate GNSS data streams for early warning systems
- Improved precision in vertical position and velocity estimates from GNSS
- Improved time series analysis for observing transient deformation
- Improved methods for integrating geometric and gravimetric geodetic systems and observations
- Detailed characterization of ETS phenomenon at the base of the locked portion of many subduction zones around the planet
- Use of GNSS SNR for soil moisture, snow depth, and volcanic plume monitoring
- Use of precise orbital tracking information to obtain accurate InSAR results without adjustments or ground control
- Use of SweepSAR/ScanSAR and persistent scatterers to improve the spatial and temporal resolution of InSAR for earthquake and volcano events.
- InSAR time series with integrated atmospheric models and basic connection to the GNSS frame
- More widespread use of optical and SAR pixel tracking for studying solid-Earth deformation

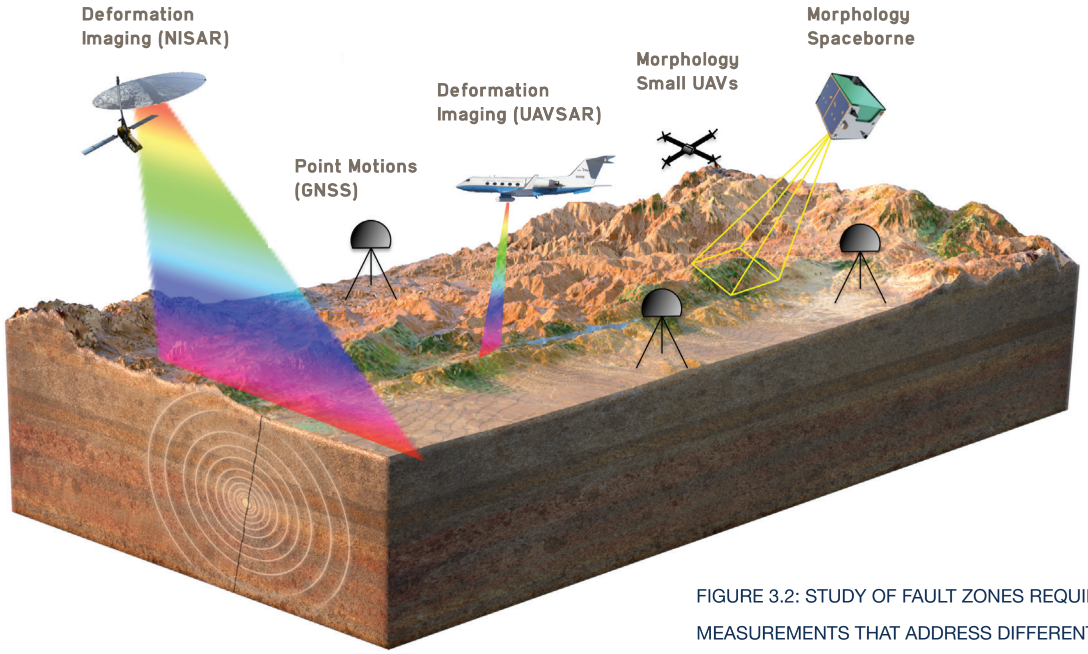


FIGURE 3.2: STUDY OF FAULT ZONES REQUIRES COMBINING MEASUREMENTS THAT ADDRESS DIFFERENT TEMPORAL AND SPATIAL SCALES.

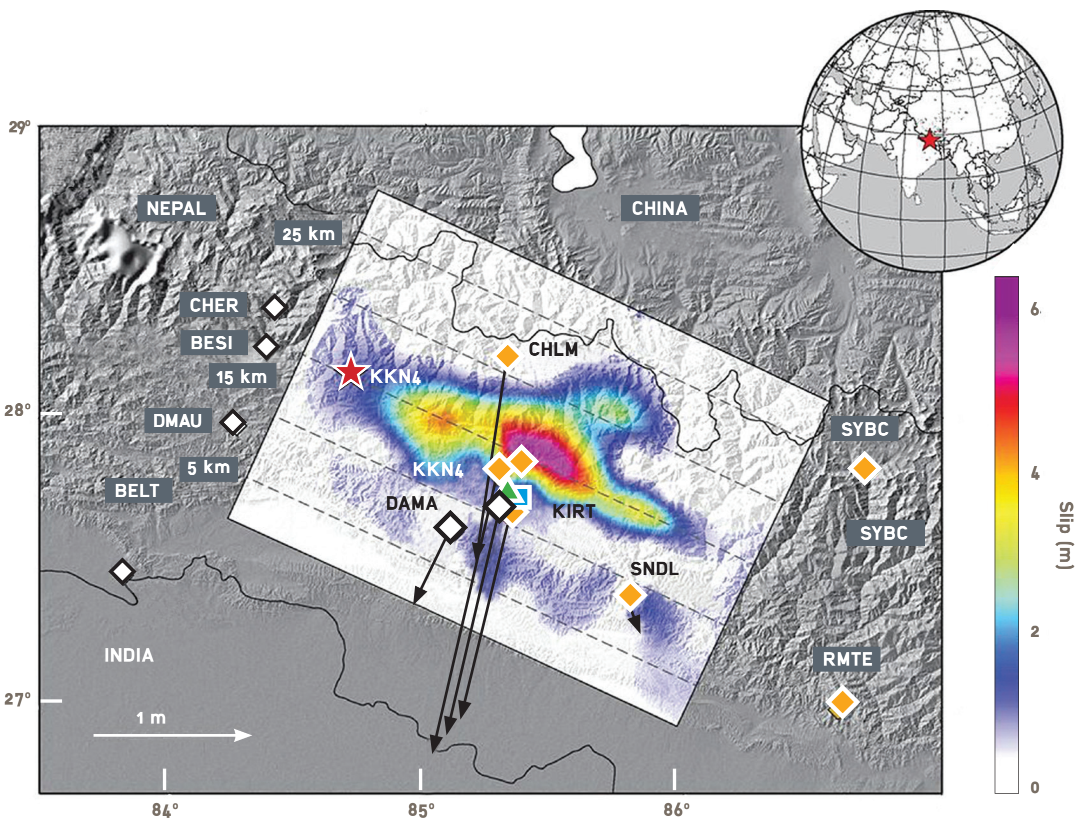


FIGURE 3.3: INSAR MEASURES LINE-OF-SIGHT SURFACE DEFORMATION WITH GREAT ACCURACY OVER A LARGE CONTIGUOUS AREA, WHEREAS GNSS (ARROWS) DETERMINES THREE-DIMENSIONAL CRUSTAL DEFORMATION AT DISCRETE LOCATIONS, AS WELL AS PROVIDING EXCELLENT TEMPORAL RESOLUTION AT THOSE SITES. (SEE FIGURE 2.11, FOR EXAMPLE.) THESE MEASUREMENTS CAN BE COMBINED TO STUDY SURFACE DEFORMATION AND INFER FAULT SLIP (COLORS).

- Seafloor geodetic observations of co-seismic seafloor motions for the 2011 Tohoku-Oki earthquake

ONGOING ACTIVITIES

- Deployment of new multi-constellation GNSS receivers
- Assessing the impact of GPS modernization
- Dedicated (non-U.S.) InSAR satellites with wide swath and/or spotlight modes
- NASA UAVSAR providing higher resolution InSAR imagery that can be oriented to optimally observe a variety of processes
- Establishment of free and open data policies for some sensors, including Sentinel and Landsat

FUTURE PLANS AND OPPORTUNITIES

- Exploiting additional GNSS constellations and increased availability of GNSS data from stations around the globe to improve precision on subdaily positioning to <1 cm
- Completion of operational early warning systems integrating surface deformation observations from seismic, strain, seafloor geodetic, and GNSS observations
- Development of automated processing of large InSAR time series as well as SAR and optical pixel tracking using precise geodetic techniques
- NISAR and other third-generation wide-swath satellites providing 12-day (or better) global coverage
- Exploring the utility of correlating volcano-plume detection from GNSS data with volcanic activity

HIGH-RESOLUTION TOPOGRAPHY

Topography of the land and seafloor is being imaged at increasing resolution from spaceborne, airborne, and ground-based sensors, making ubiquitous high-resolution topographic datasets possible, but with variable spatial coverage. In the last decade, significant progress has been made toward increasing the resolution of global DEMs using InSAR, ASTER, ICESat, and SRTM. Additionally, a plethora of high-resolution regional DEMs using aircraft and commercial high-resolution stereo-optical satellites with special access given to scientific researchers (SPOT, Pleaides, WorldView), are now available. High resolution typically refers to sub-meter sampling of Earth's surface or overlying canopy and built environment. This fine scale is where processes of interest operate and important transitions and phenomena occur (e.g., hillslope–fluvial transition and surface-rupturing earthquake displacements). The next decade will likely see an increase in resolution and repeat coverage (differencing new and legacy observations) yielding new insight into Earth processes and hazards. LIST, a high-resolution land topography mission, was recommended in the 2007 Decadal Survey.

Near coastal high-resolution topography and bathymetry are critical for advancing understanding of many tectonic and volcanic processes, ice sheet variability, landslide hazard assessment, sea-level change impacts, and evaluation of tsunami and hurricane inundation extent. Acquiring the needed high-resolution bathymetry of the near-coastal ocean region from aircraft, satellites, and ships is a technological challenge as well as a policy-fraught endeavor due to individual countries' security policies.

One of the goals for obtaining high-resolution topography from the SESWG Report was to "automate the measurement of landslide areas and volumes using differences in topographic

High-resolution topography typically refers to sub-meter sampling of Earth's surface or overlying canopy and built environment.

observations prior to and after each landslide event." Whereas we have obtained data for individual landslides, we have not reached or moved beyond this goal due to the spatial resolution of most current global topographic datasets. An important priority identified in the last 15 years has been to produce landslide hazard assessments using satellite data. A resolution of better than 5 m is needed for accurate landslide mapping, especially for area and volume estimates. A resolution of 1 m is preferred with vertical accuracy of better than 0.5 m (such as obtained from aircraft LIDAR).

InSAR and other imagery sources are providing new insights into deformation mapping for landslides, but the repeat time of any of these sensors is often the limiting factor in true estimation of pre- and post-landslide area/volume, and especially hazard assessment. Landslide and active faulting as well as fluvial and other hillslope processes require the fine sub-meter scale to characterize ground deformation and critical process transitions. Repeat observations are needed to understand processes and hazard response. The launch of Sentinel-1A in 2014 and 1B in 2016 will provide a 6-day repeat interval in tectonic zones of interest to the ESA community at C-band; NISAR will provide full global coverage at a 12-day cadence and improved L-band coherence.

The solid-Earth science program has the opportunity to provide input for and benefit from advanced spaceborne radar and LIDAR missions. LIDAR missions that provide repeated measurements for monitoring areas in which InSAR returns are incoherent—such as earthquake rupture and landslide zones, tundra, and marshes—are especially important. SWOT, in particular, will provide improved global bathymetry. To achieve the vision of repeat and ubiquitous topography and bathymetry for science, the solid-Earth science program can continue to invest in research in modeling and analysis, as well as in use of cyberinfrastructure. In particular, as high-resolution topographic and bathymetric data become ubiquitous, a critical challenge will be to provide processing and analysis solutions that enable rapid extraction of information from these datasets.

ACCOMPLISHMENTS SINCE SESWG

- Produced revolutionary SRTM and ASTER near-global 30-m topography data having significant impacts on the fields of geology, geophysics, hydrology, and geography
- DEMs provided significant improvement of topographic corrections for InSAR analyses
- Acquired aircraft LIDAR data for high-resolution topography in fault zones, coastal processes/bathymetry, volcanoes, landslides, and flood plains
- ICESat provided elevations with decimeter-level accuracy of land and glaciers for global geodetic control and measuring volume changes

ONGOING ACTIVITIES

- TerraSAR Tandem-X is providing the next generation of global topography at 12-m resolution
- Merging SRTM, ASTER, and ICESat are improving accuracy and coverage
- Improved marine gravity maps from CryoSAT-2 and Jason-1 are improving global bathymetry maps

- ICESat-2 (2017) will continue ICESat's measurements of change in volume of the Greenland and Antarctic ice sheets as well as long-term trend analysis of sea-ice thickness
- GEDI (2018) will expand upon ICESat's land topography and vegetation vertical structure profiles
- Sub-meter resolution stereo optical DEMs from commercial sensors such as WorldView 1,2,3 and GEOEYE sensors are becoming available for specific scientific and application targets

FUTURE PLANS AND OPPORTUNITIES

- Global Lidar or radar missions to map and monitor the 3D topography and vegetation cover of Earth for natural hazard and geomorphic process studies
- Rapidly expanding UAV imaging for commercial recreational uses to produce massive photogrammetric 3D point clouds with great value for integration with synoptic coverage from NASA assets
- SWOT (2020) altimeter mission will provide improved global bathymetry

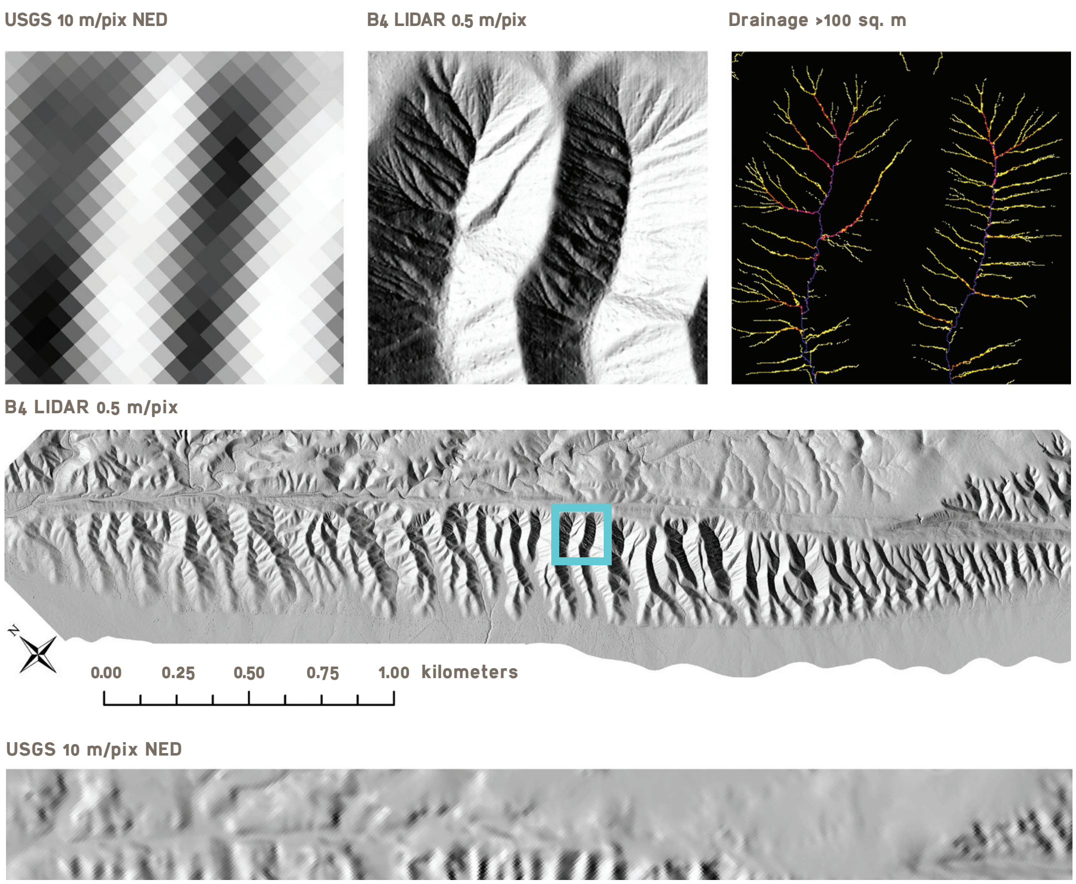


FIGURE 3.4: HIGH-RESOLUTION TOPOGRAPHIC DATA CAN BE USED TO DERIVE GEOMORPHIC METRICS FOR SURFACE PROCESS CHARACTERIZATION. THIS FIGURE ALSO ILLUSTRATES THE SIGNIFICANCE OF RESOLUTION IN REPRESENTATION OF CRITICAL LANDSCAPE ELEMENTS AT THE APPROPRIATE SCALE.

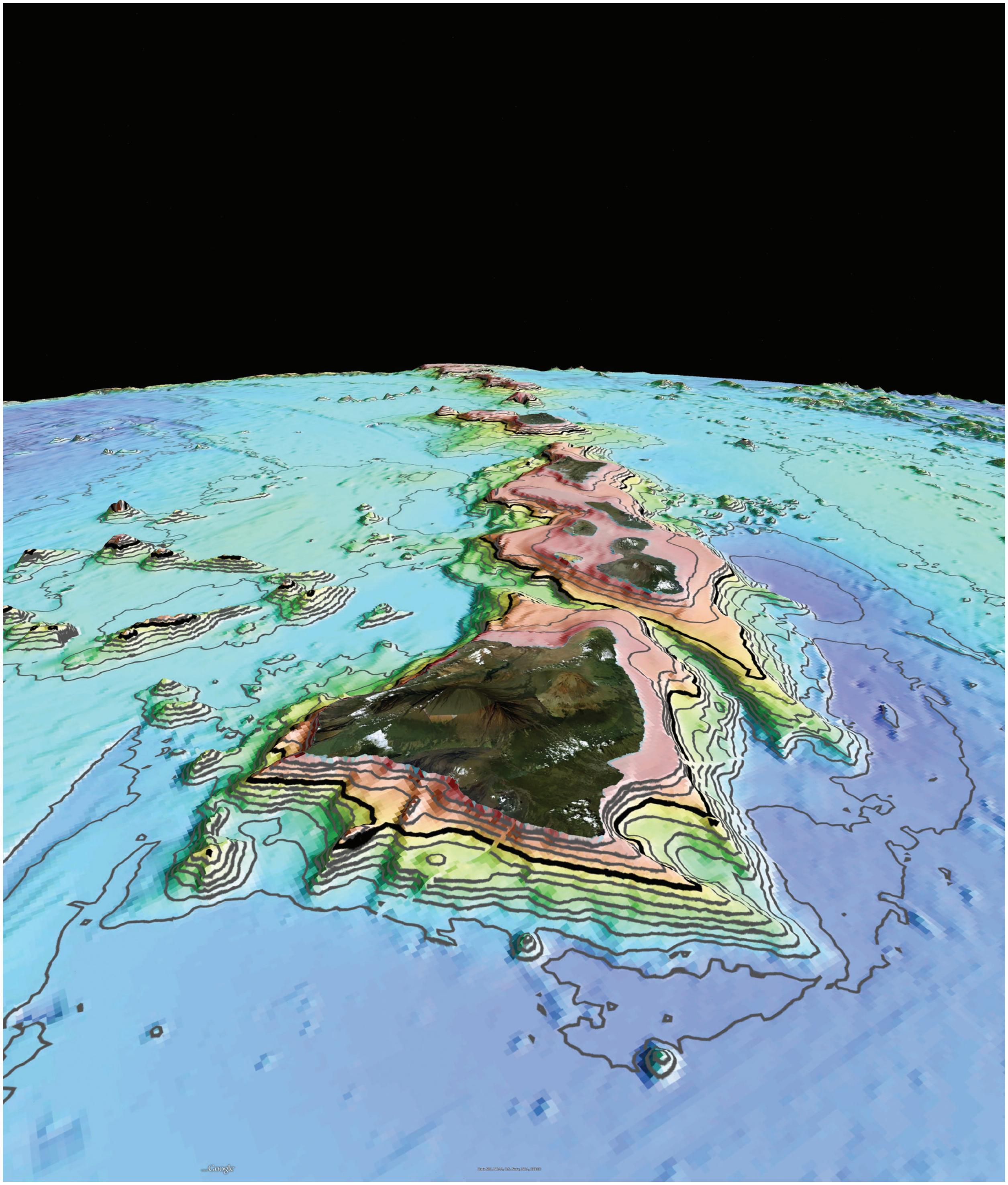


FIGURE 3.5: SATELLITE ALTIMETERS MEASURE THE TOPOGRAPHY OF THE OCEAN SURFACE, AN APPROXIMATION TO THE GEOID. ADAPTIVE PROCESSING OF THE GEOID IS USED TO PREDICT THE BATHYMETRY OF THE 83 PERCENT OF THE SEAFLOOR NOT SURVEYED BY SHIPS. COMBINING SHIP SOUNDINGS AND SATELLITE ALTIMETRY PRODUCES HIGH-RESOLUTION BATHYMETRY LIKE THAT OF THE HAWAIIAN ISLANDS AND SURROUNDING SEAFLOOR (ABOVE).

VARIABILITY OF EARTH'S MAGNETIC FIELD

After the successes of Ørsted, CHAMP, and SAC-C in the 2000–10 timeframe, ESA launched the three-satellite Swarm mission in 2013. Modeled on the CHAMP spacecraft, Swarm is a dedicated magnetic field mission that includes measurement of electric fields and plasma, as well as non-gravitational spacecraft accelerations, in order to improve source separation. Depending on solar variability, the three-satellite aspect of the mission may extend into the 2020s, ultimately descending to altitudes below 300–400 km with unrivaled sensitivity to observe lithospheric fields.

NASA has two geomagnetic initiatives: a multi-year effort to develop a space-ready helium scalar-vector magnetometer package under the auspices of NASA ESTO, and a more exploratory program with ONR and NGA to develop a technique to measure mesospheric (~90 km) magnetic fields. The helium magnetometer would allow virtually simultaneous measurements of the scalar and vector fields, and might, with the addition of a star camera and a boom, be added in a piggy-back configuration to missions with related interests. The mesospheric magnetic field measurements rely on atomic sodium from the decomposition of micro-meteorites. ONR, NGA, and NASA are supporting initiatives that could take this technique to orbit, a process that may take a decade or more.

In the future there should be opportunities for NASA leadership in magnetic satellite missions involving multiple simultaneous observation platforms. Initiatives for assessing the variability of the magnetic field might make use of both orbital and sub-orbital assets. For example, CubeSats, with university involvement, are a burgeoning class of inexpensive orbital assets; however, because they are small the problem of magnetic cleanliness becomes more important. The design of a non-magnetic bus would allow these orbital assets to address science questions related to the variations of the magnetic field. Sub-orbital assets flying at altitudes from 2–20 km with the scalar-vector helium magnetometer, exemplified by the Global Hawk and its smaller kin, can address topical questions with magnetic aspects, and do so much closer to the source. For example, the magnetic and gravity signatures associated with serpentinization in the lower crust along subduction zones can assist in illuminating factors contributing to earthquake processes, and those same magnetic measurements can contribute to our understanding of the magnetic signature of ocean circulation.

ACCOMPLISHMENTS SINCE SESWG

- Launch of Swarm in 2013, with a possible 7 to 10+ year lifetime
- Accurate prediction of core field variability over a 5- to 10-year period with data assimilation
- Global very high-resolution (5 km) maps of the lithospheric magnetic field using satellite, airborne, and marine magnetic data with implications for tectonic, igneous, and impact processes
- Determination of high-degree (≥ 30) core dynamics with high-frequency (sub-decadal) secular variation
- Successful separation of various near-Earth magnetic field sources such as core, crust, lithosphere, ionosphere, magnetosphere, and oceanic M2 tide

ONGOING ACTIVITIES

- Airborne testing of scalar-vector helium magnetometer
- Ongoing efforts for combination of Swarm data sets with other magnetic data sets for separation of geophysical signals
- Validating the concept of remote sensing of magnetic fields in the mesosphere using GuideStar technology

- Long-term (> 100 y) comprehensive magnetic field modeling

FUTURE PLANS AND OPPORTUNITIES

- Swarm-2 magnetic mission in the 2020s using SmallSat or CubeSat buses measuring in situ fields and gradients, and remotely sensed mesospheric fields
- Long-term, continuous monitoring (and analyses) of geomagnetic variations related to climate

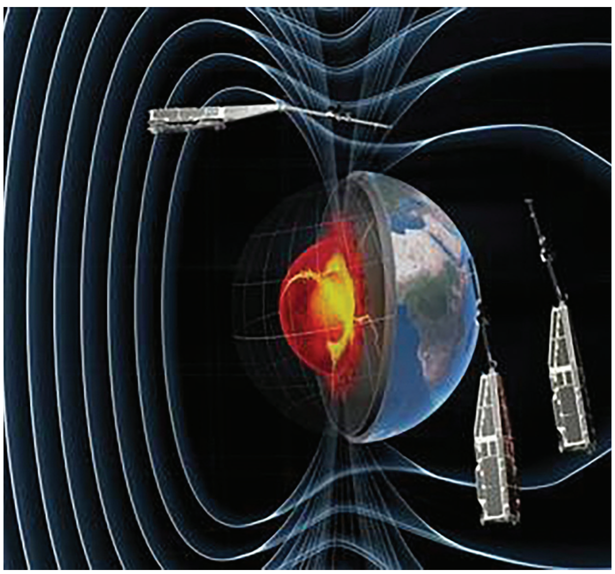


FIGURE 3.6: THE ESA SWARM MISSION MEASURES EARTH'S MAGNETIC FIELD.

VARIABILITY OF EARTH'S GRAVITY FIELD

The GRACE (2002–) and GOCE (2009–13) missions have been used to investigate Earth's time-varying gravity from multiple sources and a spectrum of spatio-temporal wavelengths. These missions have had a profound impact on scientific understanding of the underlying processes involved in fluid mass transport at the surface of Earth, as well as on the public's awareness of the impact of climate change.

Rigorous data combinations using GRACE with other space and terrestrial data sets hold much promise for separating physical processes as well as for improving the spatial and temporal resolution of the combined estimates. By improving the observations of GIA in North America and Scandinavia using GNSS and other data, the GRACE residual trend may be capable of resolving water storage trends to less than ±5 Gt/yr, for example. Combination of tide-gauge data, satellite sea-surface altimetry, and GRACE data may be useful in separating spatially and temporally variable sea-level signals as well as in estimating the GIA contribution to sea-level change.

The GRACE mission produced a paradigm shift in the view of the importance of observing time-variable gravity data, from that of being a useful and highly interesting scientific experiment to being a necessity in a period of climate change for the continuous monitoring of global ice mass changes and the exchange of water among Earth's systems. In order to reduce the potential data gap following the end of GRACE, the GRACE Follow-On (GRACE-FO) mission was proposed using essentially the same technology as GRACE; in addition to the K-band ranging system, GRACE-FO will also test an experimental laser-ranging instrument using lasers instead of microwaves, with a potential ranging accuracy improvement of a factor of ~20.

Goals for future observational systems that would significantly assist in separating sources of gravity variability include improvements in the accuracy of background geophysical models, errors that lead to aliasing; and improvements in the star tracker, and accelerometer. Planned improvements for the latter should account for a factor of 3–4 reduction in error. Use of multiple GRACE-like satellite system pairs would also significantly reduce the resonance error leading to "stripes" in the GRACE fields.

Solid-Earth science can benefit significantly from GRACE (and follow-on) missions. GIA causes deformation of the crust that can be measured using GNSS systems; gravity and sea-level observations provide different views of the same process. The challenge is in separating the various processes that simultaneously impact deformational, gravity, and even sea-level measurements. Investigating GIA is therefore useful on several levels. Improvement in GIA fields lead to insights into Earth's rheological structure. At the same time, improved GIA predictions improve our estimates of cryospheric mass loss and other exchanges of water-mass among Earth's systems. While significant advances have been made recently in GIA models, these models are highly non-unique and observational approaches are still vital.

ACCOMPLISHMENTS SINCE SESWG

- Launch of GRACE in 2002 and extension of the GRACE mission
- Observations of co- and post-seismic gravity variations constrain seismic source parameters
- Improvement of models of Earth's viscosity structure from earthquake and GIA observations
- Observations of global seasonal water exchange
- Estimation of mass loss in major glaciated regions of Earth: Greenland, Antarctica, Patagonia, Alaska, and others
- Discovery of accelerated mass loss in Greenland and Antarctica
- Observation of mass loss due to droughts, in California, for example
- Observations of seasonal and event-driven mass exchange between continents and oceans

ONGOING ACTIVITIES

- GRACE-FO (not before late 2017)
- Ongoing efforts for combination of GRACE and other geodetic data sets for separation of geophysical signals

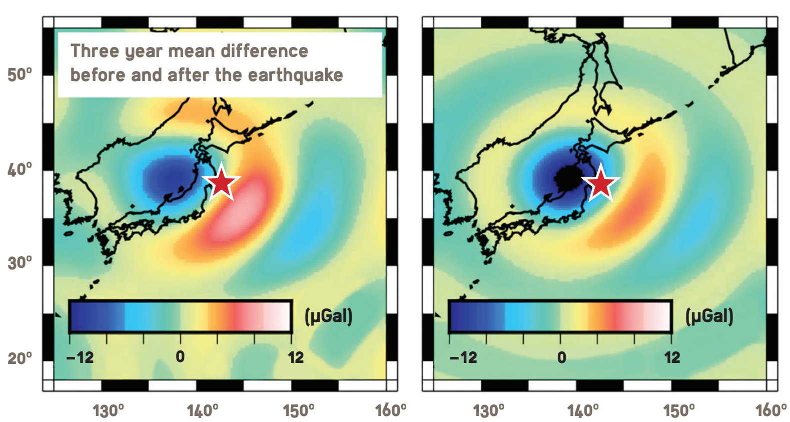


FIGURE 3.7: RAPID GRAVITY CHANGES OVER LARGE AREAS FROM GRACE ARE A NEW WAY OF STUDYING SEISMIC EVENTS. SHOWN: COMBINED CO-SEISMIC AND PARTIAL POST-SEISMIC DEFORMATION FROM THE 2011 TOHOKU-OKI EARTHQUAKE USING (A) GRACE DATA AND (B) A CO-SEISMIC RUPTURE MODEL.

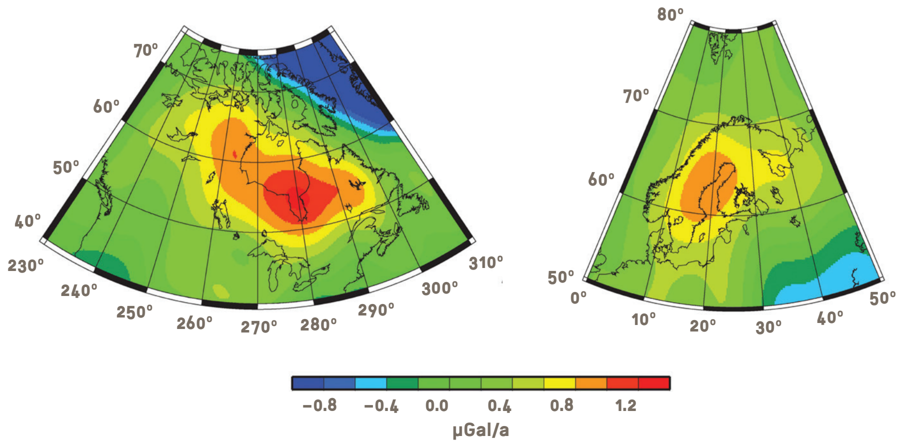


FIGURE 3.8: STUDYING GIA HELPS US IMPROVE OUR UNDERSTANDING OF THE STRUCTURE AND DYNAMICS OF THE SOLID EARTH, AS WELL AS THE IMPACT OF PAST AND PRESENT-DAY CLIMATE AND SEA-LEVEL CHANGE. GRACE HAS PROVIDED DETAILED MAPS OF GRAVITY CHANGES DUE TO GIA IN (A) CANADA AND (B) FENNOSCANDIA.

FUTURE PLANS AND OPPORTUNITIES

- GRACE-II
- Extend mission time to several decades to observe non-secular changes in gravity
- Fly multiple satellite pairs to achieve better spatial and temporal resolution.

IMAGING SPECTROSCOPY

Imaging spectroscopy (or "hyperspectral imaging") provides a means of identifying the composition of near-surface minerals and gases for a wide range of science questions and applications. The technique can, for example, contribute to our understanding of plate boundaries, by providing information about the surface geochemistry and mineralogy that directly reflect plate boundary pressure and temperature regimes, history, and evolution over large scales. Applications include determining the availability of mineral resources and assessing the susceptibility of a region to certain hazards like landslides, volcanic eruptions, or coastal erosion. (The SESWG Report provides a detailed discussion of applications.) Temporal variations in these measurements allow for assessment of natural and human-induced changes like dust clouds, soil moisture, and volcanic plumes.

An important trade-off in spaceborne remote sensing spectroscopy measurements relates to the spectral, spatial, and temporal resolution of the measurements. The higher the spectral resolution, the weaker the signal from the ground, and vice versa. In addition, for a given instrument in a Sun-synchronous orbit, the image width controls the revisit time with a wider image providing a more frequent revisit but higher data volume. In the future, data volume will increase further as the spatial and spectral resolutions increase, presenting challenges for downlinking of all data in a timely fashion. These technological challenges have, in part, limited the development of spaceborne imaging spectroscopy missions and led to a focus since the SESWG Report on airborne spectroscopy missions. Recent orbital missions include the U.S. EO1-Hyperion (currently past its nominal end of life) and the ISS-based HICO mission (2009–2014).

The technological challenges described above have now been largely overcome with the development of more sensitive detectors, new optical approaches, and onboard processing, and there are now several spaceborne imaging spectrometer missions in development. These include the German EnMAP mission, the Japanese HISUI mission, the Italian PRISMA mission, and the U.S. HyspIRI mission (see below). With the exception of

HyspIRI, all of the aforementioned missions operate only in the visible to short-wavelength infrared (VSWIR) part of the electromagnetic spectrum. Longer wavelength, thermal infrared observations provide greater compositional discrimination for surficial materials. Such missions are now possible due to recent technological advances that have been demonstrated on airborne instruments.

The HyspIRI mission is a major initiative of potentially great benefit to the solid-Earth science program. HyspIRI is the only future mission concept carrying an imaging VSWIR spectrometer and multispectral MIR and TIR imager, and will be used in a large range of science and applications including volcanology, surface mineral mapping, studying the impacts of climate change on terrestrial and aquatic ecosystems, and land use changes. The main relevance of HyspIRI to solid-Earth science will be for volcanic studies, since its multispectral instrumentation is uniquely suited to allow identification of changes in surface composition, temperature, and gas and aerosol emission that will improve our understanding of and perhaps even facilitate forecasting of volcanic eruptions and lava flow hazards. For example, HyspIRI's TIR and VSWIR instruments will enable us to monitor the temperature, area, and color of volcanic crater lakes to quantify energy and chemical fluxes that provide indirect evidence of the activity of the underlying magma bodies.

ACCOMPLISHMENTS SINCE SESWG

- Operation of AVIRIS, AVIRIS-NG, and HyTES on airborne platforms
- Operation of Hyperion and HICO on spaceborne platforms
- Recent advances in detectors, optics, and electronics have enabled imaging spectroscopy throughout the optical region (0.4–12 um).
- Demonstration that hyperspectral imaging can identify the composition of surface and atmospheric gases (e.g., methane and sulfur dioxide leaks)
- Mineral discrimination and detection over visible to thermal infrared wavelength range

ONGOING ACTIVITIES

- Continued development of international spaceborne VSWIR platforms to be launched in the 2018–2023 timeframe: EnMAP (Germany), HISUI (Japan), PRISMA (Italy)
- Planning for the HyspIRI mission recommended by the 2007 Decadal Survey that would include hyperspectral imaging in VSWIR, and unique multi-spectral capabilities for an orbital platform in the MIR and TIR
- Continued flights of AVIRIS, AVIRIS-NG, and HyTES for geologic and other studies, including the first joint flights of AVIRIS and HyTES on a NASA ER-2

FUTURE PLANS AND OPPORTUNITIES

- Development of imaging spectrometers spanning multiple wavelength regions
- Systematic mapping of the entire land surface of Earth by HyspIRI
- Development of a spaceborne TIR imaging spectrometer for study and forecast of volcanic behavior
- Development of a spaceborne VSWIR and TIR imaging spectrometer for mineral mapping

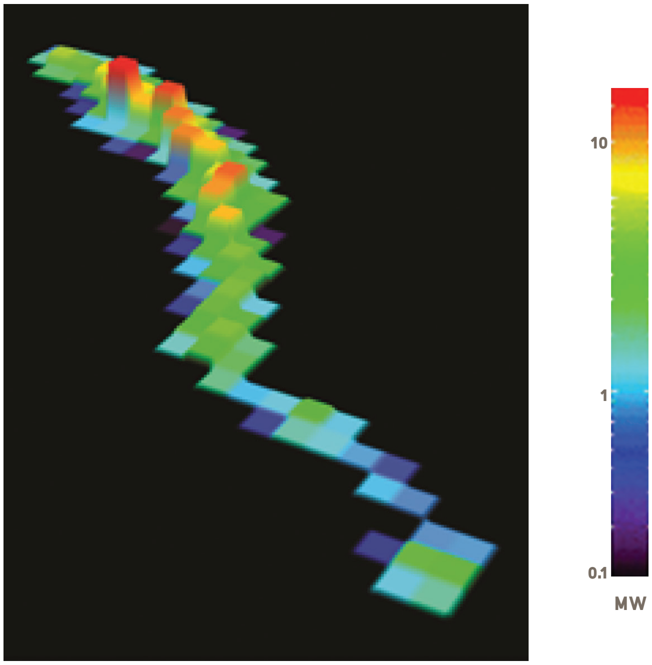


FIGURE 3.9: HYPERSPECTRAL DATA CAN BE USED TO MEASURE THE COOLING RATE OF LAVA FLOWS. HERE, HYPERION OBSERVATIONS OF COOLING OF AN ACTIVE LAVA FLOW AT MOUNT ETNA, SICILY.

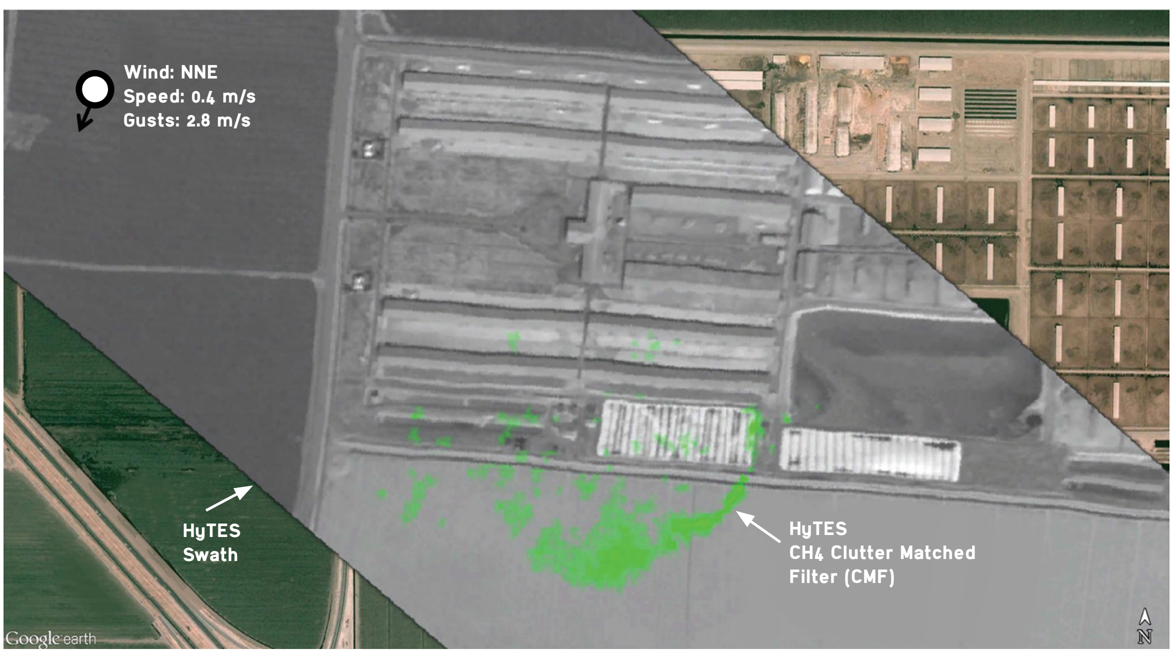
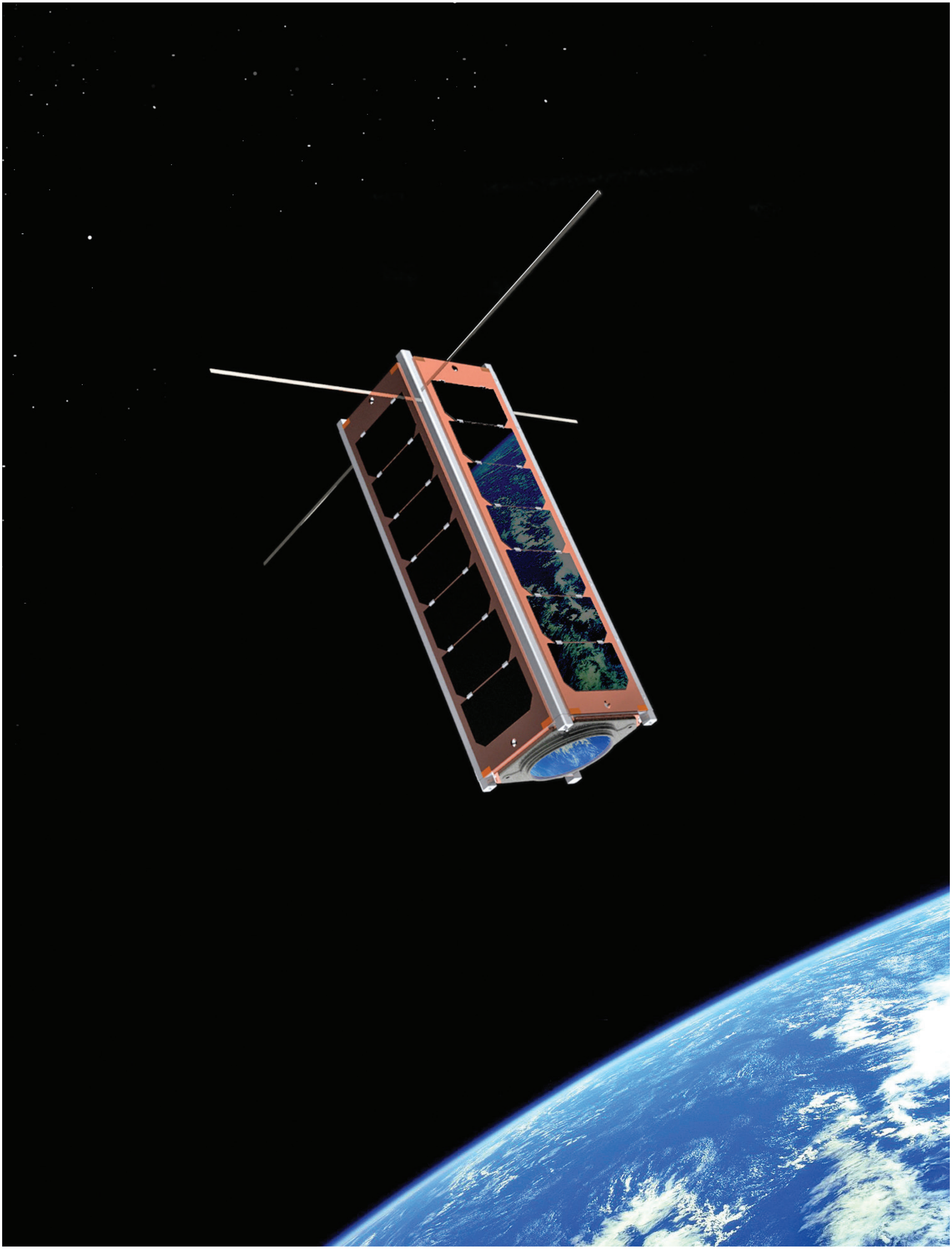


FIGURE 3.10: HYPERSPECTRAL IMAGING HAS MANY SOCIETAL BENEFITS. HERE, A METHANE PLUME FROM A DAIRY FARM IS DETECTED WITH HYTES.



3.2

Science Enablers

In this section, we review activity in several areas that contribute significantly to the solid-Earth science program. Two of these areas—one involving analysis of large data sets and use of high-performance computational assets, the other involving low-latency or near-real-time data—were at a much more nascent stage at the time of the SESWG Report. All topics in this section are linked to rapid changes in technology, and are thus "moving targets" that nevertheless could have large payoffs for solid-Earth science.

TECHNOLOGY DEVELOPMENT

Advancing the scientific research goals described in this document depends critically on continued technology development. The observational systems discussed above utilize cutting-edge technology or require the development of new technology. New technologies are required as we gain an increasing appreciation of the complexity of interactions within the Earth system and seek simultaneous improvements in the spatial resolution, temporal resolution, and accuracy of observational systems.

The overall landscape of technology development has significantly evolved since the SESWG report, with new actors including commercial space systems developers who are making rapid progress towards space exploration, and low-cost systems such as the CubeSat program. These very different developments create potentials for new partnerships, innovation, and engaging broader sectors of the general public in space exploration of Earth's surface and interior. CubeSat, for example, involves a large number of students in CubeSat building and development, while commercial launch providers can get these small satellites into orbit rapidly and inexpensively. These developments present both opportunities and risks for long-term science exploration.

Development of technology significantly impacts science, but often with a time delay. Investment in technology today may have a modest impact initially, and a profound impact several years later. The specific role for the solid-Earth science program in the development of a particular technology may vary greatly; coordination between NASA directorates, divisions, programs, and missions is crucial to identifying specific opportunities and possible benefits. These interactions benefit from a culture of openly available data and the existence of robust data centers that facilitate information exchange and computational facilities that enable modeling.

The benefits have been two-way. The solid-Earth science program has benefited from technologies developed for other areas, and the reverse is also true: technologies developed specifically for solid-Earth science have been critical to advances in other areas. For example, the technology used in the GRACE mission emerged from technology

LEFT: ARTIST'S CONCEPT OF A CUBESAT IN EARTH ORBIT.

and techniques developed for solid-Earth geophysics and has impacts that cross disciplinary boundaries, such as enabling scientists to map changes in groundwater reservoirs, especially during droughts. Another example is the GNSS signal-to-noise ratio (SNR) measurements, originally studied to help mitigate multipath errors, and not generally used in high-accuracy geodetic solutions. These SNR measurements have been shown to yield information on soil moisture, snow depth, volcanic plumes, and water height.

BIG DATA, HIGH-PERFORMANCE COMPUTING, AND COMMUNITY SOFTWARE

The past two decades have seen the accelerating acquisition and availability of high-resolution 4D observational data, together with increased computational power for both data analysis and for modeling and simulation of Earth processes. This creates both a need, and an opportunity, for leadership in four key areas of computational capability for solid-Earth research and applications: acquisition and management of large, complex, and diverse space-based data; high-quality software for data analysis, modeling, and simulation; computational power for analysis and modeling; and skills, knowledge, and leadership in computational science related to solid-Earth sciences—the human factor.

Datasets for solid-Earth science research have grown in size by orders of magnitude due to increases in the number and variety of ground, airborne, and spaceborne observing platforms and stations, increases in sampling rates, and improvements in telemetry. The field has essentially moved from "data poor" to "data rich." For example, geodetic investigations of active tectonics have gone in the past two decades from painstakingly acquired GNSS and VLBI to real-time characterization of topographic change using continuous GNSS, LIDAR, InSAR, and related technologies, as noted in Section 2.4 and throughout in this report. Future Earth science missions will produce terabytes of data per day. The volume and complexity of Earth science data increasingly requires advanced computational capability at all stages, including onboard processing during data acquisition, high-rate and high-volume data telemetry, easy and sustained access to data and data products by the scientific community, automated data mining, modeling, analysis, and visualization of data, quantification of uncertainty in data, computing capability for integration of diverse data and models, and sustained curation of data to enable accurate long-term studies of changes in Earth's surface and interior.

Many of the science objectives stated in this document rely not only on acquisition of data using space-based technology, but also on development and sustaining of the high-quality software used to analyze the data, and the computational models required to interpret the observations. Well-vetted community scientific software is essential to the goals of the solid-Earth science program. These needs include code for converting low-level data into higher-level products useful for extracting scientific information, and scientific modeling software. Redundancy is essential to ensure quality of data analysis and to minimize uncertainty; the science requires multiple groups using several software approaches to independently analyze data and compare results, resulting in improved and validated code. Advancing the science goals in this report will benefit greatly from having multiple open software packages for analysis of each data type, developed using best practices, to enable benchmarking, testing, and quality control. For example, community codes, such as the large assemblage of programs supported by the NSF-funded Computational Infrastructure for Geodynamics (CIG), enhance continued scientific advancement from the broad community.

In addition to calibration and validation of satellite data from well-documented ground sites, an essential way to ensure that data are correctly processed is to have multiple groups process the same datasets using a variety of software and algorithms. This approach also requires that the different groups have a complete understanding of the inner workings of their algorithms and software so that modules can be repaired and updated. Effective use of scientific software requires high-quality documentation, training, tutorials, and standard workflow examples to develop the computational skills of current and future scientists. This development of the workforce includes not only training on specific software, but development of computational thinking and a workforce prepared to develop software that takes advantage of new computer architectures. Training and workforce development are further discussed in Section 3.6. There is also an ongoing need for a source of stable funding for the most heavily used software packages, including the staffing of qualified developers and user support. As packages and processing methods mature, analysis packages should evolve to cloud-based computing to accommodate more users who do not want to be experts.

Analysis and interpretation of big data and forward modeling of complex processes and systems in Earth's surface and interior increasingly require high performance computing for sufficient resolution and speed. Near-real-time simulation and modeling of fault systems, landslides, and volcanoes that assimilate 4D data on surface changes is essential for rapid response to hazards, and requires high-speed communications and high performance computing. For example, the CATMIP Bayesian framework has been used to understand earthquake fault slip across different phases of the seismic cycle. This software is routinely run on thousands of computer cores, and its successor, ALTAR, is being developed to scale similarly on GPU nodes. Similarly, deep-Earth research on problems such as Earth's dynamo are running on the world's largest supercomputers, enabled by advances in computational methods and hardware. These and other important computationally driven research can benefit from NASA investments and partnerships on advanced cyberinfrastructure.

Future Earth science missions will produce terabytes of data per day. The volume and complexity of Earth science data increasingly requires advanced computational capability at all stages, including onboard processing during data acquisition, high-rate and high-volume data telemetry, easy and sustained access to data and data products by the scientific community, automated data mining, modeling, analysis, and visualization of data, quantification of uncertainty in data, computing capability for integration of diverse data and models, and sustained curation of data to enable accurate long-term studies of changes in Earth's surface and interior.

Big data and high-performance computing for analysis, modeling, and simulation have become essential components of nearly every aspect of research on Earth's surface and interior. Sustained investments in community software, data, high-performance computing, and education and training will be ongoing needs and provide an opportunity for ongoing leadership in computing for science.

LOW-LATENCY DATA AND DATA PRODUCTS

Low-latency data refers to datasets that are de facto real-time (available within a few seconds), or available more quickly than typical standard data or data product streams. There has been a dramatic increase since the SESWG Report in the availability of low-latency data, and the communication, computational, and modeling infrastructure to support their exploitation for a variety of applications. Such data are scientifically useful and contribute to monitoring, forecasting, and response activities.

Low-latency data are critical for a broad range of monitoring and forecasting needs and clearly demonstrate the relevancy of our space-based observations for society. Low-latency data acquisition after a geophysical event helps inform appropriate and timely deployment of limited resources in order to capture rapidly evolving processes. Low-latency data serve multiple purposes: they enhance our understanding of the short-term or transient deformation at plate boundaries; they provide feedback between basic research and applied sciences; and they are useful for study and mitigation of hazards such as earthquakes, tsunamis, and landslides. In addition, development of low-latency data products, models, and forecasts drives improvement in the quality and accuracy of both the data and models, which advances the solid-Earth science program more broadly.

Low-latency data are key to several current NASA projects, including READI, which focuses on developing a prototype earthquake and tsunami early warning system based on high-rate GNSS observations, and ARIA, the goal of which is to produce high-quality geodetic imaging data and data products, including InSAR- and GNSS-derived ground deformation images and damage proxy maps. Coordination of research in the solid-Earth science program with these and similar projects—both for the development of new technology and for technology transfer—is essential.

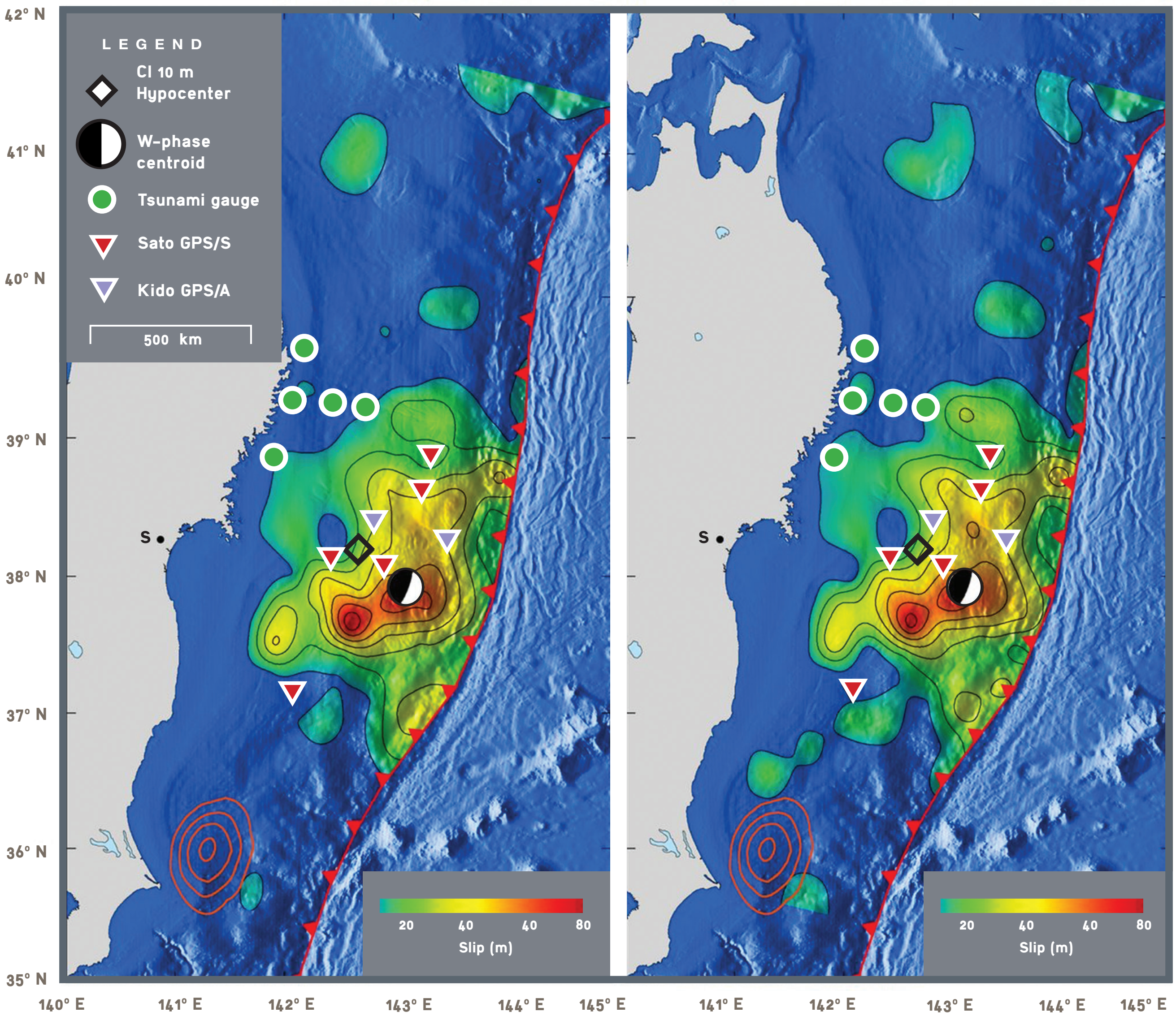
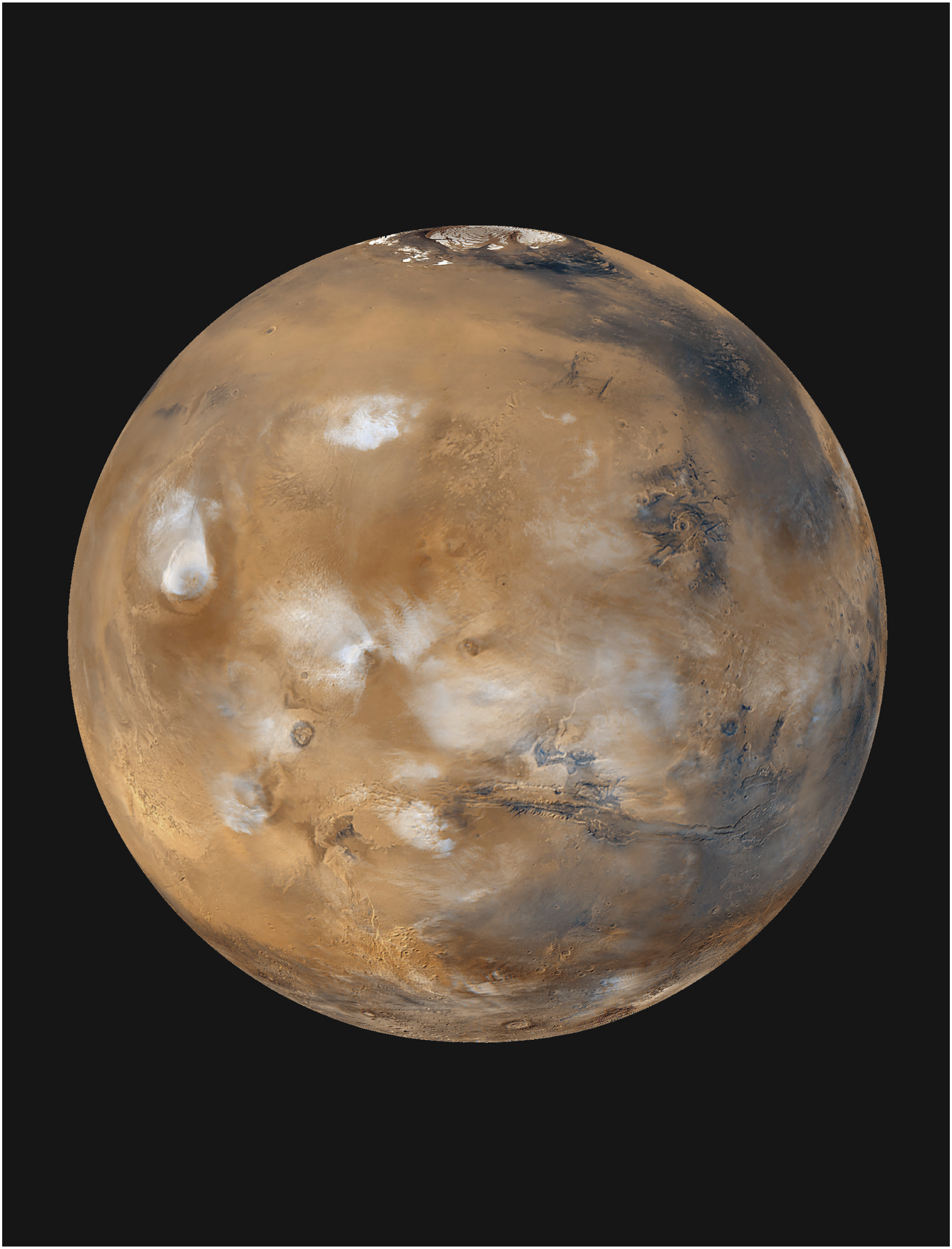


FIGURE 3.11: MEAN POSTERIOR SLIP DISTRIBUTION FROM STATIC INVERSION (LEFT PANEL) AND JOINT KINEMATIC-STATIC INVERSION (RIGHT PANEL) FROM THE 2010 TOHOKU EARTHQUAKE, COMPUTED USING NASA'S PLEIADES SUPERCOMPUTER. RED CONTOUR LINES DENOTE SLIP MODEL FOR LARGEST AFTERSHOCK SHOWN WITH A CONTOUR INTERVAL OF 1 M. THE LOCATION OF THE CITY OF SENDAI IS MARKED BY THE LETTER S.



3.3

Comparative Planetology

Comparative planetology is most often used to study the terrestrial planets by comparison with Earth, but the reverse process is also valuable. Smaller terrestrial planets have evolved at different rates and to different stages than Earth, and the processes that shaped and continue to shape the surfaces and interiors of those bodies are often easier to understand and model than comparable processes on the rapidly changing and complex planet Earth. The value of comparative planetology and its relevance for the solid-Earth science program were strongly voiced at the CORE Workshop and are articulated here.

There are a number of areas that present immediate opportunities for study. For example, in research on the origin and evolution of planetary magnetic fields, observational evidence of field strength, dipole orientation, and other characteristics from the other planetary bodies may at the very least serve to limit or constrain models of the long-term evolution of Earth's field. Other opportunities for comparison include planetary volcanism, tectonics, gravity, and landscape evolution. The context offered by many planets of differing sizes and masses, where processes relevant to Earth's own evolution may operate on different spatial and temporal scales, is vital to understanding to what extent the products of Earth's long history are unique. The clues to what might have been, and how Earth might have evolved differently, can certainly be imagined; the records seen on other worlds provide the realistic constraints that limit unbounded speculation.

Constraints in planetary evolution are useful also when considering the growing field of exoplanets. There are likely limits to what the many "super Earths" now being discovered can actually be, because although there is diversity in rates of evolution and ultimate states of terrestrial planets in our system, the basic geologic processes at their most basic physical and chemical levels are the same. It is reasonable to ask how those same processes might operate in a system in which rocky planets can be several times larger and more massive than the largest in our system, and as a result how quickly and to what end state those planets will evolve.

In addition, synergies can arise from shared methodologies. The success of the GRACE mission on Earth has been extended to the Moon as the GRAIL mission, which has revealed the lunar gravity field in previously unobtainable detail. Future crewed exploration of Mars would benefit from a satellite constellation analogous to GNSS for navigation and communications. Benefits derived from shared methodologies can flow in both directions. For example, the extremely high resolution of the GRAIL data required development of new mathematical approaches that can now be used in the development of Earth gravity and magnetic models. Models for atmospheric radio refraction were initially developed for Mars missions, but

LEFT: THOUGH MARS IS OBVIOUSLY DIFFERENT THAN OUR HOME PLANET, GEOLOGIC PROCESSES ARE SURPRISINGLY SIMILAR.

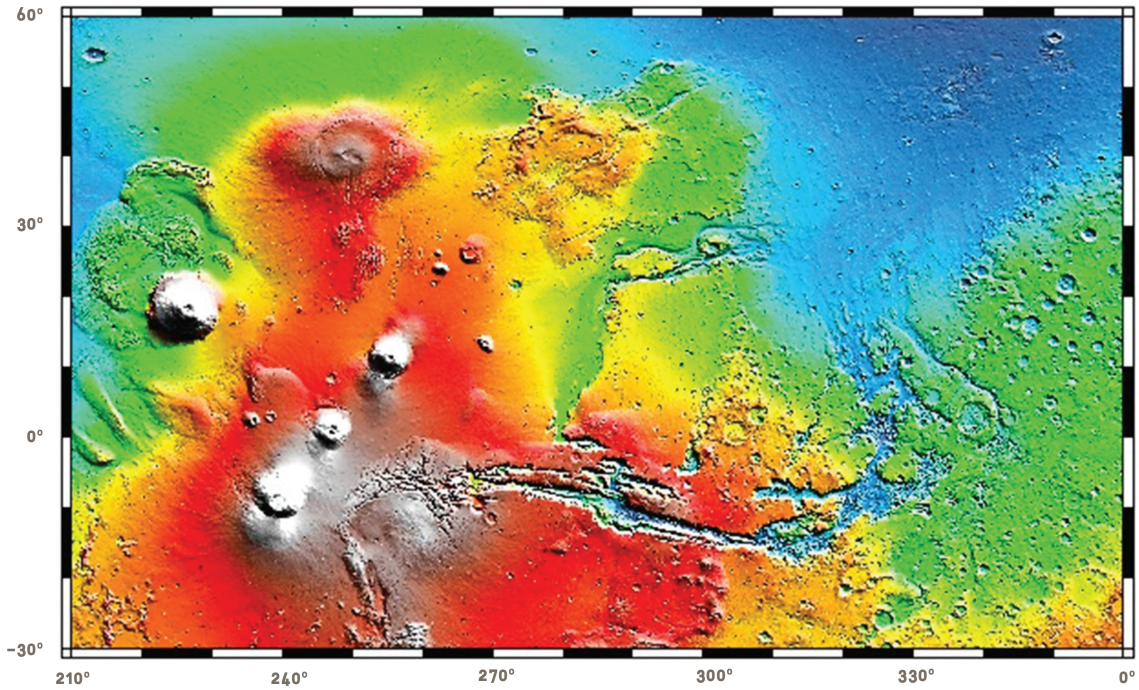


FIGURE 3.12: THERE IS AN OPPORTUNITY FOR NEW COLLABORATIONS BETWEEN SCIENTISTS STUDYING EARTH AND OTHER PLANETS. HERE, THE TOPOGRAPHY OF THE THARSIS REGION OF MARS FROM THE NASA MOLA MISSION IS SHOWN.

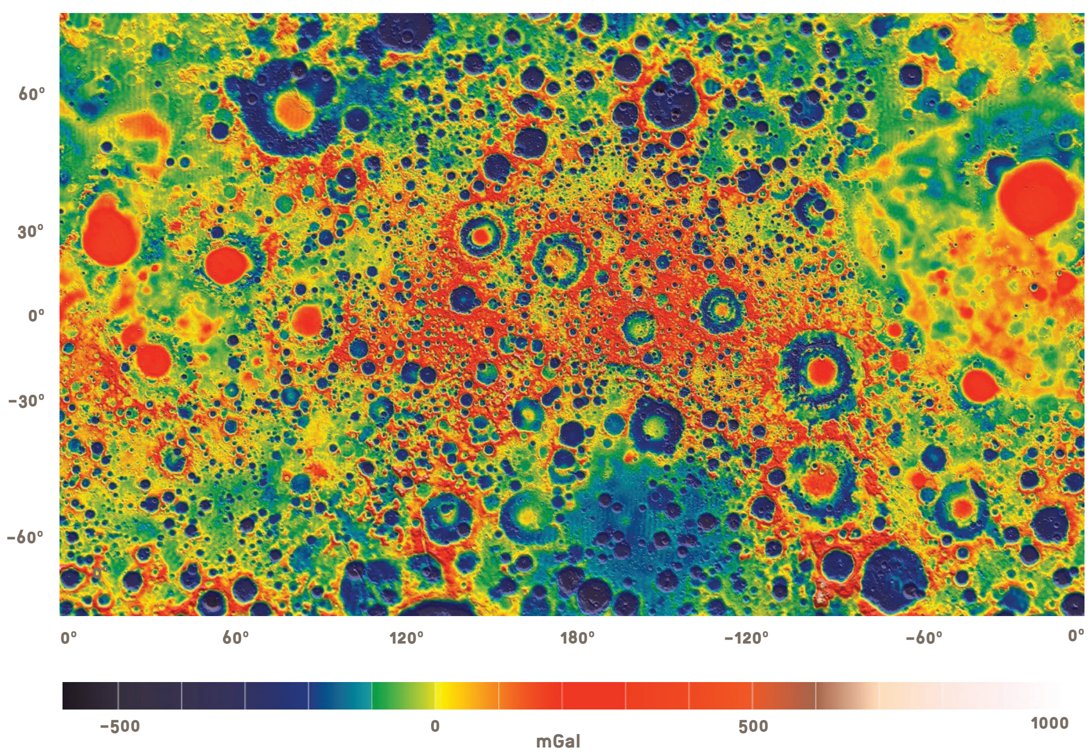


FIGURE 3.13: MANY TECHNIQUES DEVELOPED FOR STUDYING EARTH HAVE PLANETARY APPLICATIONS, AND VICE VERSA. HERE, A LUNAR GRAVITY MAP FROM THE NASA GRAIL MISSION, BASED ON METHODOLOGIES DERIVED FROM THE GRACE MISSION.

were improved for space geodesy (and can now be used on future Mars missions). Occultation measurements in which the passage of a spacecraft behind a planet provided information on the temperature and density profile in the atmosphere (as well as a measure of the planetary radius at the occultation point) now have a modern counterpart in the use of GNSS occultations to probe Earth's atmosphere and ionosphere. Impact cratering was an advanced planetary science long before it was fully appreciated how that process must also have affected Earth, both early in its history and sporadically throughout its history.

More broadly, the leadership role of NASA in planetary missions can be harnessed to guide collaborations relevant to both the solid-Earth science program and NASA's planetary science programs. There is an opportunity to advance this goal in the near future through workshops on themes with appeal to multiple communities, such as planetary seismology. Identifying shared interests and aligned goals is the first step in leveraging existing strengths within NASA.

3.4

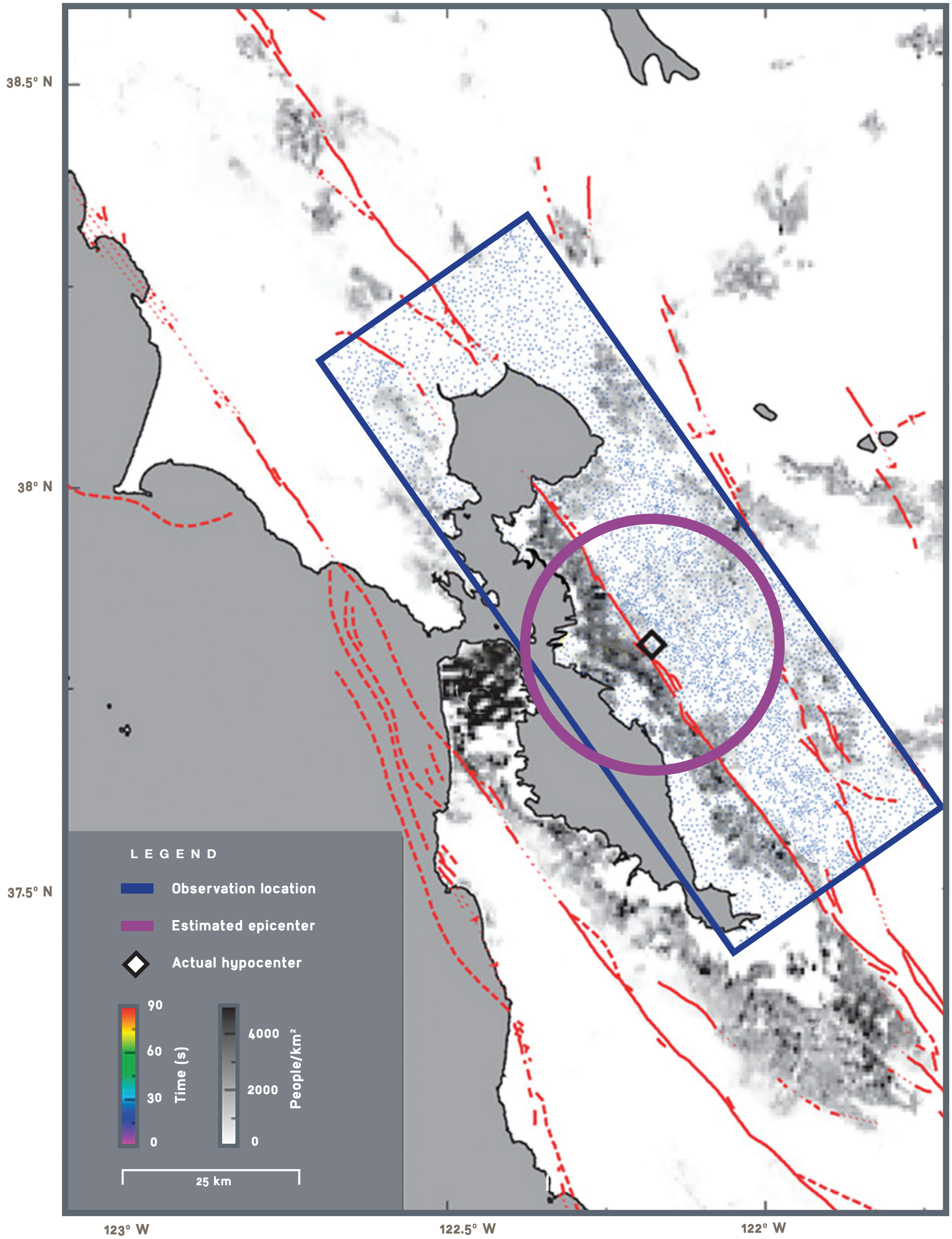
The Increasingly Interconnected World

Technology connects humanity around the world as never before. Social interaction as well as awareness and sensing of Earth processes and events are immediate and at a very large scale. Integration of shared human experiences via smart phones and related technology along with social media represent important opportunities for the solid-Earth science program. Massive networks of smart phones and other connected devices potentially enable a rich but simple measure of phenomena. In addition, experiences are now shared globally via social media. As such, they represent potentially important additional observations as well as essential educational and communications opportunities. Finally, social media enables communities to come together around common interests such as Earth and space science. It thus opens connections for dissemination of knowledge and may be a gateway to more formal education.

The direct sensing of geophysical phenomena by scientifically oriented networks of seismometers and GPS receivers has improved by coordinated arrays of sensors, but many of us have primitive sensors of acceleration and position in our smart phones, as well as numerous other connected devices. This “internet of things” and people organically organizes around events such as earthquakes, volcanic eruptions, landslides, floods, changing sea level, and global temperature. While not designed with the intention of measuring such Earth processes, the near ubiquity of connected simple sensing of acceleration, position, temperature, etc., represents a large suite of data streams to be harnessed for scientific, emergency, and educational purposes. Scientists from the USGS and several universities are prototyping earthquake early warning systems that draw on these consumer-grade accelerometers combined with data from GNSS and high-quality seismic networks to provide seconds to minutes of warning of the shaking following an earthquake.

As mentioned above, experiences of both minor and major events are now shared globally via social media. These experiences include direct observations such as the sensing mentioned above, imagery and movies, and information from other connected devices (such as activity sensors). Such measures bridge a gap between the objective, quantitative, and typically sparse geophysical network or space-based characterization of the event, with the direct, qualitative experience of thousands (or more!) of people. In addition, people express their observations and feelings during and after a significant geologic event. Sifting social media, for example, has enabled effective early earthquake characterization from tweets, and can provide rapid communication for earthquake response.

LEFT: ENHANCED GPS TECHNOLOGIES CAN BE USED TO DEVELOP NEW HAZARD WARNING SYSTEMS.


38.5° N
38° N
37.5° N
123° W
122.5° W
122° W
LEGEND
Observation location
Estimated epicenter
Actual hypocenter
90
60
30
0
Time (s)
4000
2000
0
People/km²
25 km

The use of crowdsourcing and social media for science is a relatively new area of research, but its success depends greatly on the use of cutting-edge Earth science, models, and analysis approaches, as well as sensitivity to community needs and clear communication of results and uncertainties in the observations. Opportunities for pilot projects, as well as workshops that facilitate communication among solid-Earth scientists, communications technologists, social scientists, members of federal agencies responsible for hazard mitigation and response, and the general public, could have a significant payoff.

FIGURE 3.14: PERSONAL DEVICES LIKE CELL PHONES CAN ASSIST IN QUICKLY SENSING AND LOCATING AN EARTHQUAKE TO PROVIDE INFORMATION ON EARLY WARNING. HERE, A SIMULATION OF A CROWDSOURCED SENSING OF AN EARTHQUAKE ON THE HAYWARD FAULT NEAR SAN FRANCISCO WAS ABLE TO DETERMINE WITHIN 5 SECONDS THE EARTHQUAKE EPICENTER WITH AN ERROR OF LESS THAN 5 KM.

3.5

Societal Benefits

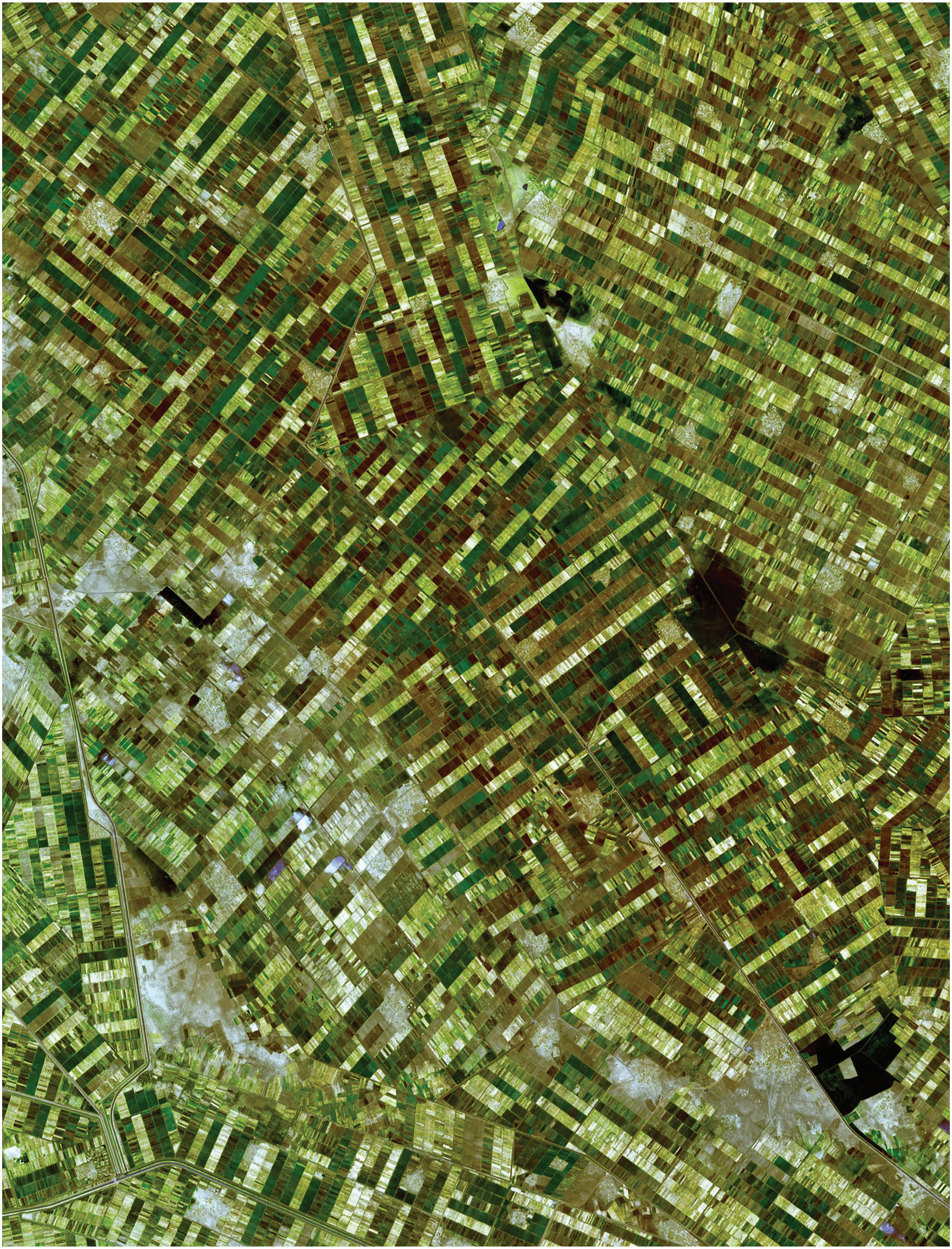
As is shown by examples throughout this report, advances in solid-Earth science have fundamental and direct value for society. Benefits to society from combinations of space-based and terrestrial measurements include the potential to predict and mitigate losses due to natural disasters by understanding the processes on Earth's surface and in its interior that lead to earthquakes, volcanic eruptions, sea-level rise, floods, landslides, and other hazards, as well as by developing technology that leads to improved monitoring of these hazards.

Our ability to measure and distinguish a wide range of simultaneously occurring natural and anthropogenic signals has steadily increased, due to continual improvement in accuracy of Earth-observing systems; deployment of complementary observing systems with enhanced resolution and coverage in both time and space; and refinement of mathematical models and techniques used to analyze, visualize, and interpret the observations.

Benefits to society of the science and technology developed through the solid-Earth science program are broad and deep, extending beyond hazards. Geodetic observing systems support a wide array of military, civil, and commercial activities, including autonomous navigation of aircraft and ground vehicles, civil surveying, precision agriculture, and groundwater monitoring. They also support scientific activities and satellite missions relevant to many other fields of endeavor. Improved models for the geomagnetic field improve the navigation capabilities of cell phones. Imaging spectroscopy can be used to identify natural resources.

The impact of humans on the environment continues to increase. Developed areas are growing in size and population density, extending the impact. The environment of urban megacities interacts significantly with their natural context; human activity induces changes to the hazards impacting these areas. For example, the impact of resource production, distribution, and utilization have significant consequences for Earth systems. One consequence of this activity is crustal deformation associated with fluid management of aquifers and oil fields, remarkable pictures of which have been provided by Earth observations (see Section 2.7). Increasing the scientific understanding of the interactions between human activity and natural Earth processes was recognized during the CORE Workshop to be a major opportunity for the solid-Earth science program.

RIGHT: AN ASTER IMAGE OF AN AGRICULTURAL REGION
IN AL JAZIRAH, SUDAN.



3.6

Professional Development

Realizing the full scientific and societal benefits of the solid-Earth science program relies critically on developing the scientific and technical capabilities of an emerging generation of students and post-doctoral scientists, and sustaining high-skill mid-career geoscientists. Salient challenges include:

- A national shortage of well-trained geoscience graduate students and post-doctoral scholars from diverse backgrounds with the quantitative skills and geoscience grounding needed for expert analysis and the exploitation of the anticipated data sets
- High barriers that limit non-expert access and use of large and complex data sets
- A lack of basic public science literacy, and awareness of NASA's Earth science research infrastructure and mission

These challenges are severe, and in fact their impact has been felt for some time. Indeed, the 2007 NAS report "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future" explored the economic impact of such challenges, noting that these problems are acute within the U.S., while at the same time other nations are making investments in fundamental science that is critical to economic leadership.

Lowering barriers to data discovery, access, analysis, and interaction is potentially one part of the solution. Use of observations relevant to the solid-Earth science program, while enabling scientific advances, is characterized by a steep learning curve for non-engineer, non-expert users. Most data handling, processing, and analysis tools are maintained with very few targeted resources, resulting in a lack of documentation that hampers new or infrequent users in the adoption of the most current algorithms and processing approaches. Community-driven online tutorial resources can significantly advance wider adoption of solid-Earth science technology and lead to better exploitation of large data archives. Short courses expose graduate students and early career investigators to relevant analysis tools. These short courses could build upon existing educational platforms such as the UNAVCO-hosted short courses by NASA and academic scientists, a CIDER-like workshop combining tutorials with research experience, field-based multi-method short courses, or one-day workshops prior to professional meetings.

Activities that increase public awareness of the solid-Earth science program can help to increase science literacy and encourage students to pursue scientific careers related to solid-Earth science. To the extent possible, the solid-Earth science program could consider integration of public outreach into science projects. Many other avenues could be used to support increased awareness of geoscience missions, data sets, and research. Development of a distinguished lecture series, for example, could expose the solid-Earth science program to a range of academic communities and public informal learning venues such as museums, libraries, and science centers. Program support for dissemination of visualizations and tutorials using social media and standard online modes is another avenue for outreach.

LEFT: THE NASA/NSF GLOBE PROGRAM PROVIDES HANDS-ON SCIENCE OPPORTUNITIES TO COMMUNITIES.

3.7

International and Interagency Cooperation

Many U.S. and international agencies share overlapping objectives with the NASA solid-Earth science program. Coordination and collaboration takes place on multiple levels, from interagency agreements that are needed for space missions, to coordination of multi-agency funding for investigator-led Earth-science projects. In several cases, NASA is part of a multi-agency coalition that supports community-based solid-Earth science projects, infrastructure, and facilities like WInSAR and UNAVCO. There are a number of opportunities that could serve as examples for the solid-Earth science program to expand the list of co-funded activities (e.g., CIDER, CIG), thereby leveraging funding from other federal agencies and enabling these groups to become more relevant to NASA solid-Earth science investigations.

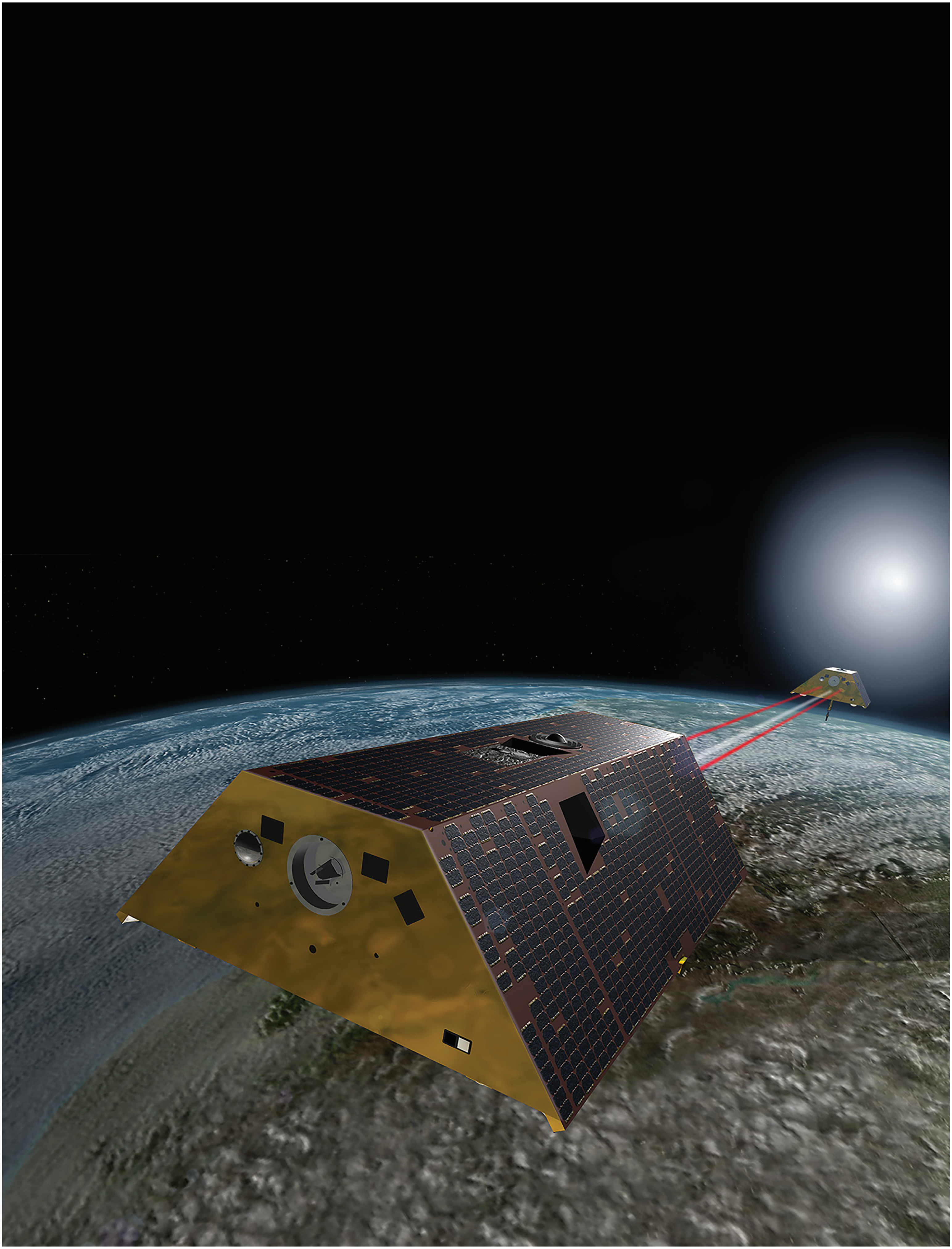
NASA plays a leadership or other primary role on some space missions (GRACE and NISAR, for example). In other cases, internationally led efforts play a critical role for enabling NASA investigators to meet scientific objectives (Swarm and Sentinel-1, for example). NASA-led InSAR and magnetic satellite missions have been noticeably absent in the last decade. NISAR will fill the InSAR gap, and there is an opportunity for the solid-Earth science program to support activities that lead to a satellite mission related to magnetics. It may also be possible to take advantage of NASA platforms that have proliferated since publication of the SESWG Report, such as CubeSats, as the basis of such a mission.

For example, participation of U.S. scientists in international services that coordinate global geodetic infrastructure—IVS, IGS, ILRS, IDS, IERS, and many other services—is difficult without NASA support. NASA, and especially the solid-Earth science program, has played a unique role among federal funding agencies in providing support for such activities, the benefits of which accrue to many areas of Earth science and to other federal agencies. Given the importance of the SGP within these networks, it may be useful for the solid-Earth science program to have a more proactive, strategic plan for these investigator-led activities.

There are overlapping interests among federal agencies that support research in fundamental Earth science and its broader applications. A number of programs and initiatives are relevant to the NASA solid-Earth science program. A partial list includes:

- Assessment of earthquake and volcano hazards (USGS)
- Water-resource monitoring (states and the USGS)
- Tsunami warning and monitoring coastal processes (NOAA)

RIGHT: THE GRACE FOLLOW-ON MISSION HAS INTERNATIONAL PARTICIPATION.



- Sea-level rise monitoring, prediction, and impacts (NOAA, USGS, state and local agencies)
- Support for basic solid-Earth science research and applications (NSF, USGS)
- Use of high-resolution global optical imagery and topography, gravity (NGA)
- Hazard warning/mitigation and disaster preparedness (USGS, DHS, USAID/OFDA, state and local agencies)
- Development of magnetic and gravity maps, including seafloor bathymetry (DOD)
- Topography, monitoring of subsidence, gravity for U.S. economic, social, and environmental needs (NGS)
- Earth rotation and terrestrial reference frames (USNO, NIST, NGA)

Each agency (and even each program within any agency) has a particular mission. The NASA solid-Earth program will continue to benefit from opportunities for collaborative efforts at both the agency and investigator level, and by leveraging existing resources.

As this report clearly reveals, to an increasing extent cutting-edge research in the solid-Earth sciences is performed using multiple observing systems that provide information about multiple Earth systems. Such studies often cross the traditional boundaries among programs within NASA, among agencies of the federal government, and even among national agencies. This is an issue of programmatic and organizational structure as much as it is one of scientific discipline. It would be to the great benefit for the solid-Earth science program to facilitate such boundary-crossing research and to play a leadership role whenever possible and appropriate.

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Figure 3.1: VLBI: Courtesy of G. Rajagopalan, MIT Haystack Observatory. DORIS, NGSLR: NASA. GNSS: UNAVCO.

Figure 3.2: Figure courtesy of A. Donnellan, JPL, based on original artwork by Chuck Carter.

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Figure 3.10: Hulley, G. C., R. M. Duren, F. M. Hopkins, S. J. Hook, N. Vance, P.Guillevic, W. R. Johnson, B. T. Eng, J. M. Mihaly, V. M. Jovanovic, S. L. Chazanoff, Z. K. Staniszewski, L. Kuai, J. Worden, C. Frankenberg, G. Rivera, A. D. Aubrey, C. E. Miller, N. K. Malakar, J. M. Sánchez Tomás, and K. T. Holmes, K. T (2016), High spatial resolution imaging of methane and other trace gases with the airborne Hyperspectral Thermal Emission Spectrometer (HyTES), *Atmos. Meas. Tech.*, 9, 2393-2408, doi:10.5194/amt-9-2393-2016.

Figure 3.11: Figure 2 from Minson, S. E., M. Simons, J. L. Beck, F. Ortega, J. Jiang, S. E. Owen, A. W. Moore, A. Inbal, and A. Sladen (2014), Bayesian inversion for finite fault earthquake source models – II: the 2011 great Tohoku-oki, Japan earthquake, *Geophys. J. Int.*, 198(2), 922–940, doi:10.1093/gji/ggu170.

Figure 3.12: NASA.

Figure 3.13: NASA.

Figure 3.14: Minson, S. E., B. A. Brooks, C. L. Glennie, J. R. Murray, J. O. Langbein, S. E. Owen, T. H. Heaton, R. A. Iannucci, and D. L. Hauser (2015), Crowdsourced earthquake early warning, *Sci. Adv.*, 1, e1500036, doi:10.1126/ sciadv.1500036. Reprinted with permission from AAAS.

CHARTER OF THE NASA CORE WORKSHOP COMMITTEE

PURPOSE AND DUTIES

The NASA Challenges and Opportunities for Research in ESI (CORE) Workshop Committee (the "Committee") will structure and lead implementation of a workshop for NASA's Earth Surface and Interior focus area (ESI), and write a report documenting workshop content.

The purpose of the CORE workshop and report is to assess progress towards meeting the goals of the 2002 Solid Earth Science Working Group report Living on a Restless Planet, and to revisit challenges and opportunities for NASA solid-Earth science in light of scientific progress and new capabilities realized over the past decade.

The Committee will participate in organizational meetings, moderate workshop sessions, and function as editors of input from workshop participants in co-authoring the workshop report.

MEMBERSHIP

The NASA Earth Surface and Interior Focus Area will solicit participation of Committee Co-Chairs, who will then lead the identification of remaining Committee members. Membership will be selected to assure a balance of relevant expertise and diversity in geography, connections to NASA ESI research, as well as those who can provide outside perspectives.

SCHEDULE

The Committee will convene in September 2015 to begin workshop planning. The workshop will be held in November 2015. Report writing will commence in November 2015, with periods of public review and editing December 2015–May 2016. The final report will be made available to the public in June 2016, at which point Committee membership will lapse. The Committee Co-Chairs may continue to support ongoing communications and outreach of report content.

APPENDIX

B

CORE WORKSHOP AGENDA

NASA CHALLENGES AND OPPORTUNITIES FOR RESEARCH IN ESI (CORE) WORKSHOP

November 2–3, 2015

DoubleTree by Hilton Crystal City
300 Army Navy Drive, Arlington, Virginia, 22202, USA,
+1-703-416-4100

DAY 1	**NOVEMBER 2, 2015**	
7:00 am	Registration	
8:00 am	Welcome	Benjamin Phillips (NASA HQ)
	Workshop overview and goals	Jim Davis (LDEO) & Louise Kellogg (UC Davis)

PLENARY SESSION I – THE 2002 SOLID EARTH SCIENCE WORKING GROUP (SESWG) REPORT

8:30 am	The SESWG Report: Rationale and Recommendations	Sean Solomon (LDEO)
9:30 am	Coffee break	

PLENARY SESSION II – FOUNDATIONS

9:45 am	Solid-Earth research in the NASA Earth Science Division	Jack Kaye (Associate Director for Research, ESD, NASA HQ)
10:15 am	NASA ESI technology directions	Pam Millar (Earth Science Technology Office, NASA)
10:45 am	NAS Board on Earth Sciences and Resources and the 2017-2027 Decadal Survey for Earth Science and Applications from Space	Anne Linn (BESR, NAS)

PLENARY SESSION III – WHITE PAPERS

11:15 am	Summary of what we learned from the white papers	Committee
12:00 pm	Lunch	
1:00 pm	Charge to breakout groups: • Identify key advances in ESI science since the 2002 SESWG Report • Address how results suggest rethinking, reframing, or adding to report goals • Identify additional themes from the white papers • Identify other themes that ESI should address	

BREAKOUT SESSION I – SESWG SCIENCE OVER THE LAST DECADE

1:10 pm	• Plate Boundaries (SESWG challenge #1) • Solid-Earth–Sea Level (SESWG #3) • Magnetic Field (SESWG #6)	
2:10 pm	Break	

BREAKOUT SESSION II – SESWG SCIENCE OVER THE LAST DECADE

2:15 pm	• Surface Processes (SESWG #2) • Magmatic Systems (SESWG #4) • Mantle-Crust (SESWG #5)	
3:15 pm	Break	

PLENARY SESSION IV – PRESENT AND FUTURE NASA MISSION CONTRIBUTIONS TO SESWG SCIENCE

3:20 pm	Gravity	Don Chambers (USF)
3:35 pm	Space Geodesy	Stephen Merkowitz (GSFC)
3:50 pm	SAR	Paul Rosen (JPL)
4:05 pm	LIDAR	David Harding (GSFC)
4:20 pm	Spectroscopy	Simon Hook (JPL)
4:35 pm	Geomagnetism	Terry Sabaka (GSFC)

PLENARY SESSION V – REPORT FROM BREAKOUT GROUPS

4:50 pm	Reports	Breakout leaders
6:00 pm	Adjourn	

DAY 2	NOVEMBER 3, 2015
7:00 am	Registration

BREAKOUT SESSION III – UPDATE OF SESWG SCIENCE OPPORTUNITIES

8:00 am	Introduction to the roundtable brainstorming activity
8:20 am	Roundtable sessions

MORNING ROUNDTABLE TOPICS:

- Anthropogenic forcings
- Cross-disciplinary research
- Comparative planetology and ESI
- Opportunities and threats for ESI
- Opportunities for low-latency data
- Computing and big data science

12:10 pm	Lunch

BREAKOUT SESSION IV – OTHER THEMATIC DISCUSSIONS

1:15 pm	Roundtable sessions

AFTERNOON ROUNDTABLE TOPICS:

- Accuracy goals for observations
- Ground & space-based data
- International and interagency
- Need for community software
- Professional development needs
- Societal benefits of ESI science

PLENARY SESSION VI – WRAP UP

4:50 pm	Wrap up
5:00 pm	Adjourn

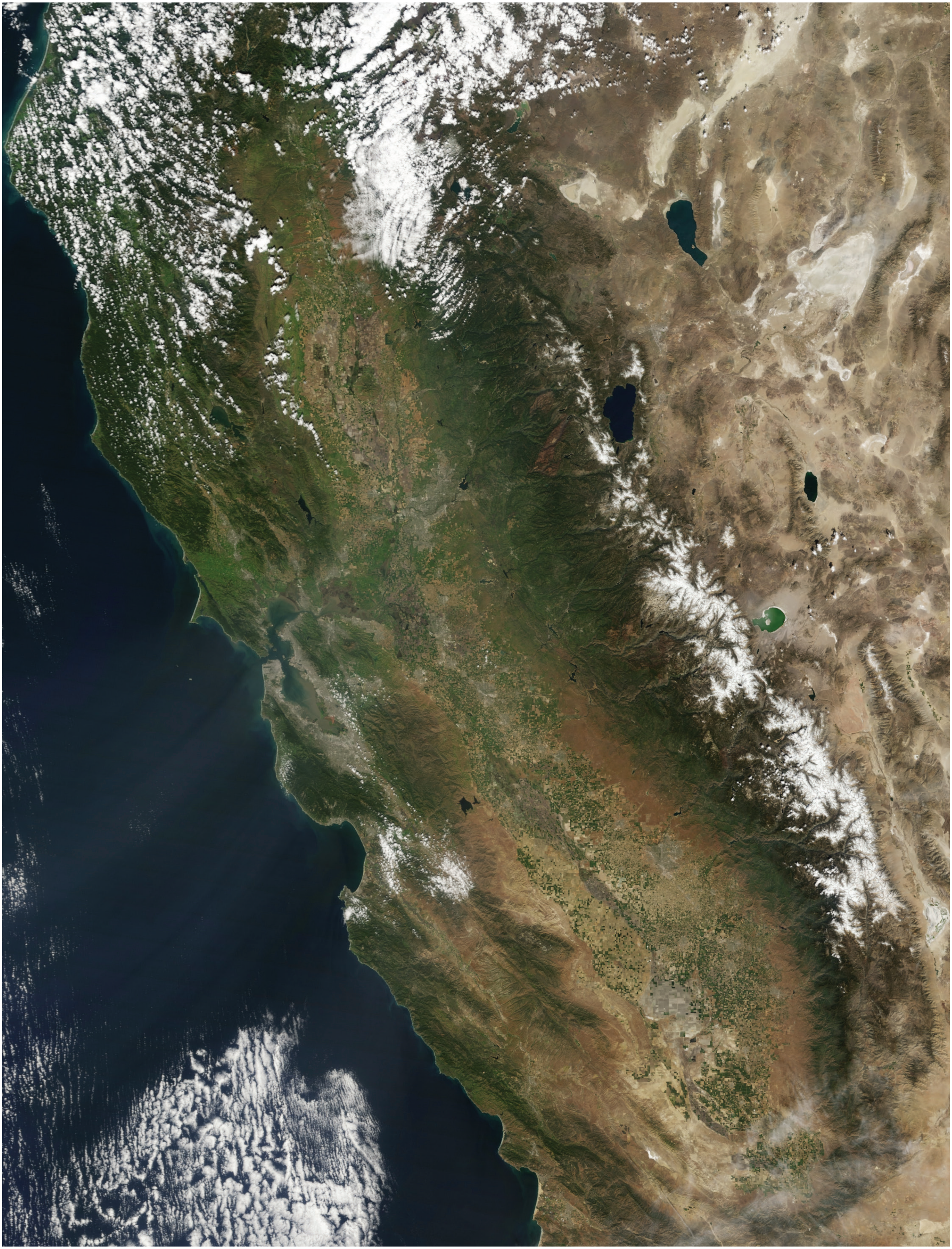
APPENDIX

C

CORE WORKSHOP ATTENDEES

Falk Amelung	University of Miami
Benjamin Andrews	Smithsonian
Don Argus	Jet Propulsion Laboratory
Ramon Arrowsmith	Arizona State University
Gerald Bawden	NASA Headquarters
Michael Blanpied	USGS
Bruce Buffett	University of California, Berkeley
Juan Ceva	Jet Propulsion Laboratory
Don Chambers	University of South Florida
Estelle Chaussard	SUNY Buffalo
Amy P. Chen	NSF
Arnaud Chulliat	NOAA/NCEI and University of Colorado Boulder
Cathy Constable	University of California, San Diego
James Davis	Lamont-Doherty Earth Observatory
Robert Detrick	IRIS
Craig Dobson	NASA Headquarters
Andrea Donnellan	Jet Propulsion Laboratory
Cynthia Ebinger	University of Rochester
Gary Egbert	Oregon State University
Eric Fielding	Jet Propulsion Laboratory
Herbert Frey	NASA Goddard Space Flight Center
Dennis Geist	NSF
Richard Gross	Jet Propulsion Laboratory
David Harding	NASA Goddard Space Flight Center
Simon Hook	Jet Propulsion Laboratory

Erik Ivins	Jet Propulsion Laboratory
Jack Kaye	NASA Headquarters
Louise Kellogg	University California, Davis
Weijia Kuang	NASA Goddard Space Flight Center
Peter LaFemina	Pennsylvania State University
Bill Leith	USGS
Frank Lemoine	NASA Goddard Space Flight Center
Einat Lev	Lamont-Doherty Earth Observatory
Anne Linn	National Academy of Sciences
Zhong Lu	Southern Methodist University
Paul Lundgren	Jet Propulsion Laboratory
Chopo Ma	NASA Goddard Space Flight Center
Charlie Mandeville	USGS
Glen Mattioli	UNAVCO Inc.
Robert Mellors	Lawrence Livermore National Laboratory
Stephen Merkowitz	NASA Goddard Space Flight Center
Pam Millar	NASA Headquarters
Meghan Miller	UNAVCO Inc.
Steven Nerem	University of Colorado Boulder
Susan Owen	Jet Propulsion Laboratory
Benjamin Phillips	NASA Headquarters
David Pieri	Jet Propulsion Laboratory
Michael Poland	USGS
Matthew Pritchard	Cornell University
Michael Purucker	NASA Goddard Space Flight Center
Paul Rosen	Jet Propulsion Laboratory
John Rundle	University California, Davis
Terence Sabaka	NASA Goddard Space Flight Center
David Sandwell	University California, San Diego
Jeanne Sauber	NASA Goddard Space Flight Center
Sean Solomon	Lamont-Doherty Earth Observatory
Rob Tyler	NASA Goddard Space Flight Center and University of Maryland
Isabella Velicogna	University California, Irvine
Shimon Wdowinski	University of Miami
Frank Webb	Jet Propulsion Laboratory
Cecily Wolfe	USGS
Robert Wright	Hawaii Institute of Geophysics and Planetology



APPENDIX

D

ACRONYMS

ALTAR	Bayesian computational framework named in honor of Albert Tarantola
ARIA	Advanced Rapid Imaging and Analysis
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CATMIP	Cascading Adaptive Transitional Metropolis In Parallel
CHAMP	Challenging Minisatellite Payload
CIDER	Cooperative Institute for Dynamic Earth Research
CIG	Computational Infrastructure for Geodynamics
CORE	Challenges and Opportunities for Research in ESI
CRF	Celestial Reference Frame
DEM	Digital Elevation Model
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EnMap	Environmental Mapping and Analysis Program
ESA	European Space Agency
ESI	Earth Surface and Interior
ESTO	Earth Science Technology Office
ETS	Episodic Tremor and Slip
GDEM	Global DEM
GGAO	Goddard Geophysical and Astronomical Observatory
GGOS	Global Geodetic Observing System
GIA	Glacial Isostatic Adjustment
GNSS	Global Navigational Satellite Systems
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
HICO	Hyperspectral Imager for the Coastal Ocean
HyspIRI	Hyperspectral Infrared Imager
HyTES	Hyperspectral Thermal Emission Spectrometer
ICESat	Ice, Cloud,and land Elevation Satellite
IERS	International Earth Rotation and Reference Systems Service
IDS	International DORIS Service
IGS	International GNSS Service
ILRS	International Laser Ranging Service
InSAR	Interferometric Synthetic Aperture Radar
ISRO	Indian Space Research Organization
ISS	International Space Station
IVS	International VLBI Service
KPGO	Kokee Park (Hawaii) Geophysical Observatory
Lidar	Light Detection And Ranging
LIST	Lidar Surface Topography
LOD	Length of day
LVIS	Land, Vegetation, and Ice Sensor
M	Moment Magnitude
MIR	mid-infrared
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCALM	National Center for Airborne Laser Mapping
NGA	National Geospatial Intelligence Agency
NGS	National Geodetic Survey
NSF	National Science Foundation
NISAR	NASA-ISRO SAR

LEFT: MODIS ON AQUA CAPTURED NATURAL-COLOR IMAGES OF CALIFORNIA'S SIERRA NEVADA AND THE GREAT BASIN TO THE EAST IN 2016.

NIST	National Institute for Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
OFDA	Office of U.S. Foreign Disaster Assistance
ONR	Office of Naval Research
PBO	Plate Boundary Observatory
PRISMA	PRecursore IperSpettrale della Missione Applicativa
PSI	Persistent Scatterer InSAR
READI	Real-time Earthquake Analysis for Disaster
SAC-C	Satellite de Aplicaciones Científico B
SAR	Synthetic Aperture Radar
SCIGN	Southern California Integrated GPS Network
SESWG	Solid Earth Science Working Group
SGP	Space Geodesy Project
SGSLR	Space Geodesy SLR
SLR	Satellite Laser Ranging
SMAP	Soil Moisture Active Passive
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SSE	Slow slip event
SWOT	Surface Water and Ocean Topography
TIR	thermal infrared
TRF	Terrestrial Reference Frame
UAV	Unmanned Aerial Vehicle
USAID	U.S. Agency for International Development
USGS	U.S. Geological Survey
UNSO	U.S. Naval Observatory
VGOS	VLBI Global Observing System
VLBI	Very Long Baseline Interferometry
VNIR	Visible and Near-Infrared
VSWIR	Visible to Short-Wavelength Infrared