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The Ring of Fire and the Mantle Convection Rolls Model: The Regularity of Subduction Zones Distribution and Relative Arrangement of Volcanic Arcs

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ABSTRACT

In this paper, the consistency between distribution of the subduction zones around the Pacific Ocean and the Comprehensive Mantle Convection Rolls Model is investigated. Mid-ocean ridges have been compared with the model, showing correlation of both location and alignment. Here, a corresponding comparison with subduction zones reveals the same mathematical relationship between divergent and convergent boundaries of tectonic plates all over the globe. The Reykjanes Ridge of the Atlantic Ocean and the Izu-Bonin-Mariana Arc of the Pacific Ocean adhere to the same mathematical equation 180 degrees apart from each other. A framework analysis of the whole Pacific Ocean is made, starting with equator, where the Pacific Ocean spans 150 degrees in between Indonesia and South America. The Pacific Ocean provides an excellent opportunity to test the plausibility of the Convection Rolls Model. The ninety degrees mathematical interval between the Reykjanes Ridge and Juan de Fuca, indicates the existence of a wholistic range of convection rolls, which could explain the mathematically regular arrangement of mid-ocean ridges. The same equation applies to the subduction zones. Every side of the Pacific, with Cascadia, Andes Mountains, New Zealand, Japan, and related areas, exhibits mathematical consistency with large scale lower mantle convection rolls model. More details are then revealed regarding the relationship between inner structure of subduction zones and the modelled smaller asthenospheric convection rolls. An intriguing relationship between mathematics of modelled convection rolls within the asthenosphere and the volcanic arcs along with the back-arcs is found. That relationship is further supported by petrological and tectonic studies. The model provides the opportunity to divide the chains of volcanoes into smaller sections of polygons, directly comparable to empirical findings in geoscientific literature. It is suggested that the relevant mathematical equations could be utilized to calculate the location and alignment of hitherto unidentified tectonic features. The distribution of geothermal and volcanic activity within the study areas is consistent with the locations, dimensions, and alignment of modelled convection rolls. Revealing that mathematically definable convection rolls were responsible for tectonic activity, would add to the general understanding of geoscience, for instance making it feasible to anticipate where geothermal resources are located by making use of the relevant mathematical preconditions introduced.

1. INTRODUCTION

Mid-ocean ridges and subduction zones are two ends of the same feature, often referred to as divergent and convergent plate boundaries. According to this study, the basic mathematical equation of the convection rolls model fits the location and alignment of both mid-ocean ridges and subduction zones. It is therefore suggested that these divisions between tectonic plates are subject to the effect of mantle currents in a mathematically comparable way.

The mathematical equation of the Mantle Convection Rolls Model is (Thorbjarnarson, 2021):

$$(x-C_n)^2 + (y-32)^2 = 35.34$$

Where x stands for latitude, y for longitude, and C_n for each central point of the circular path on the x-axis, found along the 32nd latitude, respectively with 1.5° intervals. The values are: C_n = {-178.7, -177.2, -175.7, …, -0.2, 1.3, 2.8, … ,179.8} for n from 1 to 240. 35.34 is the horizontal diameter (in units of degrees of latitude and longitude) of the mathematically circular rolls.

This single formula with the values of C_n, describes two different layers at once. In the northern hemisphere, the western part of the resulting circular path stands for the upper layer, and the eastern half for the lower layer. The same phenomena are observed when mapping ocean currents or weather systems. The preconditions for this formula have been described in detail. By comparing the model with geological features all over the world, the regular intervals found along equator, the chains of volcanic arcs around the Pacific, and long sections of mid-ocean ridges, all become explainable.

Most severe earthquakes and volcanic eruptions occur within the Ring of Fire. It is a wholistic geological feature surrounding the Pacific Ocean, surprisingly regular and diverse at the same time. In this paper, surprisingly, the starting point for examining it is Iceland, in the middle of the Atlantic Ocean. The first link between the Atlantic and Pacific Oceans is the 90° span between the Reykjanes Ridge and Juan de Fuca. Both ridges are associated with divisions between large scale convection rolls but offset 1.5° west of them due to the arrangement of small-scale convection rolls of the asthenosphere. They follow the equation by inserting C_n = -7.7 for Reykjanes Ridge and -97.7 for Juan de Fuca. The lower mantle divisions, considered to be the main factor determining the location of the said ridges, can be drawn on the map with C_n = -6.2 and C_n = -96.2 respectively. The difference stands for the 90° mathematically separating the lower mantle division lines. At the other end of the Pacific Ocean, the huge complex of the Izu-Bonin Arc extending from Japan follows the same formula. The western edge of the ridge can be traced southwards from Mount Fuji by inserting C_n = 173.8. The two sides of the Pacific Ocean, as represented by Juan de Fuca and Izu-Bonin Arc are thereby separated by 90°.

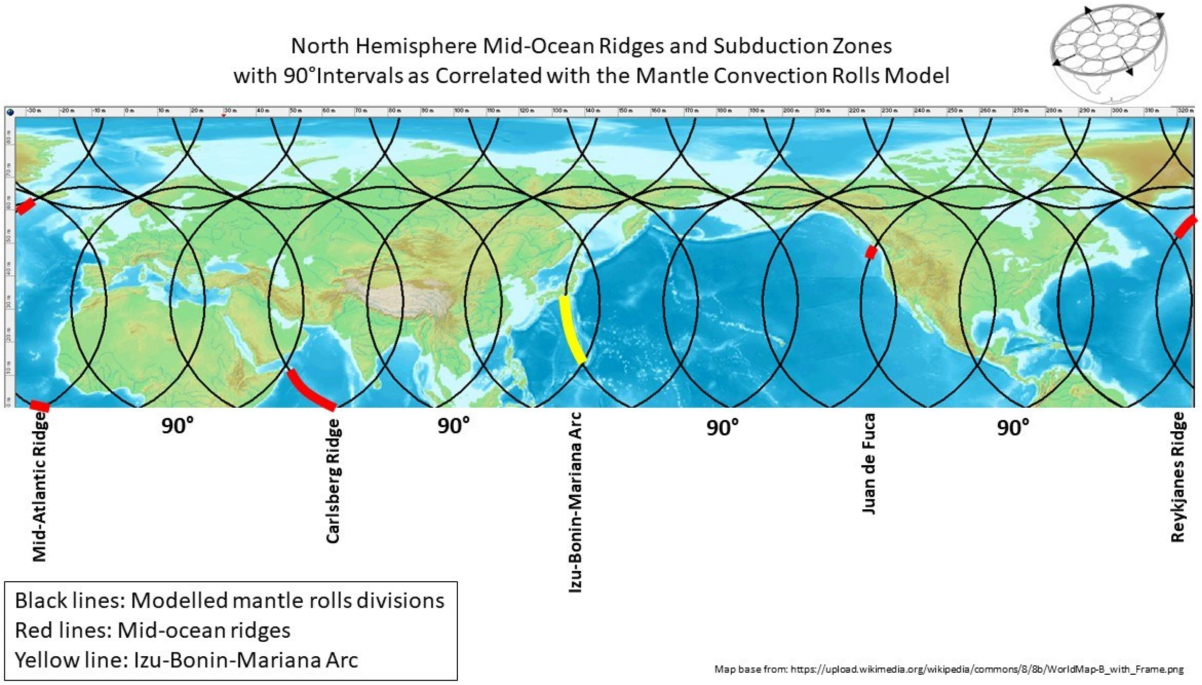


Figure 1: The features marked on the map are found associated with calculated division lines between lower mantle convection rolls. The modelled mantle divisions are 90° apart from each other. Map base from Wikimedia.

The Mantle Convection Rolls Model adds a perspective to this picture, as the effects of the convection rolls are decisive when it comes to distribution and qualities of the resulting geothermal and volcanic activity. First, Indonesia must be mentioned with subduction found on both western and eastern sides, exactly 30° apart, along the equator. These locations are both exactly in harmony with the model here being tested. The trenches of South America and at the west coast of Indonesia are 180° apart on the equatorial line. This has been pointed out before, as statistically this cannot be a coincidence. Here, another starting point for exploring the consistency of other subduction zones should be emphasized. Mount Fuji in Japan stands at the end of a long subduction zone extending far to the south, referred to as the Izu-Bonin-Marriana Arc, following the calculated curved line of the convection rolls model accurately. At the other end of the arc, the lowest point on Earth, the Challenger Deep, lies on a modelled lower mantle division line, in a context with both Indonesia and Japan.

The outer framework of the Pacific Ocean is marked by trenches of remarkable consistency, for instance the twin formations of the ridges extending from Japan and New Zealand, and two round connective trenches of Indonesia and South America, extending from the two equatorial end points of the Pacific Ocean.

If mantle convection rolls are prevalent within the mantle, affecting the formation and functions of subduction zones, how can that knowledge be applied? An answer is provided here, as comparison indicates that the volcanoes, and thereby geothermal areas as well, tend to be aligned above a single modelled convection roll of the asthenosphere. The area can then be further divided into segments, according to the model, and each segment can then be studied separately.

As already mentioned, this is a continuation of former studies, where the emphasis was laid on the effects of rifting along mid-ocean ridges and its implications. The volcanic zones of Iceland have for instance been related with the Mid-Atlantic Ridge, and the modelled convection rolls shaping it, with the same methodology. The whole western edge of the Philippine Sea Plate coincides with the said modelled division lines.

The model is derived from the knowledge we have about the thickness of Earth's layers, and the finding that convection rolls form at the physical threshold in which convection sets in and stay continuously in the vicinity of the threshold and the system maintains a well-defined steady pattern. Such convection rolls have a section, defined by the convectional and rotational planes, of equal height and width under the conditions considered to be prevalent within the mantle. The horizontal alignment of the rolls is then found according to the preconditions, analyzed by Paldor and Killworth (1988), of no retarding forces obstructing the propagation of the fluid element, swaying in accordance with the rotation and geoid shape of the Earth.

2. REGULAR DISTRIBUTION OF RIDGES AND SUBDUCTION ZONES EXPLAINED

Regular distribution of the main divisions of the north hemisphere can be directly compared with a simplified model of mantle convection rolls. The Reykjanes Ridge, Carlsberg Ridge, Juan de Fuca, and Izu-Bonin-Mariana Arc all follow the calculated division lines between large-scale convection rolls of lower mantle.

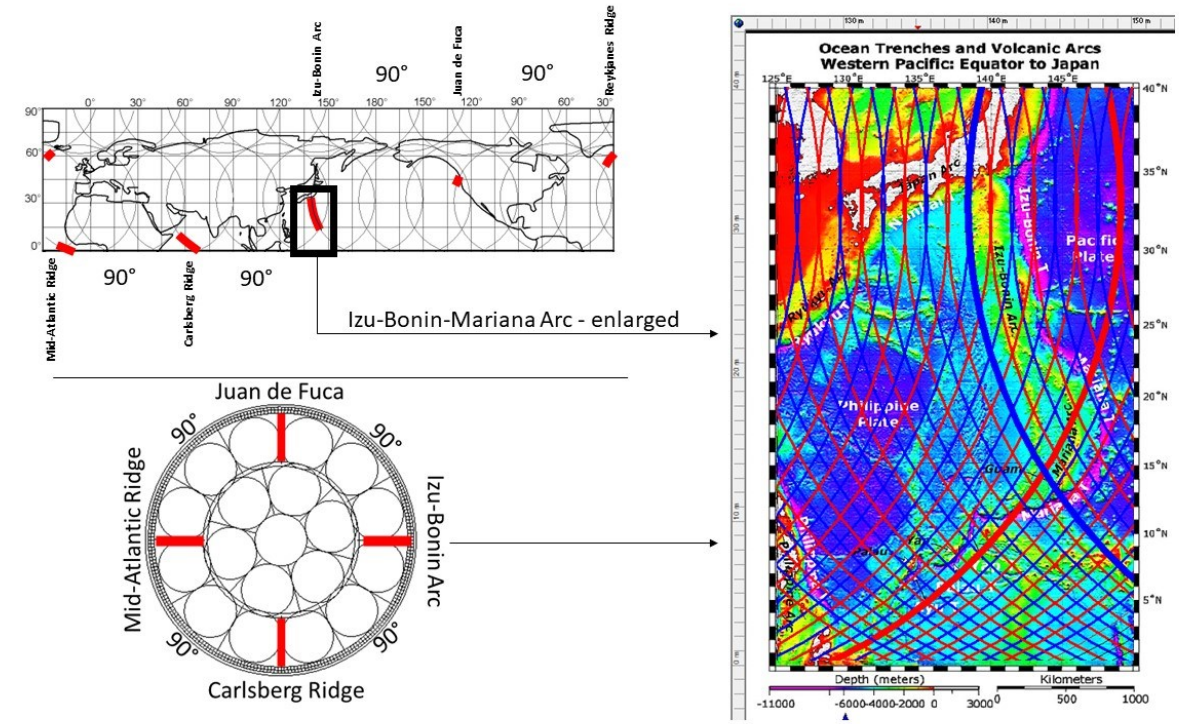
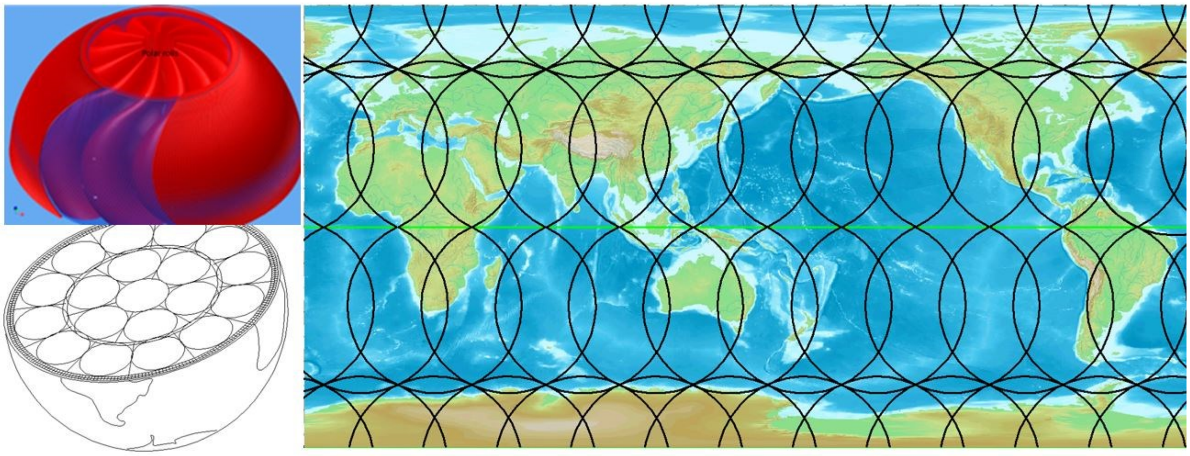


Figure 2: The Izu-Bonin Arc is consistent with the calculations presented here. The asthenosphere rolls are marked with 1.5° interval from east to west. The thick blue line marks the lower mantle large scale division, coinciding with the division between upper most convection rolls. The Izu-Bonin Arc is about 3° wide from east to west, corresponding to two upper mantle convection rolls. The red, curved, lines show up-welling and blue lines down-welling. Superimposed on NOAA map.

This gives rise to a further investigation, first because this consistency between four main tectonic plate divisions, found 90° apart from each other can hardly be random, and second because this is in harmony with the convection rolls model which is based on physics and experimental results. In addition, it must be emphasized that all those mapped bathymetrical features are aligned with the mathematically drawn division lines over distances on the order of thousands of kilometers. This is consistent with the findings of Hess (1963), who reasoned that mid-ocean ridges were associated with convection rolls within the mantle. The same is apparently true for subduction zones.

The consistency is probably most apparent close to 32°N, a special case where the division lines are expected to be aligned directly N-S, and all convection rolls arranged directly on top of each other. This makes direct comparison between model and mapped features easier. It will therefore be taken as the first example when examining different conditions found around the Pacific Ocean.

The regular distribution of these main divisions between tectonic plates is used here to compare the mantle convection rolls model and the geology of adjacent areas. An explanation for this regularity is provided here. The convection rolls of the mantle are supposed to have equal height and width (Walzer, 1971), as compared to the convectional and rotational planes. At equator, the two planes are unified in one single plane. The basic equator version of the system is very simple, and it fits perfectly with the main divisions found mapped on the surface. The lower mantle gives space to rolls spanning 30° each, and all main divisions on the equatorial surface are found with 30° intervals. The sequence is: East Pacific Rise, West Coast of S-America, East Coast of S-America, Mid-Atlantic Ridge, West Coast of Africa, Great Rift Valley, Central Indian Ridge, West Coast of Indonesia, East Coast of Indonesia. Tectonic drift is a continuous process, and eight equal intervals of 30° each along equator cannot appear without a rational cause. We look for an answer within the mantle, as convection rolls could provide the preconditions for maintaining this regular sequence while rearranging the tectonic plates simultaneously. Experiments have shown that mantle material forms convection rolls when subjected to stable conditions (Manneville, 2010). Some basic features of the Mantle Convection Rolls Model will therefore be reviewed here, emphasizing those of importance when examining subduction zones.



Equatorial section and 3D drawing representing the mathematical model of mantle convection rolls.

Large-scale pattern emerging from division lines between mantle convection rolls.

Figure 3: The mathematics of the Convection Rolls Model are based on measurements of Earth's layers on one hand and the physics of Rayleigh-Bénard convection rolls on the other hand. Each layer represents a set of convection rolls with equal height and width. When drawn to scale, the rolls fit accurately with the layers. Referring to the physical properties of mantle rolls, a 3D model can then be fully developed and tested. Map base from Wikimedia.

In the figure above a section the Earth is shown drawn to scale. The proportion between length and thickness of Earth's layers does fit for a fixed number of convection rolls with equal height and width within these limits. Within geoscientific literature, mainly petrological reasons are mentioned for these discontinuities (McBirney, 1993). The mathematical model provided here provides additional clarification regarding these global discontinuities.

It is very easy to insert the convection rolls model and compare it with vertical layers within the Earth and mapped features on the surface. Comparison fits vertically as horizontally. A vertical analysis shows that the 410 km and 670 km discontinuities are mathematically coherent with the height-to-width ratio of convection rolls. The large-scale convection rolls of lower mantle fit accurately with the said proportions, as inserted in between the 410 km discontinuity and the core-mantle-boundary at the depth of about 2,900 km. All this leads to a very clear mathematical model, based on well-defined experimental results. The model, in turn, shows perfect consistency with division points on the surface.

When examining the details of both mid-ocean ridges and subduction zones, more attention is paid to the upper convection rolls of the asthenosphere in between the 120 km and 410 km discontinuities. But when monitoring the slab of descending crust from the subduction zones, another aspect of the model must be considered, namely secondary convection.

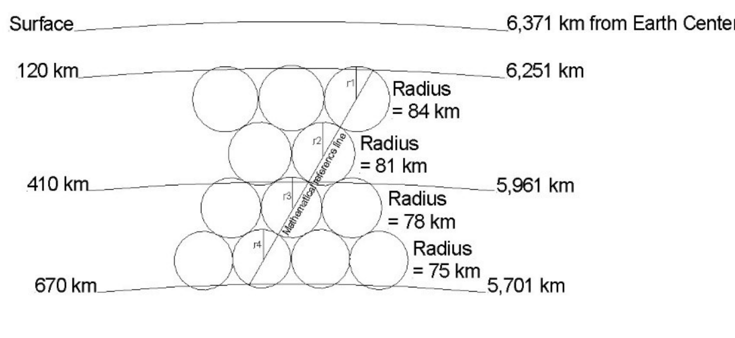


Figure 4. A mathematically consequent sequence of convection rolls fits into the measured layers in between the main discontinuities of 120 km, 410 km, and 670 km, respectively, around the Earth. The layers are drawn to scale (Allen, 1983). The termination of earthquakes due to subduction below the 670 km discontinuity correlates with the main principle of the convection rolls model, namely that the height and width are always the same, as compared with the convectional and rotational planes of the Earth. Each roll spans 1.5° from east to west. The division lines between these convection rolls can then be traced horizontally.

The radius of each roll section is then calculated as $2\pi R_c / 240$, where R_c is the distance from Earth's radius to the center of the convection roll section. The number of rolls around the Earth is 240, as they span 1.5° as measured directly from east to west. It is well known that the 670 km discontinuity does play an important role regarding subduction zones, as Wadati-Benioff Zones do not exceed that limit (Benioff, 1949). The section drawn here, including convection rolls of four layers, gives rise to a vertical examination of subduction zones. The division lines between the rolls can be traced all over the globe, and therefore the exact position of each roll can be anticipated. The interaction between a descending plate with this set of rolls can then be studied. The layers affect the surface, due to coupling effect and Munroe effect (Torrey, 1945). Therefore, mapped polygons, where divisions at the side of one convection roll marks two sides of the polygon, whereas the division lines around the next roll below mark the other two sides. Each polygon has its own characteristics to be studied separately.

To find the main directions of convection cell rolls at any place on the Earth, another formula can be derived, based on derivation of the circle. In a regular quadratic grid with center at (x,y) = (0,0), the slope (a) of the tangent to a circle at a given coordinate is:

$$a = -(x/y)$$

And the angle (γ) given in degrees from x-axis (from west) is:

$$\gamma = \arctan(a)$$

For the spherical form, the intervals between values on the x-axis are shortened by $\cos(\varphi)$, where φ is the latitude. Therefore 'y' is multiplied with $\cos(\varphi)$ for correction, and a rectangular grid of squares for degrees is obtained. When the rectangular grid of squares, where degrees of latitude and longitude are drawn of equal length, is substituted with the spherical grid of longitudes and latitudes, the formula showing the correct direction anywhere on the surface of the globe becomes:

$$\arctan\,[-(x/y)\ (1/\cos\varphi)]$$

Where φ is the latitude (works both for northern and southern latitudes). This gives the correct angle between the convection roll and west. A formula for direction (α) for hemispheric convection rolls can then be found. As directions on a map are traditionally referred to as compared with north rather than west, the outcome of the preceding formula is subtracted from 90°. The convection cell system is always symmetrical around a north-south axis, so two different directions are found with a single calculation, both east and west of north. For the lines extending from equator, the alignment Nα°W and Nα°E is found by applying this equation:

$$\alpha = 90° - \arctan\,\{[(35.34^2 - (\varphi - 32)^2)^{0.5} / (\varphi - 32)]\ (1/\cos\varphi)\}$$

This equation can be used anywhere in the world for first reference. It is quite explicit in Iceland, where divergent forces are dominant, and fissures and dykes often become aligned accurately according to this equation. It should be remembered that the formula refers to conditions within the mantle, and we want to see how that affects the circumstances on, or near, the surface. Both the ductile and the brittle parts of a tectonic plate can react to these effects in predictable ways, but further calculations are most often necessary. Knowing the outlines of the surrounding local polygon, secondary alignments can also be calculated. This model provides preconditions for advanced mathematical methods, for instance applying the Mohr's circle for ductile material (Pluum and Marshak, 1997). It should be emphasized at this point, that it is important to compare general knowledge about geophysical conditions within each polygon, acquired by means of direct measurements, with this model.

When dealing with subduction zones, the implications of both primary and secondary convection become apparent. It should be kept in mind that what is being mainly examined here is the possibility that convection rolls do form within the mantle below the depth of 120 km. The reason for examining this possibility is the fact under laboratory conditions, where mantle material has been kept under stable conditions, namely at the melting point, it does form convection rolls (Manneville, 2010). It is logical that immediately underneath the 120 km limit, where convection replaces stagnant, ductile mantle, it has reached the melting point (Francis, 1993). Below that limit, the temperature gradient is adiabatic, maintaining the said stable conditions. If these laboratory experiments and the behavior under real conditions within the Earth match together, convection rolls should exist inside the Earth.

3. THE MIRRORED ASPECT OF IZU-BONIN-MARIANA ARC AND THE KERMADEC-TONGA SUBDUCTION ZONE

Comparing the ridges extending to the south from Japan and to the north from New Zealand immediately reveals many similarities. As mentioned before, the Izu-Bonin-Mariana Arc is aligned along the calculated division line between convection rolls. Not only does the alignment fit to the said arc, but also fits as the fourth part into the 90° global pattern of Juan de Fuca, Carlsberg Ridge, and the Reykjanes Ridge. That relationship has been studied in detail before (Thorbjarnarson, 2023). A cross-section of Izu-Bonin subduction zone at 32°N can be compared to the model quite easily because the convection rolls should be aligned directly N-S at that latitude and be arranged directly on top of each other.

The Izu-Bonin Arc is therefore a starting point of this study, with location and shape appearing quite convincing (Fig. 2). Studying the details of the arc is just as revealing, especially the chain of volcanic islands along the middle of the ridge, following C_n = 175.3 of the model as shown here:

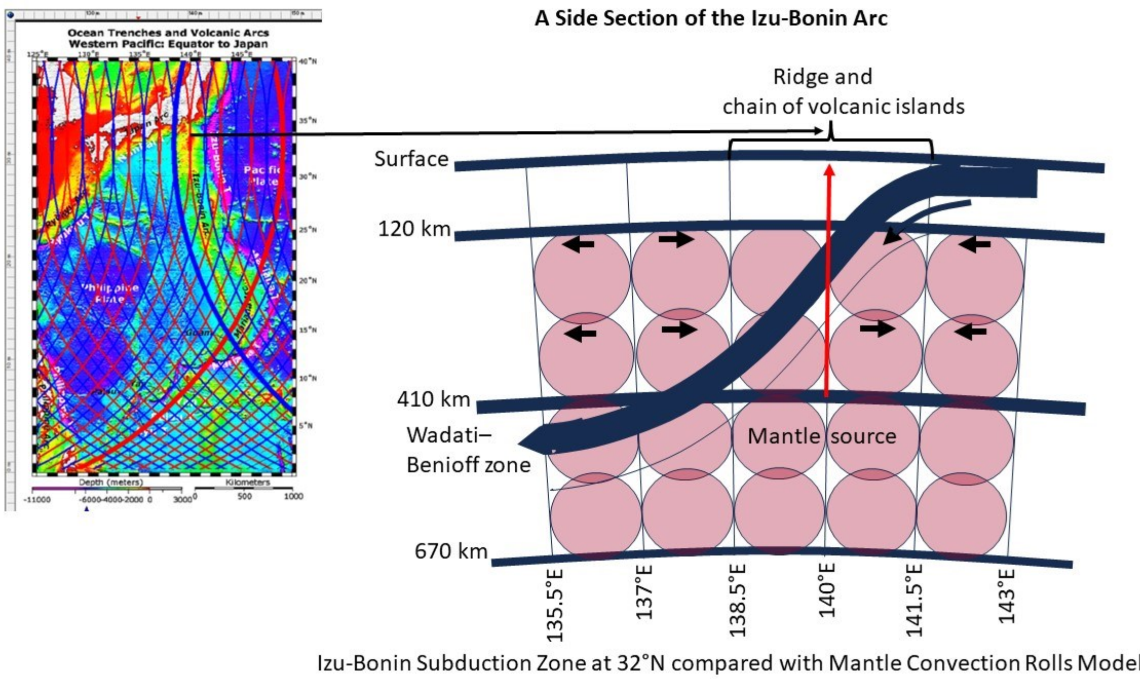


Figure 5: In this schematic cross section, the modelled convection rolls are compared with the Izu-Bonin subduction zone and the relevant Wadati-Benioff zone as measured close to the south coast of Japan. Reading from the model, the mantle source responsible for volcanic activity along the ridge should be found at the 410 km discontinuity. A possibility for formation of a mantle wedge providing magma above the subducting plate is not found. Data from Stern (2002).

In this study, the arrangement of subduction zones versus mid-ocean ridges is emphasized on, so the vertical relationship between convection rolls and subducted slab is not dealt with in detail. It is important, though, that the main preconditions for the plausibility of the modelled convection rolls really exist. In this case, the source of ocean island basalt is found below the subducting plate. The physics leading to the process, according to the preconditions provided with the symmetrical energy flow of convection rolls, called Munroe effect, have been explained by Torrey (1945). The formation of island arcs, ridges and extension zones can all be studied by comparing the effects of the different layers of convection rolls. The most prominent manifestation for this arrangement is the width of the ridge, spanning 3° from the east to west, with a row of volcanic islands in the middle, the alignment following the equation of this model, and its relative position, forming 90° angle globally with mid-ocean ridges of the North Hemisphere; Juan de Fuca and Carlsberg Ridge, and 180° compared with the Reykjanes Ridge (Thorbjarnarson, 2023). This is further manifested by petrological evidence, as subduction zones have access to a less depleted mantle source of the well-known OIB-type of lower layers (Fig. 5), because the upper most convection rolls are deactivated or replaced by descending slab, but mid-ocean ridges provide the more depleted MORB-type from the upper layers.

The 3D model of mantle currents can therefore be used to explore both mid-ocean ridges and subduction zones, not only on a two-dimensional map, but also in the third dimension downwards into the Earth. Comparing model and maps of subduction zones, as for the examples provided here, the main interaction between convection rolls and down-going slab seems to be that trenches are repeatedly associated with a convection roll which appears to take part in the bending process of the relevant tectonic plate. The diminishing process of the Pacific Ocean tectonic plate should therefore take place in 'jumps', when transition from one convection roll to another takes place. Geological features such as the ridge and back-arc of the Izu-Bonin-Mariana trench are confined within the width limit of convection rolls. These so-called jumps are well known in Iceland, as the development of new volcanic zones in response to tectonic drift is not a continuous process but is manifested by 1.5° intervals between the zones (Thorbjarnarson, 2021), appearing one by one every 7 million years or so (Einarsson, 2008).

Then attention should also be paid to the South Hemisphere because a similar feature as the Izu-Bonin-Mariana Arc is found extending from New Zealand, namely the Kermadec-Tonga Subduction Zone. The Kermadec-Tonga Subduction Zone is aligned in the same way as its northern counterpart, as the deviation from north is equal, and the length is the same. The connections between ridge and land, both for Japan and New Zealand, are strikingly similar. Both subduction zones are found on the same modelled division line between large scale convection rolls of the lower mantle, as it extends to north and south from the same point of the equator.

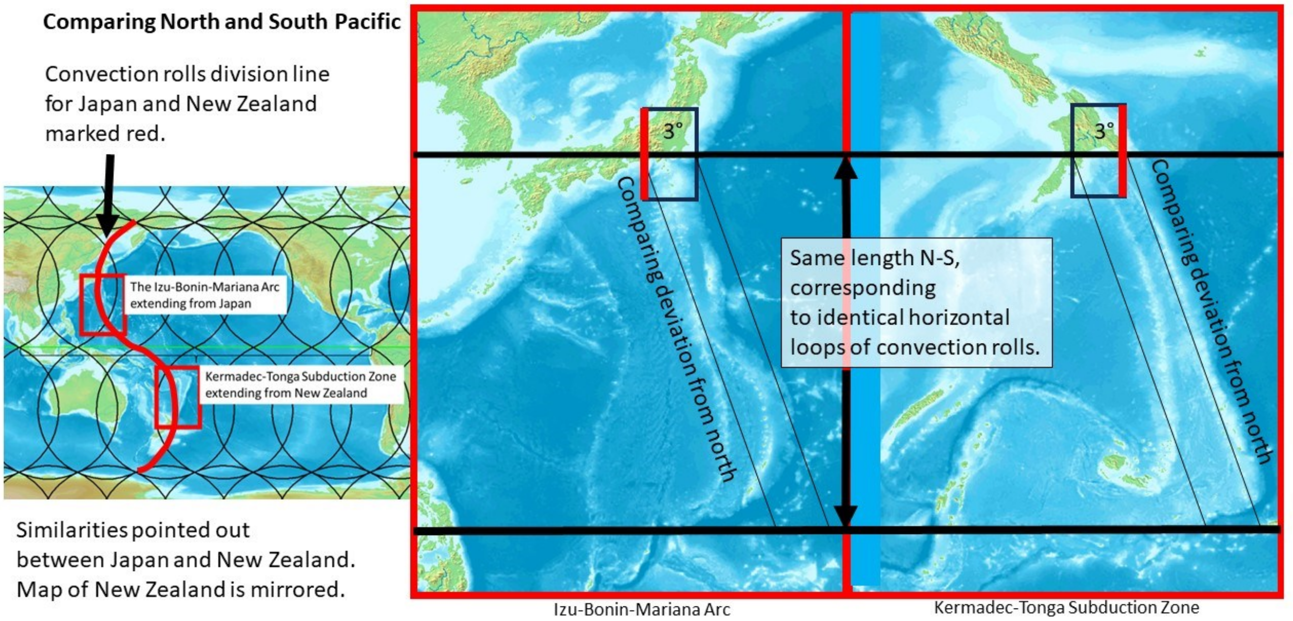


Figure 6: The ridges, where extending from Japan and New Zealand, are both 3° wide from east to west, corresponding to two upper mantle convection rolls. New Zealand has been mirrored around a line 1.5° south of equator to make direct comparison possible between the northern and southern hemispheres. Superimposed on map from Wikimedia.

Both of those zones have westwards oriented subduction, resulting in formation of very similar ridges, and at latitudes closer to equator both have back-arc basins, or rift zones due to the pulling effect of the subducting plate, that have some of the characteristics of mid-ocean ridges (Stern, 2002). This similarity is emphasized by adding straight, parallel lines to show the mirrored aspects more clearly, and presenting the two subduction zones side by side. The large-scale division is found at the western edge of the Izu-Bonin-Mariana Arc and the eastern side of the Kermadec-Tonga Subduction Zone (marked with red lines).

Notes regarding the Izu-Bonin Arc: It is aligned along the lower mantle division line. The arc is mathematically separated by 90° from Juan de Fuca at the other side of the Pacific and 90° from the Carlsberg Ridge of the Indian Ocean, besides 180° from the Mid-Atlantic Ridge. The width of the arc is 3°, corresponding to a pair of convection rolls of the upper mantle. It appears that the polygons drawn on the surface according to the division lines of different layers of convection rolls play a vital role in shaping the topography and geological characteristics of the area. A good example is the Izu-Bonin Ridge itself, following the shape of one pair of convection rolls with a chain of volcanic islands in the middle. The Mariana section includes a rifting zone, where convection rolls oppose the pulling effect of the receding subduction zone. The scope of the rifting zones is limited to the 1.5° width of a convection roll. An interval is found between an old rifting zone and a new one (Stern, 2002), which can be explained by referring to the model, claiming that the rifting had to 'jump' over one convection roll which did not oppose the subsiding effect due to opposite rotation.

The same is true for the Kermadec-Tonga Subduction Zone extending from New Zealand. The width of the ridge close to New Zealand covers 3° from east to west, and the length is the same as that of the Izu-Bonin-Mariana Arc.

4. THE VOLCANIC ARCS OF SOUTH AMERICA AND KAMCHATKA

The close fit between model and the Izu-Bonin-Mariana Arc is probably what triggered the writing of this paper, but there are many other examples (Fig. 12) of how the model shows consistency with actual circumstances, position, alignment, and length.

Trenches and volcanic zones also tend to coincide with convection rolls, the trench following the scope of a roll, then one roll is found in between the trench and the volcanic roll, and finally the bulk of volcanic activity is found in context with one roll. These three rolls are parallel to each other. The volcanic activity also tends to terminate at the border of a polygon.

Here, two examples of this type of subduction are provided, from different corners of the Pacific Ocean:

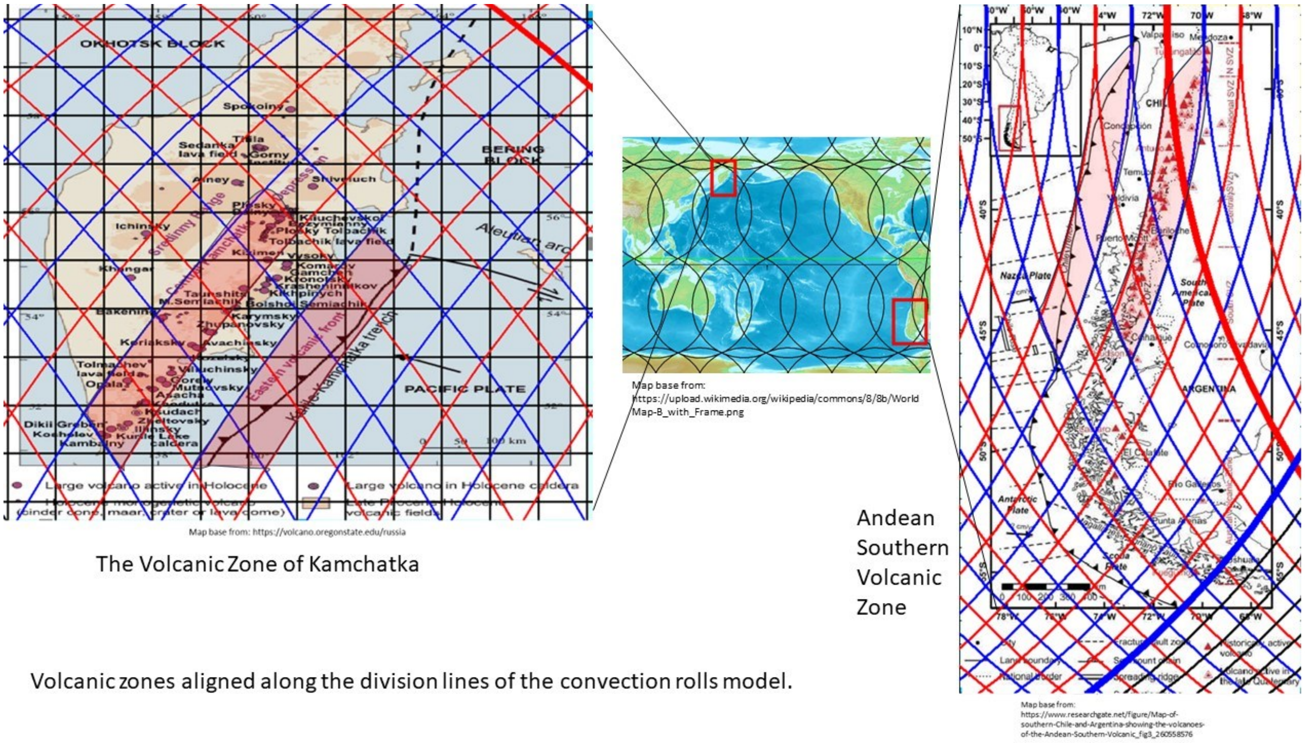


Figure 7: Kamchatka and Andean South Volcanic Zone compared. Both show the same kind of consistency, whereas trenches and volcanic zones are separated by one convection roll. The volcanoes, shown with red dots, line up along a convection roll, within an area close to a division line. Map base from Oregon State University (Kamchatka) and Natural Earth (South America).

The similarities between Kamchatka and South America are quite striking. On the two maps, the parts of the most relevant rolls are colored red. One aspect that should be noticed, which might be neglected, is how the volcanic zones terminate at the border of the polygons. The volcanoes are mainly distributed within the relevant row of polygons, and line up with the sides of them.

As these two subduction zones are found to the east and west of the Pacific, the perfect consistency of alignment of the two volcanic zones should be elaborated on. We find the same mathematical preconditions for volcanic zone alignment in Iceland (Fig. 11). The Pacific Ocean is diminishing, whereas the Atlantic Ocean is growing, and subduction zones around the Pacific provide the conditions necessary to devour the oceanic parts of tectonic plates at the same time as the floor of the Atlantic Ocean has expanded and occupied a larger share of the globe. Here, the most distant corners of the Pacific are chosen as examples of repeated consistency with the Mantle Convection Rolls Model. When it comes to the application side of these studies, individual polygons should be studied. When the outer forces shaping the tectonic characteristics of each polygon are understood, then the preconditions for geothermal and other resources can be analyzed or identified more accurately.

It is well known that east and west oriented subduction zones have, on average, a different dip angle. This has been explained by referring to the different age of the seafloor, and thereby greater specific gravity (Stern, 2002). The Mantle Convection Rolls Model, on the other hand, is based on the effect of different rotational velocity. As for descending material, there is a considerable difference between kinetic energy at the surface and at 670 km depth. If Earth's radius is set as 1, the radius of the 670 km discontinuity is close to 0.9. At the equator, the proportion of kinetic energy dissipated to the surrounding material can be roughly calculated:

$$½mv_s^2 – ½mv_b^2 = ½ (1)(1)^2 – ½ (1) (0.9)^2 ≈ 0.2$$

Where v_s is the velocity at the Earth's surface and v_b is velocity at 670 km depth, here both converted into velocity along a straight line instead of rotational velocity for simplification. The mass (m) is given as one unit, to find the proportional difference of kinetic energy at these levels. The loss of kinetic energy of the slab is in this case close to 20%. Considering the speed up to 1,674 km/hour at the equator, the kinetic energy of each cubic kilometer of slab is a very high figure, even for those subduction zones at higher latitudes.

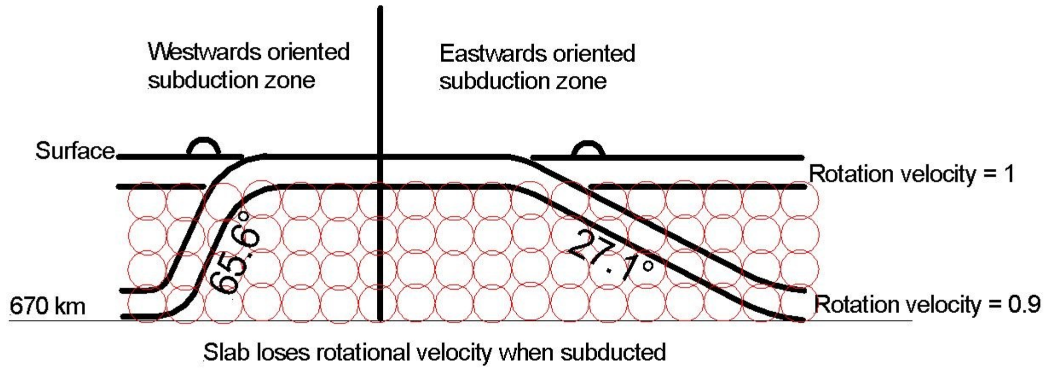


Figure 8: The difference between average westwards and eastwards dip of subduction zones corresponds to different kinetic energy levels within the interval between surface and the 670 km discontinuity. Deviation of slab dip takes place at the same time as kinetic energy is gradually dissipated to the surrounding mantle material. Data from Doglioni and Panza (2015).

The aggregate effect of this kinetic energy being released into the subduction system is manifested at the eastern side of the Pacific Ocean, as pressure is induced between the two converging plates, whereas at the western side of the Pacific Ocean this leads to a pulling effect between the plates. According to the model, the slab enters an environment of balanced geophysical conditions, i.e. ductile, convecting mantle. The average dip of westwards and eastwards oriented slab is 46° (Doglioni and Panza, 2015), and the effect of rotational velocity contributes to explain the ~20° average deviation of inclination for east and west oriented subduction zones, respectively.

The horizontal aspect of the Mantle Convection Rolls Model is based on the same principle. The shape of convection rolls can be calculated because horizontally moving particles are always subject to the same mathematical deviation from a direct line within the rotating geoid, as rotational velocity alters regularly with latitude. The factors determining the inclination of down-sliding slab are more diverse, but by and large predictable.

5. THE VOLCANOES OF COSTA RICA AND PETROLOGICAL DIFFERENCE WITHIN THE REALMS OF DIFFERENT POLYGONS

In the last chapter, it was emphasized that volcanic activity can be correlated with both individual convection rolls, and the sections of that roll marked by the next roll below, thereby dividing the area into polygons. Central America provides a good example for studying individual polygons in context with a subduction zone, being geologically exceptionally active. The area is interesting for studying the model, because the land mass and geological features largely coincide with a set of polygons. The Fisher Ridge and Cocos Ridge are aligned along with modelled division lines, and so do the directional vectors of subduction. An inherent part of the Convection Rolls Model is the study of polygons resulting from the combined effect of different layers.

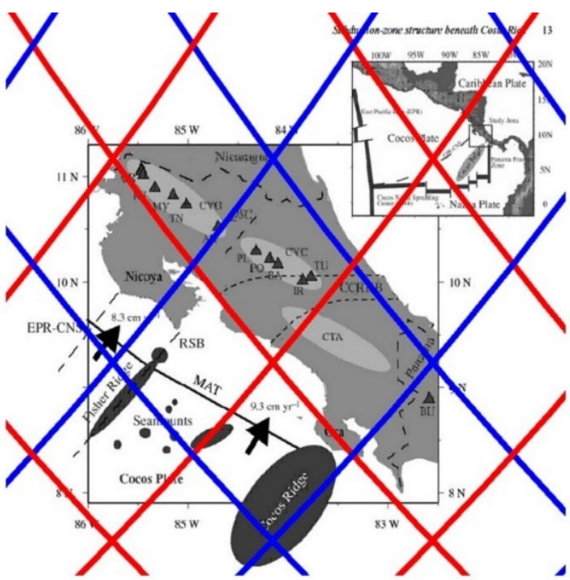


Figure 9: The grid of Convection Rolls Model compared with volcanic zones of Costa Rica. The polygons provide different conditions leading to a profound petrological difference between the grouped volcanoes. Map base from Husen (2003).

According to Husen (2003), the volcanic zone of Cordillera Volc´anicade Guanacaste (CVG) has geochemical signatures that are transitional between the depleted mantle source and a high subduction signal of the Nicaragua volcanoes and the enriched mantle source and low subduction signal of the central Costa Rica volcanoes. Cordillera Colcanica Central (CVC) has the geochemical signature of ocean island basalt (OIB) with little influence by the subducting Cocos Plate. The slab is much steeper underneath the CVG than CVC. Is it possible to explain all this by referring to the model? Conditions are in a way similar, because the same convection rolls parallel to the trench affect both zones. But within the next layer, opposite vectors of convection flow create different circumstances. One exaggerates the dip for CVG, whereas the other does diminish it for CVC. The flattened slab below CVC can then provide the conditions for rather uncontaminated OIB source to find its way to the surface, from a source below the subducted plate, as pointed out earlier. The contrast between the two volcanic systems of CVG and CVC is in harmony with the dual aspect of two adjacent polygons of the Convection Rolls Model, and all the topographical and geological settings are directly comparable with it. Within the third polygon, active volcanism stopped 8 Ma in southeastern Costa Rica, but as elsewhere around the world, the location can be compared to the pattern of polygons. The meeting of OIB source flowing in from below and water with the slab sliding in from above, leads to formation of lava with exceptionally high water content (Stern, 2002). Many other processes lead to different petrological qualities, such as mentioned here, and must be dealt with separately.

5. THE CASCADE SUBDUCTION ZONE AND GENERAL OVERVIEW

The Cascade Subduction Zone is very well studied, and the regular NS distribution of volcanoes is immediately noticed. The zone differs from the other zones given here as examples, because the arrangement is not strictly associated with the alignment of one division line between two adjacent convection rolls. The trench itself follows the relevant convection roll, though, in the same way as for the other examples. But when it comes to comparing the model with the Cascadian Volcanic Zone, a match with polygons is found, coherent with the NS trend of the subduction zone in general, as shown here:

C

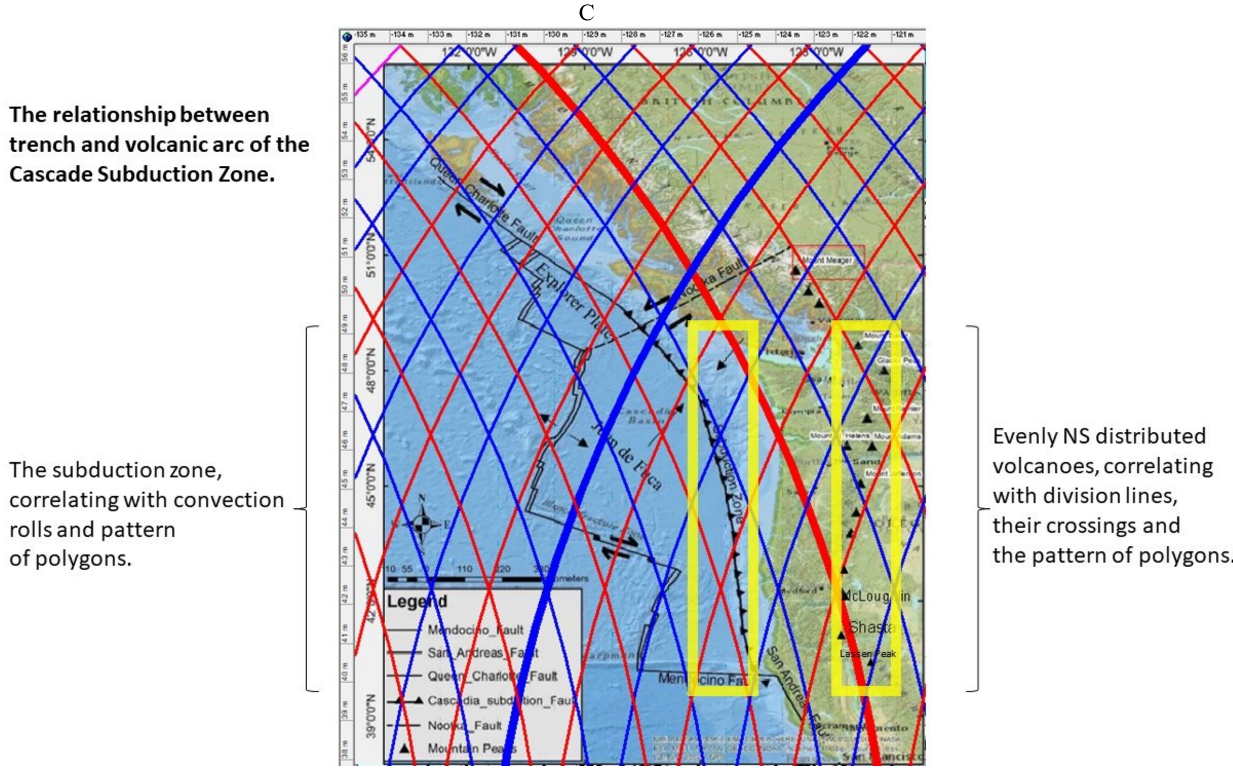
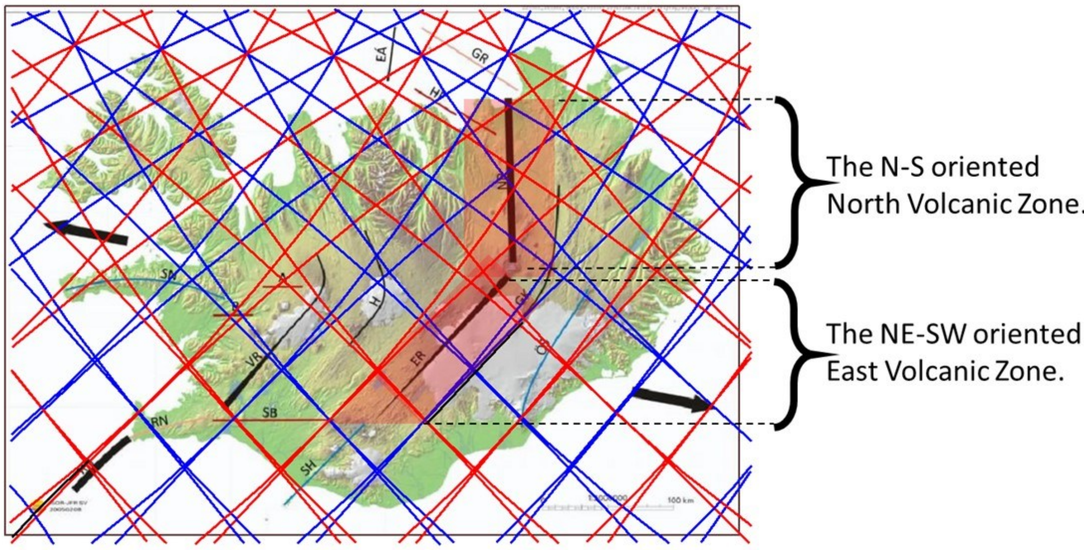


Figure 10: A common question about the Cascadian volcanoes is: "Why are they so evenly distributed?" The subduction is reflected by volcanic arc directly east of it. The volcanoes are distributed within the range of polygons, oriented NS, and the distance is rather equal because three volcanoes tend to line up along one polygonal side. Map base from Leonard et al. (2010).

The Cascades trace their origin to the continuous subduction zone, but it is divided into two polygons. Within the volcanic arc, the northern half is characterized with down-welling, whereas the southern half has up-welling pairs of convection. This will affect the descending plate in different ways. St. Helens has been the most active volcano of the 48 adjacent states of North America for the last 4,500 years (Harris, 1988). According to this model, St. Helens is located at the crossings of division lines.

This NS alignment of the subduction zone can be compared with similar phenomena in Iceland, the so-called North Volcanic Zone. This example is provided here to emphasize the effect of arrangement of polygons. Iceland provides a very clear example of the two main outcomes of alignment of volcanic zones, as the map below shows. The polygons break from one corner to another, which explains why the whole system becomes aligned accurately N-S. The convection rolls of different layers below are always symmetrical, as they strictly follow the equation for mantle rolls alignment, and the opposite sides of the polygons drawn on the surface are therefore identical.



Two adjacent volcanic zones of Iceland, one with NE-SW orientation (East Volcanic Zone) and the other N-S oriented, (North Volcanic Zone).

Figure 11: The volcanic zones of Iceland and within the Ring of Fire follow the same mathematical equation. A set of polygons does correspond to the East Volcanic Zone, mathematically in the same way as shown in this paper for Kamchatka and South America. The North Volcanic Zone in Iceland is oriented directly N-S, comparable to the alignment of the Cascade Mountains Volcanic Zone. Map base from Iceland Geosurvey.

In this overview, with examples taken from the eastern and western sides of the Pacific Ocean, comparisons with the Mantle Convection Rolls Model are constantly made. The model is mathematical, and according to this study, it does correlate with both divergent and convergent plate boundaries. The examples taken here are pointed out with arrows on the overview map below:

Figure 12: The Ring of Fire and the main locations mentioned in this paper. Map base: Encyclopædia Britannica, Inc.

The Ring of Fire surrounds the largest tectonic plate in the world, with the larger half constantly drifting from the SE to the NW end of the elliptical shape of it, away from the mid-ocean ridges to the subduction zones. Simultaneously, it creates the San Andreas Fault as an inherent part of the 'ring', as the tectonic drift vectors coincide with its shape there. When it comes to studying local details according to this model, such as specific geothermal areas, knowledge about the factors affecting each polygon, as defined here, is of crucial importance. The tectonic framework of each area is marked by the forces acting on the relevant polygons, providing the possibility of calculating plausible alignment of faults and fractures, besides understanding the geological processes involved better.

6. CONCLUSIONS

Comparing the Mantle Convection Rolls Model with the geological circumstances of the Ring of Fire provides some interesting results. The Izu-Bonin-Mariana Arc accurately follows the mathematical equation for convection rolls, besides that it fits into a pattern of 90° intervals between ridges of the Atlantic, Indian and Pacific Ocean. The arc is found to be located above large-scale convection rolls of lower mantle and can then be studied in detail by referring to smaller convection rolls of upper mantle and the asthenosphere. The Izu-Bonin Ridge is consistent with the model, spanning 3° from east to west, centered with a chain of volcanic islands, whereas each convection roll is 1.5° wide. Examining other subduction zones around the Pacific, similar consistency is repeatedly found, where one roll takes part in the bending process, and the width of one roll divides the trench and the relevant volcanic zone. According to the model, ocean island basalt ascends from the mantle below the subducting plate.

Examining the mapped details of different sections of subduction zones around the Pacific Ocean is equally rewarding. The volcanic zones of Kamchatka and Andean Southern Volcanic Zone are aligned along convection rolls division lines in accordance with the same mathematical equation. In Costa Rica, separate volcanic zones are found within the modelled polygons, resulting from the convection rolls system, having distinct petrological characteristics. The Cascades have a NS trend, which can be related to the formation of NS-oriented polygons. The same mathematical equation is used for examining mapped areas in Iceland as everywhere around the Pacific Ocean. Mid-ocean ridges and subduction zones can therefore be compared directly, being two ends of the same system. In turn, this provides unique opportunities for examining small, geothermal areas, within this larger context.

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