Breakout 1 Summaries
Earth Structure, Rheology, and Dynamics

- Supporting Undergrad and Grad Education and the U.S. and Abroad (Mogk/Long/Stearns)
- Long-term, Global Scale Seismic, Geodetic and MT Arrays (Holt/Lay/Hammond/Fischer)
- New Types of Observations (Agnew/Lowry)
- Temporary Targeted Seismic, Geodetic, and MT Arrays (Evans/Wagner/Borsa)

Supporting Undergrad and Grad Education and the U.S. and Abroad

What are the key scientific questions, emerging opportunities, technical advances?

- Capacity in handling large datasets for E&O
  - Building tools to allow for seamless connections from raw data to the classroom. Student-collected and crowd sourced data. Making models and datasets accessible and local.
- Preparing for the NGSS (Next-Generation Science Standards) – students will come in with a different background (inquiry-based).
  - How do we change the way we teach our intro courses? How do we scale inquiry-based, interactive exercises to large intro classrooms?

Foundational capabilities

- Involvement of E&O staff at facilities is crucial: developing resources, enabling and coordinating community efforts, training, mentoring, …
- Undergraduate opportunities: REUs (RSESS, IRIS interns), curriculum modules, Teachable Moments, etc.
- Graduate opportunities: Workshops, short courses, community building efforts, field-based training and research.

What are the frontier facility capabilities we need?

Frontier capabilities

- Targeted and intensive efforts to improving student and faculty/scientist diversity: culture shift to become more welcoming to underrepresented groups, removing barriers to participation. Community-driven facilities are particularly well positioned to help shift the culture.
- Workforce development, broadening participation: Geosciences provide a friendly introduction to coding skills – instead of “Hello, world!” how about “Hello, Earth!”
- Giving graduate students more of an early professional network – continued development of cross-disciplinary modules, workshops (e.g. CIDER model)
- Integrating science learning objectives with research at the undergraduate level; every student should be able to access and use data (2012 PCAST standards)

Long-term, Global Scale Seismic, Geodetic and MT Arrays

- Structure and rheology of the Earth
  - How do slabs move? What is their shape and evolution in the global context?
  - How do plates couple with the mantle?
  - How fast does the mantle flow?
  - Do mantle plumes exist and what is their role in mantle dynamics?
  - Discontinuities and anisotropy that constrain mineralogy and flow of the mantle
  - What are Earth's thermal and chemical properties?
  - What is the distribution of volatiles?
  - How do faults slip? We need to understand earthquake processes, and the seismic cycle as a measure of deformation and rheology; Episodic tremor and slip, occurrence and physics.
- *Finer resolution desired for many questions; topics couple with temporary array goals.*

- Interseismic strain, distribution, style and rate
- Inelastic/viscoelastic component of Earth deformation
- Postseismic afterslip
- Characterization and study of earthquake and tsunami sources, including long period source processes
- Orogenesis and mountain evolution
- Overall relationship between stress and strain in the lithosphere; global lithosphere processes; Plate Tectonics 2.0.

- Transient deformations in some cases clearly last for decades; what is their relationship to Earth rheology and the earthquake cycle? Long-term precursors to megathrusts(?)
- Examples of questions that are best addressed by integration of seismic and geodetic methods:
  - Links between subduction zone cycle and fore-arc structure and rheology
  - Links between elastic and viscous behavior.
  - Understanding the earthquake cycle in the context of broader rheology and structure
  - How fast does the lithosphere move with respect to the mantle?
- Need structure as a driver of buoyancy, and slabs are key to buoyancy, we don't know in detail what happens to slabs in the transition zone (TZ). Support a USArray in the oceans to better address this (and many other topics).

- Where is Earth's water and how does it move and affect rheology, magmatism, …?
  - Free water in the shallow Earth (hydrologically linked observations and study)
  - Mineralogically bound water in the deep Earth
- Sea level change. Detection, measurement and drivers; coupling to tectonic and other solid Earth processes.
- GIA and ice loading/unloading of the solid Earth (and influence of mantle viscosity).
- Dynamics and loading of the atmosphere as seen with geodesy and seismology; can this be used to constrain Earth structure/processes?
- Hazard and warning science (these facilities provide long-term calibrated observations of high hazard regions).
- What are the interactions between climate, surface processes, tectonics and deeper earth processes (e.g., sea level effects on ocean floor volcanism).
- How does of life co-evolve with tectonics and climate?

Foundational

- Long-term calibrated and globally distributed networks of permanent geodetic and seismic instrumentation are critical for hazards and science.   MT as well where motivated (4D MT).
- Need continuous observations that assure detection of transient deformation.
- Need high quality broadband continuous recording global seismic networks in the oceans.
- Very broadband instruments (e.g., need very long periods to see normal modes and W-phases). O&M swamps initial cost of sensor, so don't be cheap; compromising bandwidth compromises science here.
- Need long wavelength structure to characterize sources.
- Need to fully integrate global networks with regional geodetic and seismic networks to fill critical data gaps
- Take stock of degrading equipment and account for depreciation of existing networks. GPS and seismology. Many instruments need replacing (preferably before they die in service). Support from NASA for GNSS receivers is key.

Foundational (cont'd)

- High performance computing, acceleration and *accessibility* for both big data and big processing. Innovation Center needed to facilitate HPC utilization specifically for Earth scientists?
- Community lithospheric deformation and mantle flow models in particular and modeling capability in general.
- Continue to nurture international collaborations
- Continue Electrical conductivity modeling
- Need to have more co-located seismic/GPS instruments to get at full wavefield and static offsets.
- Need to have low latency with instrument communications to avoid station down-time and assure data quality.
- Stable reference frames part of global geodetic infrastructure and need to be maintained.
- Seismo-geodesy, generation of high rate time series for science applications could be supported by facility providing GPS or merged displacement data streams.
- Continue to support borehole strain networks.

Frontier Facilities

- Long-term sea floor positioning and seismology.
- Higher resolution bathymetry in the ocean.
- Improvements in GNSS models and utilization of GNSS signals to improve positioning, especially vertical. Situation is rapidly evolving.
- Important to incorporate data from heterogeneous GNSS sources.
- Broader analysis, particularly for geodesy, to get at effects of atmosphere on signals, atmospheric loading, groundwater, surface water, ionosphere effects.
- Stable long-term GPS networks capable of detecting vertical rates near 0.1 mm/yr.
- Observational and modeling capability to tropospheric signals and enhance geodetic measurements
- Enhanced collaborations (and co-instrumentation) with atmospheric community; numerous opportunities.

Frontier Facilities (cont'd)

- Enhanced connections to mineral physics communities (e.g., COMPRES).
- Global arrays of seismograph and GPS arrays (these have dual uses as regional and global facility).
- Integration of magnetometers (e.g., to help constrain distribution of volatiles).
- Integration of infrasound/barometry.
- Large N geodesy (great for refining regional structure, but will not replace VBB GSN).
- Upgrading some regional network stations to bring them to VBB level.
- Community cyber-infrastructure facilities to process data, cope with increasingly large data volumes, and enable new analyses. Measurements of ocean surface geocentric sea level (e.g., via satellite altimetry) to integrate with onshore measurements of vertical motion.
- More complete integration of accelerometers into community use (GNSS+MEMs).
- Improve connections with GRACE/global gravity modeling.

What facility capabilities are needed to support broader impact needs post-2018 (EPO, training and workforce development, international)?

- Recognize that these permanent networks are *inextricably linked* within the operational capabilities and missions of many agencies (DOE, USGS, CTBTO,NOAA, …) for monitoring, many other uses.
- Ability to respond rapidly and effectively to earthquakes in with USGS, States, other agencies; collect and distribute data and products widely; rapid and effective response to teachable moment opportunities.
- Offshore and onshore capability must include strong partnerships between solid Earth and ocean science communities and agencies.
- Long-term networks are key to, and rely on, developing international collaborations (in-country, in the oceans, and in Antarctica).

New types of observations

Breakout Session 1: Earth Structure, Rheology, Geodynamics
The case for new types of observations

What are the key questions, opportunities, and advances to pursue in the future?	What capabilities are needed?
Rheology: How do we best constrain time-dependent rheologies? What is the viscosity structure of the asthenosphere and mantle? How do we best integrate MT and seismic observations to infer rheology?	There is a need for: • More offshore observations. • Additional mineralogical/geochemical/laboratory constraints (e.g., COMPRES). • Boreholes for heat flow that refine old measurements and supplement sparse data.
Structure: How can we enhance the resolution of both crustal and deep mantle structure? How can we improve our ability to more confidently interpret this structure? How best to deal with non-linear near-surface structure?	There is a need for: • Repeat airborne gravity to constrain mass changes, to combine with loading responses to improve our knowledge of structure. • Smaller diameter (i.e. cheaper) boreholes with smaller instruments which help to reduce noise. • Supplemental hydrologic data to eliminate noise. • Better measurements of displacement gradients (strain and rotation) in the seismic band.
Emerging Technologies: Applies to questions above.	• Muon imaging; Geoneutrinos • Rotational seismometers • Smaller/portable/low-power seismometers

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Subduction Processes: Can we resolve deformation related to flexure & dynamic topography? How can we better resolve transient processes and use these events as natural experiments?	There is a need for: • Improved telemetry, power, durability, and stability (calibrated drift) of offshore instrumentation. • Co-location of OBS, APG, and MT. • Improved atmospheric phase masks for InSAR. • Smaller uncertainties on vertical GPS.
Volatiles and Melt: What is the state of volatiles within the crust and mantle? What are the rates of volatile cycling? How can we better resolve melt volumes?	There is a need for: • Wide aperture seismic/MT arrays • Dense arrays for fine-scale structure.
Intra-plate Deformation: What are the strain rates within tectonic plates and the inferred strength of cratons?	• Need long-term time series to reduce noise.

Breakout Session 1: Earth Structure, Rheology, Geodynamics
The case for new types of observations

What facility capabilities are needed to support broader impacts?
Offshore instrumentation for improved assessment of natural hazards (subduction settings).
Refined data sets to improve estimates of sea level changes that are complicated by tectonic processes (GIA, subduction settings).
Tools to archive and distribute data and data products among the discplines.
Greater efforts to exploit synergies with other disciplines (i.e. geohydrology, atmospheric science).
Improved resources for impressive graphics/animations of scientific products so that results are more accessible to the public and useful to educators.

Temporary Targeted Seismic, Geodetic, and MT Arrays

Science Questions

1.) What is the nature of mantle/lithospheric coupling at and away from plate boundaries, how does it change with time, and how is it expressed in the characteristics of fault systems and (micro)seismicity?

2.) What are the relevant length scales of mantle convection, from plumes to whole mantle convection, and how does convection relate to mantle structure and couple to the lithosphere to drive deformation and dynamic topography?

3.) How does rifting initiate, propagate and fail in both oceanic and continental environments, and how does it relate to magma production and flow?

4.) How do fluids and volatiles cycle through the earth in subduction zones and other environments, how do they relate to magma production, and what are the connections between deep magma and geothermal systems?

5.) What is the state of stress in the lithosphere and how is stress dissipation partitioned between brittle failure and other types of deformation?

6.) How does oceanic and continental lithosphere grow, how does it evolve together with the asthenosphere, and what is the resulting vertical and lateral heterogeneity of rheology?

7.) What processes control induced seismicity in settings influenced by human activity?

8.) What are the short and long term responses of the solid earth (e.g. GIA to orogeny) to past and present climate change?

Foundational Facility Capabilities

- A pool of well-maintained portable field instruments, including instrumentation designed to perform in extreme environments (polar, oceans, etc.)
- A center of excellence to provide expertise and training to ensure the successful collection of high quality geophysical data
- A center of excellence that can promote sensor and other instrument development in partnership with vendors.
- Integrated observations of various types of geophysical data (seismic, geodetic, infrasound, MT) at continental scales (or scales larger than individual PI) similar to what was deployed at EarthScope TA stations.
- Data storage/archiving at the scale required for present and probable future instrument deployment.

Frontier Facility Capabilities

General

- Improved, integrated amphibious capabilities (seismic/geodesy/MT)
- Capacity for joint collection of diverse geophysical data sets on PI driven projects.
- Access to telemetry for all temporary terrestrial geophysical deployments. Development of acoustic telemetry for ocean bottom instrumentation
- A center of excellence for ALL geophysical data types to provide expertise and training to ensure the successful collection of high quality geophysical data
- A center of excellence to pursue new commercial technologies (e.g. optical fibers, AUV telemetry) for geophysical observations.
- Capacity for multi-scale geophysical data collection

Geodetic (GNSS)

- Develop new equipment with lower power requirements for longer deployments in remote locations
- Expanded networks of static monuments for campaign deployments on fixed points (quick setup, elimination of reoccupation error).
- Contribution to the realization of global reference frames.

Geodetic (InSAR)

- Access to multi-mission InSAR data for deformation studies

Frontier Facility Capabilities

Seismic

- Large N deployments
- High performance computing capacity to take full advantage of wavefield imaging
- Data format and data quality standardization
- Capability to acquire continental-scale reflection seismic data on land. This includes the ongoing need for a source facility that can also be used for seismic data refraction studies.
- Extended infrasound capabilities, integrated or standalone

MT

- Access to MT data and results (e.g. via training, field engineering) for entire geophysical community.
- 3D CSEM capability offshore
- Expanded instrument pool to support 4D MT

Data/Computing

- Facility based, HPC capabilities involving computing and support.
- Archive coordination between international and other national data centers
- Coordinated multi-agency/multi-facility computational capabilities
- Centrally hosted standardized codes