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Favorable Structural–Tectonic Settings and Characteristics of Globally Productive Arcs

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ABSTRACT

There are currently 74 productive geothermal systems associated with volcanic centers (VCs) in arcs globally, including actively producing systems, past producing systems, and systems with successful flow tests. The total installed or tested capacity of these 74 geothermal systems is 7,605 MWe, ranging from 0.7 MWe each at Copahue, Chile and Barkhatnaya Sopka, Kamchatka to 795 MWe, Larderello, Italy, and averaging 90.5 MWe per system. These 74 productive VCs constitute 10% of 732 VCs distributed across more than a dozen major arcs around the world. The intra-arc (within-arc) tectonic setting is highly variable globally, ranging from extension to transtension, transpression, or compression. Furthermore, the shear strain associated with oblique plate convergence can be accommodated by either intra-arc or arc-marginal deformation. The structural-tectonic settings of these 74 productive VCs were characterized to add to a global catalog of parameters to help guide future exploration, development, and regional resource potential.

Five summary parameters were characterized; tectonic setting (e.g., extensional or compressional), angle of plate convergence relative to the arc axis, distribution of Quaternary fault activity (e.g. scarps), fault slip rates, and local structural setting. Each of these parameters have associations with the electrical productivity of volcanic centers (MWe/VC) and capture different aspects of the structural-tectonic influence on the geothermal potential of each VC. The regional tectonic setting of the 74 VCs include 11 (15%) extensional, 43 (59%) transtensional, 4 (5%) transpressional, 7 (9%) compressional, and 9 (12%) unknown environments. Importantly, 73% of the VCs are in extensional or transtensional environments and these are responsible for 88% of the total known MWe capability in global arc settings. At a local scale the VCs are associated with a number of structural settings, including 10 (14%) in pull-aparts along strike-slip fault zones, 15 (20%) in association with displacement transfer zones where strike-slip faults merge with normal faults, 4 (5%) in normal fault accommodation zones, 7 (9%) in normal-fault step-overs, 22 (30%) associated with fault intersections, 4 (5%) in other settings, and 12 (16%) in unknown settings. Of these structural settings, the pull-aparts, displacement transfer zones, step-overs, and accommodation zones accounted for 49% of the productive VCs and 76% of the total MWe. In contrast, the fault intersections included 30% of the VCs but only 16% of the total MWe. Quaternary fault densities and fault slip rates also show positive relationships with MWe capability. One of the primary conclusions is that productive geothermal systems associated with arc VCs are mining convective heat flow co-located with areas of active, extensional, intra-arc strain.

1. INTRODUCTION

The Play Fairway Analysis (PFA) initiative by the Geothermal Technologies Office (GTO) of the U.S. Department of Energy has provided a valuable platform for propelling quantitative, regional-scale, geothermal potential assessments that incorporate a variety of input data sets. These PFA studies were implemented across a range of geologic settings and geothermal play types, including volcanic arcs (Cascades and Aleutians), mid-ocean plate volcanic hot spot (Hawaii), amagmatic fault-controlled systems (Basin and Range), and amagmatic hot sedimentary aquifers (Appalachian Basin). Critical to the success of these GTO-funded PFA studies are baseline geologic, geophysical, and geochemical data on well-studied hydrothermal resources and/or expert guidance for selecting, weighting, and modeling this input data to produce predictive fairways. One challenge is that unlike the petroleum and mineral industries, comprehensive inventories of favorable structural settings for known geothermal resources are not yet well developed, especially for arc systems. A recent and notable paper by Moeck and Beardsmore (2014) provided key categorical distinctions of global resources according to dominant process of heat transfer (convection or conduction) and subdivided convection-based resources according to broad geologic settings (magmatic, plutonic, and extensional/amagmatic). However, a publically available catalogue of structural-tectonic or volcanologic metrics with quantifiable geothermal favorability are still largely missing for arc settings.

Play Fairway Analysis of the Cascade and Aleutian volcanic arcs was one of 11 PFAs funded for phase I study from 2014 to 2015. To date no geothermal power plants have been developed in the Aleutians or the Cascades. Globally, there are currently 74 productive geothermal systems associated with VCs in arcs, including actively producing systems, past producing systems, and systems with successful flow tests but not yet developed (Hinz et al., 2015; Shevenell et al., 2015). The total installed or tested capacity of these 74 geothermal systems is 7,605 MWe, ranging from 0.7 MWe each at Copahue, Chile and Barkhatnaya Sopka, Kamchatka to 795 MWe, Larderello, Italy, and averaging 90.5 MWe per system. These 74 productive VCs constitute approximately 10% of the 732 VCs distributed across more than a dozen volcanic arcs around the world. The distribution of producing systems is partly controlled by restricted access such as in wilderness areas or national parks (e.g., Mount Lassen, California, USA), and by proximity to markets (accessibility in the Cascades versus limited accessibility in the western Aleutians); however, the distribution and range in MWe per system is also influenced by the physical characteristics of each resource.

Volcanic arc hydrothermal systems generally require a combination of heat, reservoir permeability, cap rock, and fluids. Variations in any one of these components can affect the overall MWe potential of a given VC. For example, at Mount Meager, British Columbia, Canada, exploration wells have intersected fluids at 240° C, however flow tests support less than 5 MWe, apparently due to limited permeability. The ultimate objective of this DOE-funded study was to assess the electricity generating potential of volcanic centers in the Aleutian and Cascade arcs. To do this, the globally productive VCs in arc settings around the world were characterized according to specific structural-tectonic, volcanological, geochemical, and geothermal characteristics to develop qualitative and quantitative metrics (Shevenell et al., 2015). Reported here are the results of the assessment of structural–tectonic settings and associated characteristics of the current 74 globally productive arc VCs.

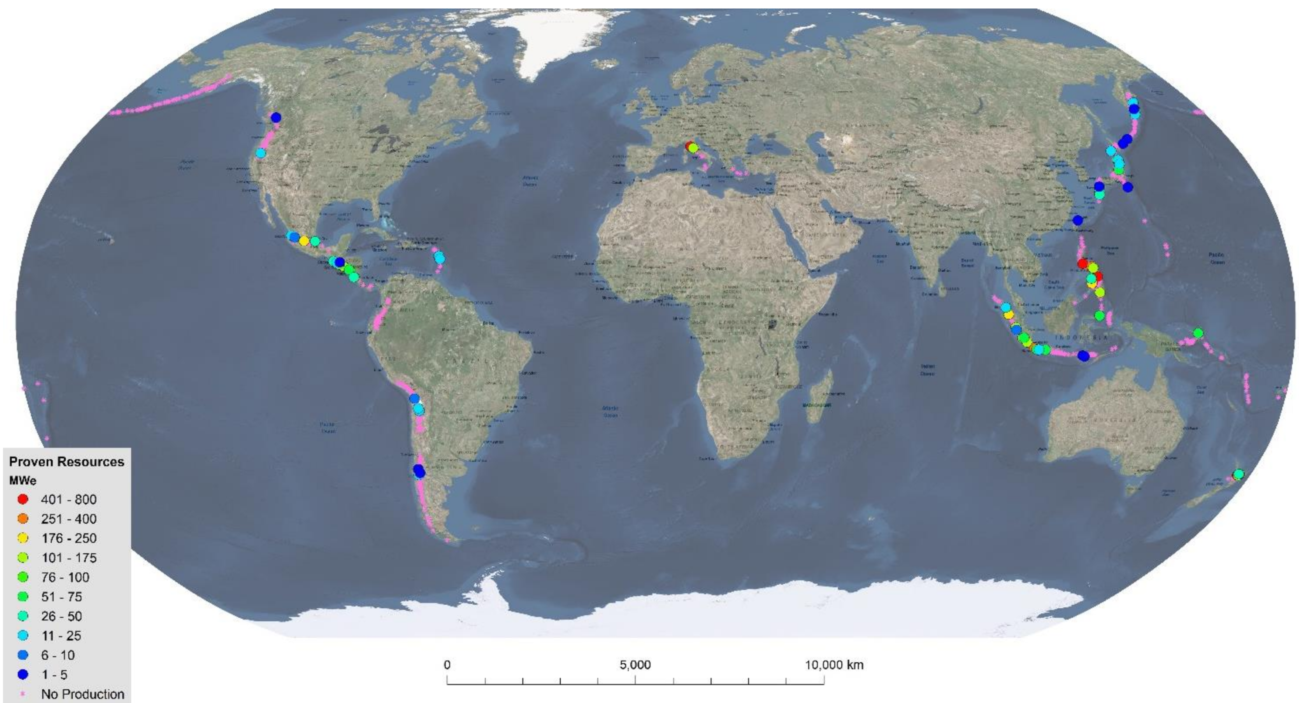

Figure 1: Distribution of globally productive volcanic centers, symbolized by installed MWe category. Background image is from ESRI World Imagery.

2. BACKGROUND AND METHODS

Subduction plate boundaries are some of the most structurally and tectonically complex regions in the world, with components of active compression, translation, and extension commonly distributed across most respective plate boundary segments. Most of the active compression associated with plate subduction is accommodated by crustal shortening in the overriding plate in the accretionary prism. The angle of plate convergence, the angle of the subduction slab, localized slab roll-back, subduction of seamounts and ocean-plate ridges, and lithospheric strength all affect the degree and manner in which compressional stress and strain are transferred inboard of the accretionary prism. Some volcanic arcs, such as Honshu (Japan) or the eastern Aleutians are dominated by compressional or transpressional strain. In contrast, other arcs such as the southern Cascades, the Nicaraguan segment of the Central American Arc, the trans-Mexico volcanic arc, or Taupo in New Zealand are largely decoupled from compressional stress and strain, and are dominated by extensional tectonism. In addition to extension or compression, translation driven by oblique subduction is associated with most subduction plate boundaries of the world. Of importance for volcanic and hydrothermal activity, a large component of the relative oblique motion between the colliding plates is accommodated through intra-arc or arc-marginal transtension or transpression (e.g., Ave Lallemant and Oldow, 2000). Large magnitude shear in arc segments is usually accommodated by large magnitude strike-slip faults (e.g. Grand Sumatra Fault, Indonesia, Yeats et al., 1997), especially in areas of higher lithospheric strength (Molnar and Dayem, 2010). In areas of lower lithospheric strength, typically oceanic or thin continental crust, shear is accommodated along meshes of smaller magnitude strike-slip faults (e.g. central and western Aleutians).

A review of existing data on the structural controls of both magmatic and amagmatic geothermal systems around the world indicates that three primary structural-tectonic characteristics are paramount for geothermal favorability: 1) type of structure and overall structural complexity, 2) extensional strain, and 3) active strain rate (e.g., Curewitz and Karson; 1997; Rowland and Sibson; 2004; Faulds et al., 2006; 2009; 2011; 2012; 2015; Faulds and Hinz, 2015; Siler et al., 2015). To assist in assessing these characteristics along volcanic arcs, we selected a list of geologic parameters that was populated for each VC that captures key regional tectonic and local structural conditions: (1) Tectonic setting, (2) Angle of plate convergence, (3) Local structural setting, (4) Fault slip rates, and (5) Quaternary fault scarps.

These data sets were collected from published geologic maps (digital and analog), digital databases such as the World Stress database (Heidbach et al., 2008) or the USGS Quaternary fault and fold database for the continental USA (USGS, 2010), and numerous peer review papers and reports (~300 references; Shevenell et al., 2015). Most of the structural parameters were populated from data within a 10 km radius of each VC, based on the observation that roughly 80% of the geothermal areas associated with VCs in arcs around the world are located within 10 km of a significant volcanic vent (Coolbaugh et al., 2015). The two exceptions for the 10 km radius were the categories of tectonic setting and angle of plate convergence, which were both assessed through evaluation of regional data.

3. RESULTS

3.1 Tectonic Setting

A qualitative characterization of tectonic setting was based on synergistic integration of local and regional structural data, stress data, and strain data. This category is useful for evaluating broad trends in the data sets, as well as providing favorability weighting based on regional data, especially where the local structural setting cannot be identified due to absence of data (e.g., unmapped and/or covered by snow). Categories of tectonic setting include: extensional, transtensional-SS (strike-slip dominant transtension), transtensional-EXT (extension dominant transtension), transpression, compression, and unknown.

Nearly 75% of productive VCs are in extensional or transtensional settings and they account for nearly 90% of the global MWe production in volcanic arcs (Table 1). As mentioned above, these benchmark VCs account for about 10% of the volcanoes in arcs around the world. We have not characterized the tectonic setting for the other 90% of the global arc VCs. Nevertheless, a brief review of global tectonic data supports that upwards of 30 to 50% of all arc VCs are in transpressional or compressional settings (Hinz, unpublished data); however further work is needed to better evaluate the remaining 90% of VCs that are not part of the globally productive list.

Table 1: Tectonic settings of the VCs with MWe per category and average MWe/VC.

Tectonic Settings	# of productive VCs	% of Productive VCs	Total MWe	% MWe/VC	Ave MWe/VC
Extensional	11	15%	1246	16%	113
Transtensional-EXT	10	14%	1363	18%	136
Transtensional-SS	33	45%	4099	54%	124
Transpressional	4	5%	463	6%	116
Compressional	7	9%	234	3%	33.4
Unknown	9	12%	202	3%	22
Total	74	100%	7605	100%	103

3.2 Geodetic Data

A summary of GPS-derived angle of plate convergence relative to the arc axis for the Aleutians, Cascades, and global benchmark VCs is provided in Coolbaugh et al. (2015). This angle is derived from the Global Strain Rate Model (GSRM v. 2.1, Kreemer et al., 2014) and represents the angle of obliquity between the motion of the subducting plate relative to the arc axis. Zero degrees indicates that the subducting plate is moving perpendicular to the arc axis. Ninety degrees indicates that the subducting plate is moving parallel to the arc axis. The greater the angle of obliquity, the greater the potential for arc-parallel, intra-arc shear.

In the global benchmark set of productive VCs, 57% of the VCs reside in areas where the subducting plate is moving within 0 to 22.5° from perpendicular and these account for 31% of the total MWe (Table 2). Contrasting this, 41% of the VCs reside in areas where the subducting plate is moving >22.5° from perpendicular and these account for 58% of the total installed MWe. The average MWe per VC in the 22.5 to 45° category is approximately 2.5 times that in the 0 to 22.5° category. This average continues to increase with greater angles of obliquity. At the top of the chart, the four VCs in the 67.5 to 90° category have twice the MWe/VC output compared to the next lower category of 45 - 67.5°.

Table 2: Angle of subducting slab motion relative to the arc axis for the VCs.

Angle (°)	# of Productive VCs	% of Productive VCs	Total MWe	% MWe/VC	Ave MWe/VC
67.5-90	4	5%	1381	18%	345
45-67.5	4	5%	684	9%	171
22.5-45	23	31%	3124	41%	136
0-22.5	42	57%	2355	31%	56
Unknown	1	1%	63	1%	63
Total	74	100%	7605	100%	103

3.3 Structural Setting

The primary structural settings associated with each VC were compiled into a qualitative characterization based on evaluation of faults within a 10 km radius of each VC. In many cases, VCs are associated with 2 or 3 major structural settings, acting singly on separate parts of the VC or in direct overlapping and compound fashion. The type of structural setting contributes to the relative geothermal potential of a structural target area. Recent research (e.g. Faulds et al., 2013) shows that structural settings with greater complexity (e.g., accommodation zones) have greater geothermal potential to host a viable geothermal resource than those with less structural complexity (e.g., fault termination). The more complex structural settings may correspond to greater bulk permeability, or broader areas with high permeability, which can facilitate larger commercial reservoir volumes and provide more efficient conduits for conductive heat transfer through the crust to drive the geothermal system (Faulds et al., 2013; Faulds and Hinz, 2015; Siler et al., 2015). In general order of relative decreasing structural complexity, these categories include: accommodation zone, displacement transfer zone, pull-apart, step-over, fault intersection, and other/unknown.

Power production is dominated by pull-aparts, displacement transfer zones, step-overs, and accommodation zones (Table 3). These four structural settings collectively account for 49% of the productive VCs and 76% of the total MWe. In contrast, fault intersections account for 30% of the VCs and only 16% of the total MWe.

Table 3: Structural settings of the VCs with MWe per category and average MWe/VC.

Structural Settings	# of Productive VCs	% of Productive VCs	Total MWe	% MWe/VC	Ave MWe/VC
Pull-apart	10	14%	1686	22%	169
Displacement Transfer Zone	15	20%	1837	24%	122
Accommodation Zone	4	5%	907	12%	227
Step-over	7	9%	1,358	18%	194
Fault Intersection	22	30%	1,057	14%	48
Other	4	5%	273	4%	68
Unknown	12	16%	487	6%	41
Total	74	100%	**7,605**	100%	103

3.4 Quaternary Normal Fault Slip Rate

Fault slip rates were compiled from data on normal faults, but not from strike-slip faults, because normal faults are the primary mode of extension. Peak slip-rates along the Grand Sumatra Fault and Philippines Fault approach and locally exceed 3 cm/yr (e.g., Yeats et al., 1997), but individual normal faults associated with pull-aparts rarely exceed 3 mm/yr globally. Active Quaternary faults are associated with 67% of the global benchmark productive VCs and account for 83% of the arc-related MWe (Table 4). The average MWe for VCs associated with fault slip rates of <0.1 or 0-1-0.3 mm/yr is about 3 times as great as the average MWe for VCs not known to be associated Quaternary faults. Average MWe for VCs associated with fault slip rates of 0.3 to 1.0 mm/yr are about twice that for VCs with fault slip rates of only 0.1 to 0.3 mm/yr. This trend continues with the upper end of the slip rate category where the average MWe for VCs associated with fault slip rates of 1.0 to 3.0 mm/yr is about twice as great as the average MWe for VCs with fault slip rates of 0.3 to 1.0 mm/yr.

Table 4: Normal fault slip rates of the VCs with MWe per category and average MWe/VC.

Slip Rate (mm/yr)	# of Productive VCs	% of Productive VCs	Total MWe	% MWe/Total	Ave MWe/System
1-3	2	3%	853	11%	427
0.3-1	9	12%	1784	23%	198
0.1-0.3	14	19%	1346	18%	96
<0.1	25	34%	2306	30%	92
0	8	11%	229	3%	29
Unknown	16	22%	1087	14%	68
Totals	74	100%	7605	100%	103

3.5 Quaternary Fault Scarp Concentration

The presence and distribution of Quaternary fault scarps provides some indication of recency of faulting (a favorable attribute, e.g., Bell and Ramelli, 2007), and also to the degree of structural complexity. Low Quaternary fault scarp density includes VCs with only one or two fault segments exhibiting Quaternary scarps. Medium Quaternary fault scarp density includes VCs with three or four fault segments having Quaternary scarps. High Quaternary fault scarp density includes VCs with five or more fault segments with Quaternary scarps.

Similar to the Quaternary fault slip rate data, the concentration of Quaternary faults (fault density) associated with VCs also correlates with productivity, but with a slightly reduced spread in magnitude of MWe per category (Table 4). The average MWe productivity for VCs with high Quaternary fault scarp density (Table 5) is almost twice the productivity of VCs with medium fault scarp density, and the productivity of VCs with medium Quaternary fault scarp density averages almost twice that of VCs with low fault scarp density.

Table 5: Quaternary fault scarp density of the productive VCs with MWe per category and average MWe/VC.

Q-fault scarp density	# of Productive VCs	% of Productive VCs	Total MWe	% MWe/Total	Ave MWe/System
High	9	12%	2410	32%	268
Medium	9	12%	1343	18%	149
Low	34	46%	2846	37%	84
Zero	10	14%	246	3%	25
Unknown	12	16%	760	10%	63
Totals	74	100%	7605	100%	103

4. DISCUSSION AND CONCLUSIONS

Our evaluation of global energy producing arc systems has shown that a number of factors are associated with productive geothermal systems. A common thread among these factors is the presence of active extensional intra-arc strain. Dilatant structures that facilitate fluid flow are common in extensional and transtensional terranes, but are less well-developed in regions of compression or transpression. Individual factors that correlate with electricity generating potential include: 1) regions of oblique plate convergence, 2) high Quaternary fault slip rates, 3) high densities of Quaternary fault scarps, and 4) local extensional structural settings that include pull-aparts, step-overs, accommodation zones, or displacement transfer zones. Together, these favorable factors can be combined in an expert-driven and data-driven weighting system to produce a valuable fairway analysis tool with which to evaluate the electricity-generating potential of arc volcanic centers around the world (Coolbaugh et al., 2015; Shevenell et al., 2015). The methodologies developed can be easily adapted to other tectonic environments.

Regional patterns are also apparent per major individual arc segments. In Table 6, arc segments are listed according to dominant tectonic setting (e.g., extension or compression) and then ordered by strain rate. The Philippines, West Java, and northern Costa Rica/Nicaragua/El Salvador arc segments all have moderate to high strain rates and average- to well-above average MWe per productive volcanic center. In extensional environments, the Taupo Volcanic Zone stands out with the highest average MWe per productive volcanic center across the TVZ arc segment. Italy also stands out as being especially productive in the lower transtensional rate category, but with only two productive geothermal areas, one of which is Larderello at 795 MWe, the average production number is not very significant.

Power density data was also imported from Wilmarth and Stimac (2015) to populate part of Table 6. The most promising average power density numbers per productive volcanic center are for the narrow, intra-arc extensional rifts of Kyushu, Japan and the Taupo Volcanic Zone. Power density numbers are also elevated for the Philippines, Sumatra and West Java, and N. Costa Rica/Nicaragua/El Salvador. Conversely, power density numbers are lower on average for the six producing volcanic centers in the transpressive-compressive Honshu region of Japan.

In Table 7, the major structural-tectonic categories and trends in geothermal productivity evident in Table 6 were synthesized to develop three simplified tectonic play types, subdivided by strain rate for a total of 5 categories. These categories include two strike-slip dominated transtensional plays, distinguished by high to medium, or low strain rates. Extensional plays fall within two categories, relatively narrow, high strain-rate rifts and broad, low strain rate extensional provinces. Compressional-Transpressional plays also fall within one category, distinguished by having active faults. The “extensional plays” capture 21% of the total MWe, the “transtensional plays” capture 73% of the MWe, the “compressional-transpressional plays” capture 4% of the MW, and unknown settings capture 2% of the MWe (Table 7; Fig. 2). Transtensional terranes are mostly dominated by strike-slip faults which are linked locally to normal faults, forming pull-aparts and displacement transfer zones. Extensional terranes are mostly dominated by normal faults which develop step-overs, fault terminations, and accommodation zones. Compressive and transpressive terranes are dominated by reverse faults and oblique reverse faults, respectively, and by conjugate strike-slip faults. Not every VC will have equal prospectivity in these tectonic plays and some will have very low prospectivity if they are not coincident with local active structures.

Table 6: Arc segment summary tectonic setting, general strain rate, number of productive VCs per segment, total MWe per segment, MWe/productive VC per segment, number of VCs with power density (Wilmarth and Stimac, 2015) data available per segment, average power density/productive VC per arc segment, type of number of structural settings represented by productive VCs per segment. Although currently non-productive, the Aleutians are also shown in this table using data from Shevenell et al. (2015). General abbreviations used: PD, Power Density (MWe/km^2); TMVB; Trans-Mexico Volcanic Belt; TVZ, Taupo Volcanic Zone. Strain rate categories: H, high (> 0.3 mm/yr); M, medium (0.3 to 0.1 mm/yr); L, low (<0.1 mm/yr). Structural settings: AZ, accommodation zone; DTZ, displacement transfer zone; FI, fault intersection; FT, fault termination; PA, pull-apart; RB, restraining bend; SO, step-over; U, Unknown.

Tectonic Setting	Strain Rate	Arc Segment	Productive VCs (#)	Total MWe	MWe/ Productive VC	# of VCs w/ PD	Ave PD/VC	Structural Settings of VCs
Extensional - Narrow Rifts	H	TVZ	5	1082	216	3	20	AZ (3), SO (1), FI (1)
	H, M	Kyushu, Japan	4	213	53	3	35	DTZ (2), FI (1), U (1)
Extensional - Broad Regional Area	M, L	S. Cascades	1	25	25	0	--	AZ (6), DTZ (1), SO (12), FI (8)
	L	TMVB	4	270	68	2	11	SO (3), FI (1)
Transtension	H, M	Philippines	7	2030	290	5	19	PA (2), DTZ (3), U (2)
	H, M	Sumatra	7	537	77	1	15	PA (3), DTZ (2), FI (1), O (1)
	M	West Java	7	1143	163	5	16	PA (1), DTZ (5), FI (1)
	M	Costa Rica, Nicaragua, S. El Salvador	6	561	94	5	16	PA (3), DTZ (2), FI (1)
	L	Italy	2	915	458	2	6	SO (1), FI (1)
	L	Guatemala, N. El Salvador	3	57	19	2	11	DTZ (1), FI (2)
	L	New Ireland	1	56	56	0	--	FI (1)
	L	Caribbean	2	26	13	0	--	PA (1), FI (1)
	L	N. Chile	4	85	21	0	--	FI (4)
	L	S. Chile	3	18	6	0	--	DTZ (1), FI (2)
	L	Taiwan	1	3	3	0	--	U (1)
	L	W. Aleutians	0	0	--	0	--	DTZ (1), FI (11), U 14), O (1)
Compression-Transpression	L	Honshu, Japan	7	294	42	6	12	FI (4), FT (3)
	L	N. Cascades	1	5	5	0	--	PA (6), FI (6), U (2)
	L	E. Aleutians	0	0	--	0	--	FI (14), FT (2), U (16)
Unknown	L	Kamchatka	4	102	26	1	14	U (4)
	L	Kuril	2	5	3	0	--	U (2)
	L	East Nusa Tenggara	2	8	4	0	--	FI (1), U (1)
	L	Sulawesi	1	63	63	1	9	U (1)
	L	Marianas	1	3	3	0	--	U (1)

Table 7: Relative prospectivity of tectonic play types and arcs according to average MWe/VC (Table 6). Examples in far right column include arcs segments with a minimum of 3 productive VCs.

Relative Prospectivity	Intra-Arc Tectonic Description	Ave. MWe/ Productive VC	Example Volcanic Arcs
1	Strike-slip dominated, high to moderate fault slip rates	70 to 290	Sumatra, Central America, Java, and Philippines
2	Narrow extensional rifts, high to moderate fault slip rates	50 to 215	Kyushu (SE Japan) and TVZ (New Zealand)
3	Broad regional extension, low fault slip rates	70	Trans-Mexico Volcanic Belt (TMVB)
4	Reverse fault dominated compression, low fault slip rates	40	Honshu (NE Japan)
5	Strike-slip dominated, low fault slip rates	5 to 20	Southern and Northern Chile

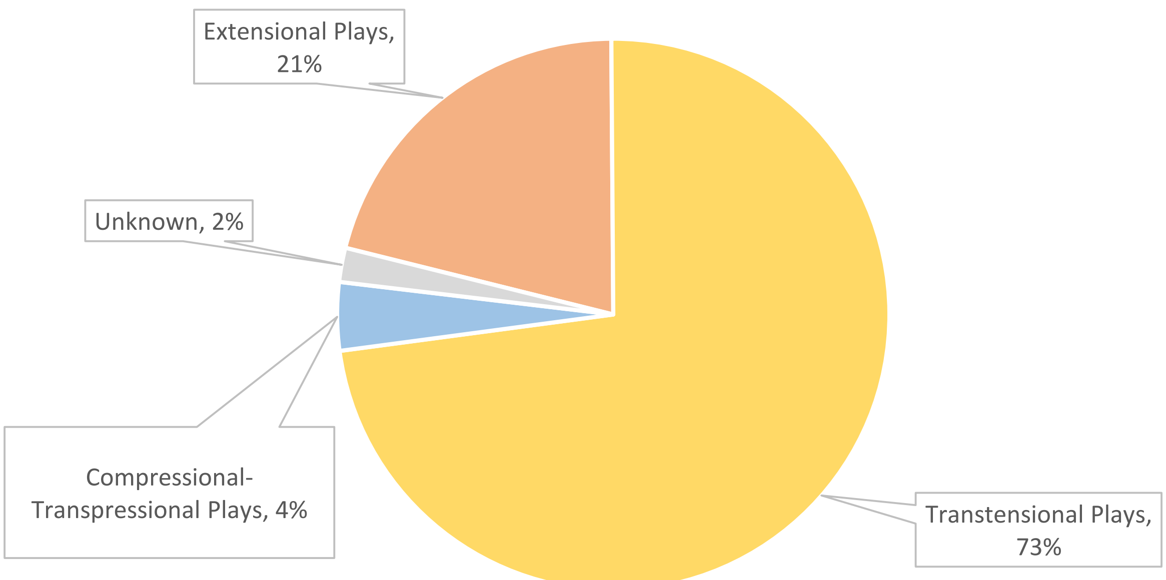

Figure 2: Total MWe per dominant tectonic setting of major contiguous arc segments (Table 7). Colored intra-arc groups in Table 7 correspond with the colored tectonic settings in this figure.

One additional tool that can be derived from this database of global benchmark VCs is the identification of analogues for use in refining specific exploration strategies and honing resource assessments. For example, based on the arc segment patterns (Tables 6 and 7), analogues were evaluated for the play fairway analysis of the Aleutian and Cascade arcs (Shevenell et al., 2015). Notably the Trans-Mexico volcanic belt presents a close analog to the southern Cascades, including numerous similarities between Lassen, California, USA and Los Azufres, Mexico. Both the southern Cascades and the Trans-Mexico volcanic belt are co-located with broad regional extensional terranes with localized transtension, have similar volcanic signatures, and have similarities in known resources. Tectonically, the western Aleutians behave similarly to Sumatra and Chile, however in contrast to those regions, the western Aleutians are an oceanic arc, and other productive oceanic arc segments like the Mariana or Kuril arcs may provide better analogs. The eastern Aleutians and the north Cascades also reside in compressional and transpressional tectonic settings. Honshu, Japan is the only broad arc segment with producing geothermal systems (7 total) that is undergoing compression and transpression. Nearly 90% of the MWe produced in arc settings worldwide come from VCs located in extensional and transtensional settings, and thus there must be some unique characteristics that coalesce in Honshu for those volcanoes to be so productive in a largely compressive environment and could be a valuable analog for the compressive-transpressive parts of the Cascade and Aleutian arcs.

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