GEOGRAPHY

Identifying SZ4D Regions of Special Interest

The main goal of the SZ4D initiative is to improve understanding of how the different components of subduction zone systems interact to produce and magnify geohazards. An integral piece of this effort is to obtain new observational data on earthquakes, tsunamis, volcanoes, and mass wasting. It has become clear that dense, consistent, long-term instrumentation along with high-level data management is key to making major advances in this area.

Our geographic needs require a hybrid approach to data collection. The FEC and L&S working groups identified technical requirements that include focused, dense arrays, while the MDE working group identified the need for a more distributed approach to data collection at volcanoes. As discussed in this chapter, for both scientific and practical reasons, to maximize scientific gain will require focusing a majority of resources on one or two regions. This geographical focus will be augmented through the development of a coalition of countries that will conduct collaborative subduction zone studies and leverage existing similar efforts at subduction zones around the world. These endeavors will enable comparisons among subduction zones and the generalization of the results of focused study.

We implemented a process, described below, to determine the best locations to seat a subduction-zone observatory that was capable of addressing the research questions of all working and integrative groups. From this activity, we found that a comparative approach to subduction-zone science, in which different subduction-zone segments could be variously instrumented and activities performed, was required to meet SZ4D objectives. The SZ4D umbrella RCN identified three primary locations that included one international site (Chile) and two domestic sites (Alaska and Cascadia).

In addition, the RCN identified the need to establish connections between efforts in other, complementary subduction zones (e.g., Japan, Central America, northern South America) to form a network-of-networks that spans subduction zone science.

SUMMARY OF REGIONAL FOCUS NEEDS

The SZ4D effort has identified the need for a backbone array of amphibious geodetic and seismic instrumentation (MegaArray), a volcano array (VolcArray), and surface and environmental change detection array (SurfArray), in addition to the complementary imaging and geological work. These efforts require a physical presence in particular regions of the world.

The modeling, geological analog, and experimental efforts are required to place the observations from the primary arrays in context, where boundary conditions from a specific region can be determined from known geometries and histories. All of these components can be tied together by concrete observations gathered in a geographic context.

As described in the Introduction to this document, the SZ4D working groups used traceability matrices to identify common science needs for all of the science questions, including the high-priority characteristics of study areas. An inventory of subduction zone segments was also collated so that individual regions could be systematically assessed for their relevance to the scientific priorities. Each group individually weighed the relative value of the segments and then met to balance needs. Those discussions led to the logic presented in this chapter.

COOPERATION WITH INTERNATIONAL PARTNERS

For all regions that are being heavily considered for components of SZ4D field activities, it is essential that, from the beginning, US and in-country colleagues establish clear and open communication. This is necessary to identify the priorities of all stakeholders, cultural differences and sensitivities, established local scientific knowledge, and existing usable infrastructure and resources. Likewise, we must identify mutually beneficial aspects of the project, including research products, application for improving infrastructure and mitigating risk, and capacity building. Cooperation will necessarily extend beyond countries in which infrastructure is developed as a part of SZ4D to include other subduction-impacted nations that can benefit from and provide perspectives to our planned activities.

THE VALUE OF COMPLEMENTARY SITES

Isolating variables is a difficult problem in the observational sciences. The most effective strategy is to form a set of comparison sites that differ in only a few, scientifically interesting ways. For instance, comparisons of fast and slow subduction zones where overlying plate composition are comparable would be useful for determining the role of plate convergence rate in controlling the style of earthquake rupture. This subductology[1] approach has yielded insights into past reviews of extant data but has not been utilized extensively as a deployment strategy.

[1] *"Comparative Subductology" was coined by Uyeda (1982) as a process of grouping subduction zones according to their geometric, geodynamic, and chronologic properties in order to study the correlation of these factors with subduction zone dynamics.*

Subductology as a part of SZ4D can leverage major international efforts for some key observables. The SZ4D 2020–2021 International Webinar Series highlighted some of these efforts: Japan, Taiwan, and Cascadia already have existing seafloor cables that are providing rich datasets that should be thoughtfully complemented with any new instrumentation.

KEY GEOGRAPHY REQUIREMENTS

Scientific Requirements

Each working group developed key scientific requirements. First, the paired experimental design advocated by the L&S group requires comparison subduction zone systems in which particular factors could be regarded as fixed, while a limited number of other factors varied. The **four essential site characteristics** required to carry out L&S's notional experiments and hypothesis testing included:

1. At least some proportion of the site must include subaerial forearc exposure (free of ice);
2. Observational constraints must exist or *be acquirable* at suitable sites; and
3. At least some portion of the sites must include rocks with minerals amenable to geochronology and thermochronology such as quartz, apatite, and zircon. Once subduction zone segments meeting these conditions were identified, a pairing of segments in which independent variation in specific factors of interest (e.g., plate convergence rate) were mapped onto the L&S notional experiments to determine the optimal pairing of subduction zone segments.

MDE Hypothesis Sets A and C will require decade-long, multiparameter characterization of inter-eruption and eruption behavior at a large number (~30–50) of arc volcanoes that exhibit magmatic unrest (active degassing, deformation, and/or seismic unrest), have a history of frequent but not continuous eruption and some prior characterization, and represent a diverse range of volcanic activity. MDE Hypothesis Set B will require geophysical imaging of trans-crustal magmatic systems and characterizing the eruptive history in detail at a small number of representative volcanoes (two per arc) in three arcs (the two SZ4D complementary sites and an additional arc segment) that represent fast, intermediate, and slow convergence. For the six target volcanoes, critical requirements are access to significant land area for certain key observations, such as wide-aperture seismic and geodetic deployments and InSAR and excellent and accessible exposures or records of past eruptive deposits for study of volume, eruptive intensity, composition, thermobarometry, geochronometry, and geospeedometry. MDE also aims to study exhumed sites that represent ancient analogs to concurrently studied active systems. Sites where crustal residence times, magmatic compositions, and storage depths during "high-" and "low-" flux time periods could be characterized are ideal. In addition, localities that preserve both contemporaneous plutonic and volcanic records could be particularly useful to connect plutonic observations to volcanic products.

The ideal sites for the FEC component would possess the following characteristics:

1. Known large and active faults in overriding and downgoing plates;
2. High convergence rates;

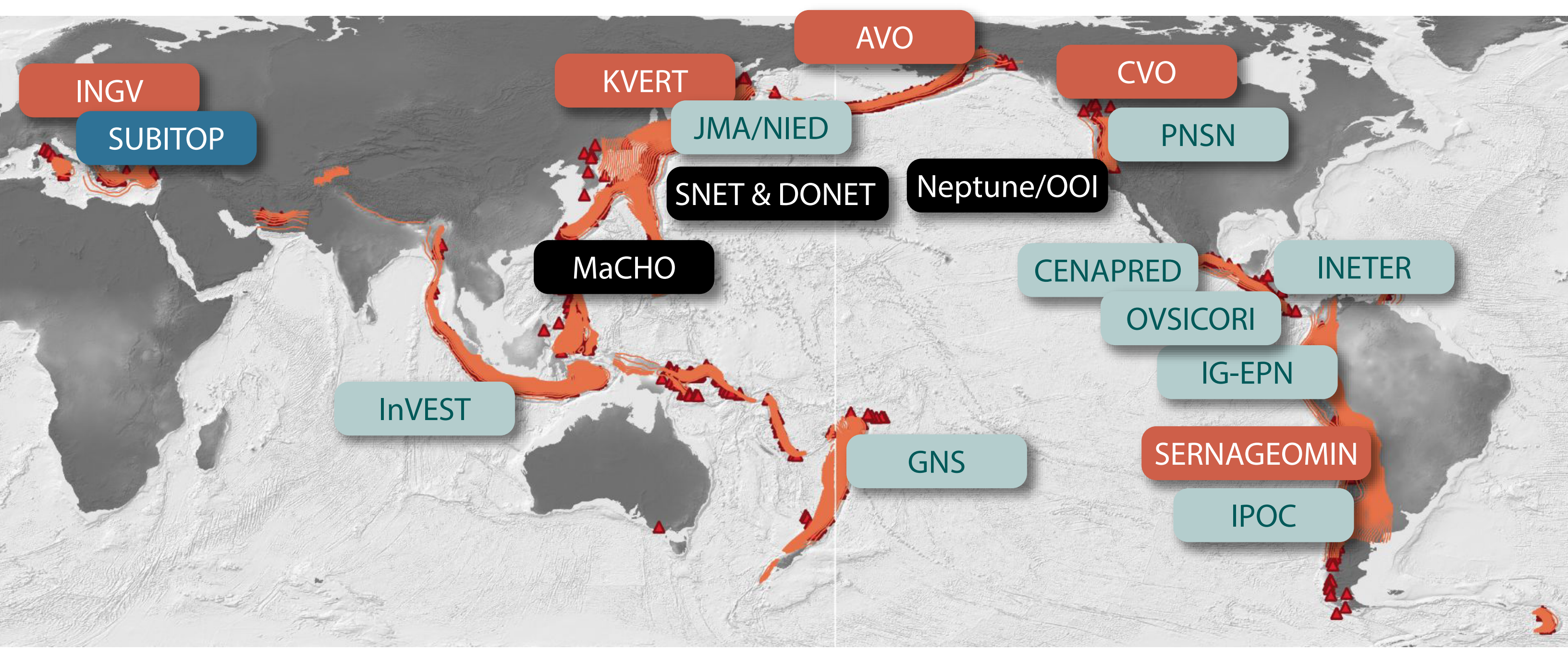
3. Known slow slip events;
4. High seismicity rates;
5. Known strong gradients in coupling along strike;
6. Known tsunamigenic event;
7. Preserved history of fault slip, earthquakes, and tsunamis; and
8. Evidence of a large earthquake that ruptured the entire seismogenic zone.

Because the overarching goal of FEC is to understand when and where along the seismogenic zone large and damaging subduction zone earthquakes occur, a fundamental requirement is that study sites are known to be capable of producing such large earthquakes. Seismic coupling is also a significant factor for all four FEC science questions; the degree to which the plates are locked is an overriding theme that affects all aspects of the seismic cycle as well as the related landscape and volcanic processes. High seismicity rates and convergence rates are favorable for observing subduction zone behavior over a decadal timescale (FEC Science Question 1). There is a preference to be late in the seismic cycle, if possible, to increase the chance of observing precursory behavior before a large earthquake (FEC Science Question 3). To capture the relevant spatial scales of large subduction zone earthquakes, study areas must span at least ~500 km along strike.

Logistical Requirements

A touchstone of the SZ4D is to enable large-scale, multidisciplinary interaction among scientists who have deep knowledge of the field context. This ambition requires taking a high degree of safety precautions for a large number of scientists who may visit the region either

Figure G-1. *Examples of regions and networks with existing instrumentation in subduction zones. Colors indicate network type. Orange: Volcano. Green: Combined earthquake and volcano. Blue: Landscapes. Black: Submarine observatory.*



directly as part of SZ4D or in complementary projects. Therefore, any region that has serious, ongoing, well-documented security concerns should not be a focus of SZ4D field efforts. The US State Department Travel Advisory list provides a useful compilation of security information. Any region that is at level 3 or 4 on this list for non-COVID reasons at the time of a proposal submission cannot be a field site (We have an understanding that COVID-related travel concerns will be reduced by the time SZ4D is first implemented.) Scientists from those regions will hopefully still be able to contribute to SZ4D through work in selected focus sites and through comparisons with other subduction zones. The establishment of a practical limit based on the federal guidelines is simply a matter of establishing a common, objective standard for work that involves a substantial number of participants traveling to the region utilizing federal funding.

As SZ4D will likely be primarily federally funded, data collected as a part of the project must be open access and consistent with NSF and other agency policies. Therefore, any collaboration internationally will need to proceed only if such open data release is permitted.

THE GLOBAL PORTFOLIO

Multiple regions of the world already have significant instrumentation and scientific focus on subduction zone processes (**Figure G-1**). Observational SZ4D efforts should complement previous and ongoing major investments. Of particular note are the major offshore cabled observatory efforts in Japan, Taiwan, and Cascadia. These significant investments should guide the technological and scientific choices of complementary sites elsewhere. Similarly, major volcano instrumentation at a blend of academic and government observatory sites informs strategic choices of study regions that can be selected to fill gaps while also leveraging prior work that establishes context for future measurements. Landscape studies have not historically had major infrastructure initiatives with a few exceptions such as the EU Horizon 2020 SUBITOP project and the long-standing efforts in Taiwan. The seascape is even a more recent focus of effort, and new work by the USGS and others in Cascadia and Alaska is beginning to show the value of regional efforts.

Critical to achieving SZ4D's scientific goals is building a global portfolio of instrumentation and activities that the international scientific community can draw upon. This strategy requires first developing a coordinated global network of subduction zone observatories to share technologies, data, and insights. Informal interactions between scientists and observatories exist, but the global portfolio would benefit from more regular and formal structures for technology, data, and human exchange.

Improving the global portfolio also requires strategic use of SZ4D resources to carefully select geographic regions that complement existing efforts. Complementary efforts should avoid redundancy, and thus SZ4D resources would not be well spent in areas that are already instrumented at the cutting edge of current technology, like Japan. Complementary efforts should also build on extant regional knowledge and data in order to maximize the potential gains over the relatively short timescale (few decades) of our work. Areas that have had little or no previous study probably should not be the primary focus of our efforts. For instance, the Scotia arc is geologically interesting, but has insufficient baseline data for a concerted effort in the next decade.

The requirement for a long subduction zone segment that is logistically feasible eliminates several other geologically significant areas from consideration. Security concerns in parts of Mexico, Indonesia, and Central America make it difficult to define a continuous segment that would meet both the scientific and practical requirements of the project.

PROCESS TO IDENTIFY REGIONS OF SPECIAL INTEREST

With these operational requirements and constraints in mind, the SZ4D RCN implemented a multi-step process to identify regions of special interest. Through detailed discussions, the working group and cross-cutting group members jointly identified sites suitable for filling gaps in our fundamental understanding of the particular geohazards, as well as sites where knowledge gained can be used to inform and reduce domestic risk from geohazards.

As a first step, discussions among the entire SZ4D RCN weighed the pros and cons of various geographic areas, including both domestic and international sites. Following several days of discussion, participants were provided with a global map of potential subduction zone sites. On those maps, they could select two locations (according to priority) that might satisfy the joint needs of the different working and cross-cutting groups. This exercise was not a vote, but instead was an informal assessment of the level of convergence on geographic sites by the working group members following the days of conversations. The density of selected areas, as well as the correspondence between sites selected by individual members, is shown in **Figure G-2**.

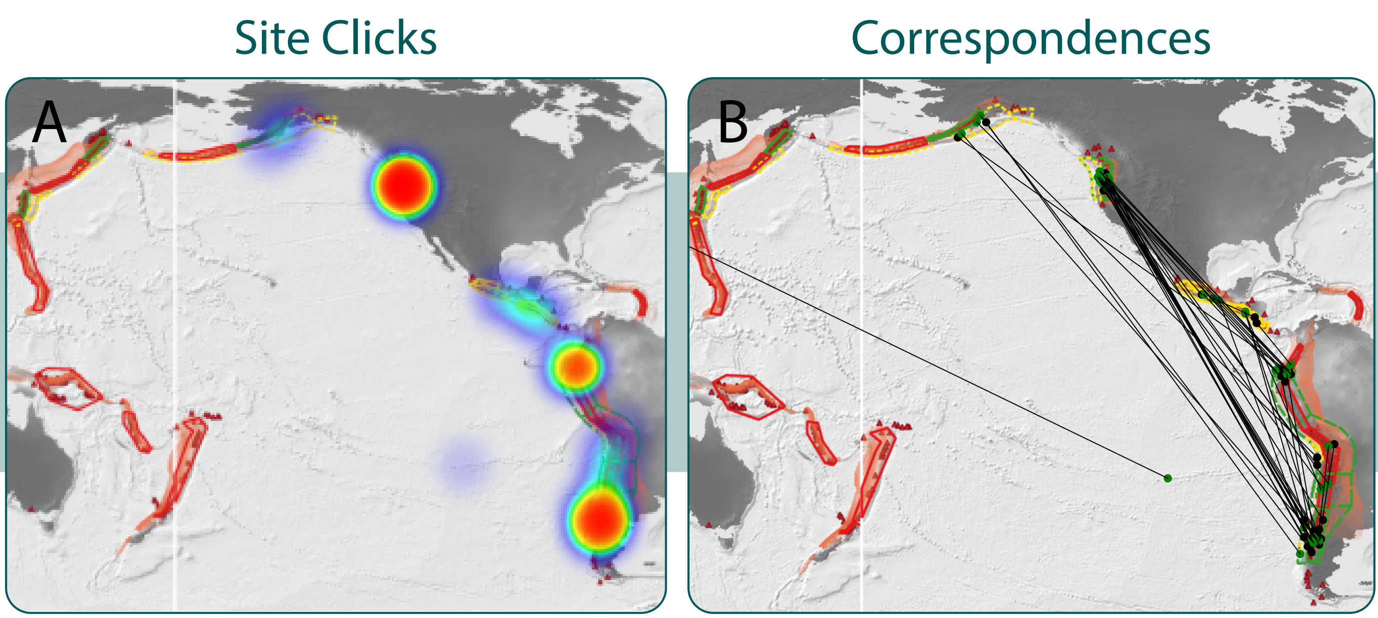


Figure G-2. *(A) Heat map of SZ4D RCN selected sites following the discussion of site characteristics, disciplinary needs, and overall site suitability. Areas that display more prominently in red show a higher density of selections. (B) Correspondences between sites selected by individuals. Each line segment links the two sites selected by each individual.*

The results of this exercise identified two main areas of convergence: Chile (24 selections total, with 16 of these selections rated as the first priority, while eight were selected as a second priority) and Cascadia (22 total, with six of these selections rated as the first priority, while 16 were rated as the second priority).The most frequent paired prioritization was between Chile and Cascadia (12 participants identified this combination, with nine calling out Chile as a first priority, and three calling out Cascadia as a first priority). The main conclusion from this exercise was that the SZ4D RCN required both an international and domestic site when designing the SZ4D efforts, and ideally these sites would provide complementary comparisons. When posed with the question, "Should the SZ4D target complementary international and domestic sites?," 41 out of 42 members of the SZ4D RCN membership voted "yes." When asked "If there is an international site, should Chile be the primary focus?", 37 out of 42 members voted "yes." Thus, there appeared a strong consensus to find complementary international and domestic sites, and of the international sites, Chile was the strong favorite. This information allowed the SZ4D RCN to identify "Regions of Special Interest," which are documented below.

REGIONS OF SPECIAL INTEREST

Chile

The Chilean subduction zone possesses nearly all of the high-priority scientific attributes identified by the SZ4D working groups. Factors such as slab dip, convergence rate, and climate vary systematically along the subduction zone, which allows many natural experiments to be carried out along a single subduction zone system. Rapid convergence leads to abundant seismic, volcanic, and landslide activity. The Chilean subduction zone experienced the largest instrumentally recorded earthquake in 1960 and many >M8 earthquakes since then, and it has 96 volcanoes with eruptions in the Holocene, and 33 discrete eruptions have been recorded in the twenty-first century. This significant exposure is constantly being assessed and characterized by in-country governmental organizations, and so scientific discoveries made by the SZ4D have a clear pathway to implementation in applied sciences through partnerships with these organizations. The opportunities presented by the Chilean subduction zone have produced efforts that have been ongoing in the region for decades with onshore and temporary offshore instrumentation. Importantly, there is a robust community of geohazards scientists working in Chile in both academic and national observatory settings. This community has developed internal networks and also built international collaborations with German, French, American, and other partners to develop instrumentation that was well situated to capture some of the most significant earthquakes in the early twenty-first century. The 4500 km of continental subduction zone encompassed in a single country make it globally unique. International collaborations have also produced a backbone of moderate-resolution bathymetry for much of the margin, allowing collection of high-resolution bathymetry in targeted areas. Significant onshore and offshore passive and active seismic imaging has been done over the last two decades, which can be strategically complemented by SZ4D efforts. Chilean and Argentine networks span the entirety of the subduction zone system and have enabled a substantial amount of on-the-ground domestic and international data collection to take place over the last 40 years. Opportunities may be present in Chile both on and offshore to complement the existing efforts.

Cascadia

The Washington and Oregon margins have the largest associated risk of any domestic subduction zone and thus deserves special attention. The societal implications associated with a major volcanic eruption or the ground shaking and tsunami associated with the eventual magnitude 9 earthquake weigh heavily on the region. Also, funded infrastructure (OSU-UW CoPes Hub) allows SZ4D activities to impact resilience efforts, which is a primary objective of the BECG efforts. The fact that science can be translated into on-the-ground, domestic risk and resilience efforts makes this site particularly appealing. Additionally, accessibility provided by this domestic site makes it an ideal area where many of the aspirations of the SZ4D BECG efforts can be implemented.

Scientifically, the Cascadia subduction zone possesses some attributes that are favorable for addressing scientific questions of L&S and MDE. Significant along-strike variability in volcanism, including erupted volumes, differ by a factor of two between the southern and northern portions of the arc. Also, Cascadia hosts major changes in the partitioning of volcanism between intermediate and silicic-dominated central volcanic edifices and fields of more mafic and dispersed monogenetic centers. The high coupling and known slow slip events are favorable for some FEC goals, but the slow convergence rate and low seismicity rates make Cascadia a suboptimal region to address many of the FEC science questions, particularly those concerning the relationships between earthquakes and other slip behavior and precursory behavior. Consequently, this region lends itself best to a subset of approaches, such as paleoseismology, geophysical imaging, deep-time study of onshore fault systems and relatively quiescent but diverse volcanoes, and slow slip and tremor.

There is a wealth of existing data that can be leveraged for studies of Cascadia and comparisons to other subduction zones, including seismic data from the Cascadia Initiative, onshore/offshore active and passive seismic imaging (including the recent acquisition on a synoptic 2D deep penetration seismic reflection/refraction dataset along the margin), magnetotelluric profiling, bathymetric mapping, extensive subareal high-resolution topographic mapping, lava geochemistry, and onshore/offshore geological studies. There are also abundant opportunities for collaborations with other US organizations, including the USGS, which is emphasizing Cascadia within its subduction initiative. The ideal study strategy is thus to combine a study of Cascadia with a faster subducting analog that can provide the information on human timescales that will ultimately be important to interpreting and predicting the future behavior of the United States' most prominent subduction zone.

Aleutians/Alaska

The Aleutians/Alaska (AA) subduction zone has frequent and diverse eruptions and frequent earthquakes, and thus some sections of this ~2000 km-long subduction zone were considered favorable study areas by the FEC and MDE. For the FEC, the history of large earthquakes, variations in coupling, rupture history, and seismicity off the Alaska Peninsula make this region an attractive possible target for study; one segment was thought to be relatively late in the seismic cycle. The occurrence of a series of large interplate earthquakes here in 2020–2021 has released some of the stored energy, potentially complicating one of the appeals of this location. The region has a rich diversity in arc structure and tectonics, sediment and volatile influx feeding primary magma generation, and crustal magma differentiation processes, with the resulting outcome the production of a complete range in eruption styles from its diverse volcanic centers. However, this region is problematic for the L&S group due to the recent glacial history, which makes many aspects of required geochronology problematic, and the lack of an extensive subareal forearc with which to study important geohazards such as landslides and flooding. The focus of their work requires a substantial exposed land surface. For all groups, the remote location and challenging weather are present hurdles.

An advantage of the AA subduction zone for the MDE and FEC is that it is a relatively well-studied system with abundant existing geochemical data. Geophysical imaging and bathymetric data have been acquired in some areas, particularly off the Alaska Peninsula, but coverage is not uniform owing to the size and remoteness of this subduction zone. As with Cascadia, there are significant opportunities for collaborations with other US entities, including the Alaska Volcano Observatory, the Alaska Earthquake Center, the USGS, and NOAA's National Tsunami Warning Center.

PRIORITIZATION OF INSTRUMENTATION AND ACTIVITIES WITHIN THE REGIONS OF INTEREST

The identification of "Regions of Interest" satisfied the requirement of complementary international and domestic sites. However, the question of how to most effectively allocate resources between the "Regions of Interest" to address the SZ4D science questions required additional, subsequent discussions. During these discussions, it became apparent that the types of resources needed would vary between the different areas, because some areas would require the construction of extensive instrumentation networks, while others contain an observational backbone that is already in place. In this sense, some sites may require extensive instrumentation, while others would require science activities (such as field study, modeling, outreach) that would leverage and augment existing instrumentation to answer the SZ4D science questions. For this reason, the SZ4D RCN members considered the "Regions of Special Interest," in terms of how instrumentation and activities might be partitioned between the different sites to maximize their utility in answering the SZ4D science questions.

After a series of discussions focused on needed (and existing) observational capabilities and activities, a questionnaire was used to gather participants' opinions on how to allocate priority for instruments and activities between these three potential sites and thus to assess convergence between all disciplinary working group members. Each participant was given a total of 10 (integer) points for instruments, and 10 (integer) points for activities. These points could be allocated to each of the three "Regions of Special Interest" for each category (instruments versus activities). Forty-two participants performed this allocation, the results of which are summarized in **Table G-1**.

While there was some variability in how instruments and activities would be allocated between the different sites that depended on the specific working or cross-cutting group,

Site	Disciplinary score weighted for number of participants in each group		FEC		MDE		L&S	
	Instrumentation	Activities	Instrumentation	Activities	Instrumentation	Activities	Instrumentation	Activities
Chile	6.9	5.1	6.4±1.7	4.9±1.1	7.1±1.8	5.2±1.3	7.2±1.4	5.1±0.8
Cascadia	2.2	3.6	2.3±1.2	3.3±1.2	2.0±1.1	3.3±1.3	2.3±1.3	4.2±1.0
Alaska/Aleutians	0.9	1.3	1.3±1.3	1.8±1.2	0.9±0.8	1.5±1.3	0.5±0.7	0.7±0.8

Table G-1. *Results of exercise to prioritize instrumentation and activities between the Regions of Special Interest*

there was a remarkable consistency in the allocation between respondents, despite the disparate objectives and needs of the different groups. This informal questionnaire indicated a broad, and consistent agreement that instrumentation should be dominantly deployed along the Chilean subduction zone (6.9), and that a lesser investment of instrumentation should be allocated to Cascadia (2.2) and Alaska (0.9). On the other hand, participants allocated activities more evenly between the sites (Chile: 5.1, Cascadia: 3.6, Alaska: 1.3). Thus, the SZ4D RCN appeared to favor heavy instrumentation investment at the international site, whereas activities should be carried out across both domestic sites, as well as within the international site. In this way, existing investments in domestic instruments could be leveraged to provide the comparative information that will be necessary to answer the SZ4D science questions.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

Key to the success of the SZ4D initiative is selecting an appropriate set of sites where the phenomena identified in the science questions are best studied. We carried out a process that first ruled out inappropriate sites (based on the presence / absence of factors that prevented one of the working groups from addressing their science questions, and logistical consideration of safely working in a region). We then compiled the properties of possible subduction zone segments to identify those that best met the needs of each working and cross-cutting group, and compared the segment properties to isolate factors of interest. The SZ4D RCN also noted that the science questions would be best answered by comparing an international site to one or more domestic sites. Using the compilation and constraints, we identified three Regions of Special Interest: the Chilean, Cascadian, and Alaskan subduction zones. The SZ4D RCN strongly and clearly favored deployment of the bulk of instrumentation along the Chilean subduction zone system, while science and outreach activities were best performed at all three Regions of Special Interest. In this way, the SZ4D envisions the deployment of the proposed arrays along the Chilean subduction zone, but science will be carried out both internationally and domestically to leverage existing domestic infrastructure and to provide direct impact to domestic hazard assessment priorities.