Linear volcanic segments in the central Sunda Arc, Indonesia, identified using Hough Transform analysis: Implications for arc lithosphere control upon volcano distribution

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Abstract

Hough Transform analysis is used as an objective means to constrain volcano distribution in the central Sunda Arc, Indonesia. Most volcanoes in the arc define four en echelon, linear segments, each of 500 to 700 km length. Javan volcanoes that do not lie on these segments either (i) formed at an early stage in the history of the arc and erupted products that are petrologically and geochemically distinct from typical arc magma, or (ii) lie along other mapped structures.

The en echelon distribution of volcanoes in the central Sunda Arc is best explained as originating from two possible sources. First, interaction with the subducting Indo-Australian Plate may induce stress in the arc lithosphere generating pathways for magma to exploit. Second, downward flexure of the arc lithosphere, as a result of mantle flow or loading by the arc, would also establish arc-normal tension towards the base of the lithosphere, where magma is supplied to volcanic systems.

To the west and east of the central Sunda Arc deviations from the distribution of long, en echelon, linear segments can be understood as responses to specific stress fields in the arc lithosphere of Sumatra and eastern Nusa Tenggara, respectively. Control of volcano distribution by arc lithosphere explains why there are large variations in the depth from volcanoes to the zone of slab seismicity in the central Sunda Arc, where there is little variation in slab geometry or the rate of plate convergence.
Keywords

Sunda Arc, volcano, segmentation, stress, lithosphere, Hough Transform analysis
1. Introduction

The overall curvature of many subduction zones is immediately apparent and the term “island arc” betrays the common assumption that subduction zone magmatism occurs in curved zones. This assumption can be expressed by approximating island arcs as segments of small circles on the surface of a sphere (England et al., 2004). Such treatments have been employed to relate the location of arc volcanoes to their vertical separation from the slab (in fact, the depth to seismicity in the slab) and require the primary control on the locus of magmatism to lie either within the subducted slab or the mantle wedge (Syracuse and Abers, 2006; Grove et al., 2009; England and Katz, 2010).

The concept of curved arcs ignores longstanding observations that magmatism in many subduction systems occurs as segments of linearly arranged volcanic centres (Carr et al., 1973; Stoiber and Carr, 1973; Marsh, 1979; Ranneft, 1979; Hughes et al., 1980). Further evidence for this distribution comes from the close relationship between magmatism and large scale, arc-parallel fabrics in some arcs (Buckart and Self, 1985; Bellier and Sébrier, 1994; Tosdal and Richards 2001; Bolge et al., 2009). Similarly, exposures of deep arc crust or mantle often reveal elongation of magmatic intrusions sub-parallel to the inferred trend of the arc (Tikoff and Teyssier, 1992; Rivera and Pardo, 2004; Bouilhol et al., 2010).

The Sunda Arc runs through Indonesia from Sumatra to Flores (Fig. 1) and provides an important test for models of volcano distribution for several reasons. First, Sunda has hosted abundant historic volcanic activity. Second, the vast majority of volcanoes in the arc are subaerial from base to cone and,
therefore, can be readily identified through a combination of local mapping and satellite imagery. Third, there are significant changes in the stress regime along the length of the arc. To the west, highly oblique convergence causes significant strain partitioning associated with the Great Sumatran Fault (Barber et al., 2005) and to the east, the arc has collided with Australian continental lithosphere (Harris et al., 2009; Fig. 1). These changes in geodynamics allow the influence of the upper plate to be further evaluated by comparison of different arc segments. Finally, much of the Sunda Arc has proved difficult to accommodate in models that try to relate volcano distribution to the depth to the subducted slab. It has, however, previously been proposed as a site where a linear model may be more appropriate for understanding volcano distribution (Ranneft, 1979).

We apply an objective line-fitting, image analysis protocol; the Hough Transform, to explore the distribution of volcanoes in the central Sunda Arc from Java to central Flores. We focus on this section because of the complicating influences of the Great Sumatran Fault and the arc-continent collision to the west and east, respectively. Volcano distribution in the central Sunda Arc is best described as linear segments, or great circles on a sphere, rather than following small circles. We discuss the orientation of these segments and deviations from linear distribution both within our study area and beyond its eastern and western extremities. We conclude that the stress field in the Sunda Arc lithosphere is the primary control on the distribution of its volcanoes.
2. The Sunda Arc

The Sunda Arc stretches from the NW end of Sumatra to Java, then through Nusa Tenggara as far as Flores in the east and is part of the plate margin where the Indo-Australian Plate is subducted beneath Eurasia (Fig. 1). Indian Ocean lithosphere is subducted beneath most of the arc but Australia has collided with, and perhaps impeded subduction in, parts of the arc east of Flores (Audley-Charles, 2004; Harris et al., 2009). Motion of the Indo-Australia Plate varies from 63 mm/yr N14° with slight dextral obliquity south of the Sunda Strait, to perpendicular convergence of 67 mm/yr N14° south of Java to slightly obliquity, but in the opposite sense, at 70 mm/yr N13° south of Bali (Fig. 2; Simons et al., 2007). The margin’s curvature, particularly around the Sunda Strait, leads to strong strain partitioning of dextral shear at Sumatra and neutral, or possibly even sinistral, shear through Java and Nusa Tenggara (McCaffrey, 1996). The dip of the slab remains relatively constant from the Sunda Strait (49°) to the Australian collision (46°; Syracuse and Abers, 2006), although tomographic evidence suggests that a slab hole may exist beneath east Java (Widiyantoro et al., 2011). The current Sunda Arc is largely a Quaternary feature in Java and Nusa Tenggara. These island groups are the focus of this work and their development is described in more detail below.

2.1. Java

Recently, the basement to much of Java has been recognised as continental fragments derived from the Australian margin of Gondwana that were accreted to the Sundaland margin in two stages during the Cretaceous (Smyth et al., 2007; Granath et al., 2011; Hall, 2011 and 2012). The first of
these was accreted at the Billiton lineament around 115 to 110 Ma and now forms SW Borneo and western Java (block 2 in Fig. 1). A suture, composed of the same ophiolitic material seen in the Meratus Mountains of SE Borneo, separates the West Java Block from the East Java – West Sulawesi Block that may, itself, be comprised of several smaller fragments (block 3 in Fig. 1). This was accreted at about 90 Ma, probably around the same time as the Woyla Arc collided with Sumatra (Hall 2012).

Subduction then terminated around most of Sundaland until the Eocene. Thus, the basement of Java changes from the SW Borneo - West Java block in the west, through the Meratus Suture in central Java to the East Java – West Sulawesi Block in the east. These terranes were then covered by Cenozoic rocks of shallow water carbonate or clastic character over the Sunda shelf and volcanioclastic and deeper marine deposits further south. The volcanioclastic components originated in a Palaeogene Arc to the south of Java constructed upon continental basement (Clements et al., 2009). Volcanism then once again ceased and this Palaeogene arc was thrust northwards during the Late Miocene or Pliocene, where parts of it are preserved as the Southern Mountains (Fig. 2). The thrusting also uplifted Neogene sediments to the north of this arc as they were folded against the Sunda shelf, producing most of the land now exposed in central and eastern Java (Clements et al., 2009; Lunt et al., 2009).

Modern Sunda Arc volcanoes developed during the Quaternary and are constructed upon basement created by the processes described above. In West Java the arc is notable for its “broadening”, for example Tankuban Prahu lies approximately 80 km further from the Java Trench than volcanoes
to its southwest (Fig. 2). This results in significant changes in the depth to the
slab along the length of the island (Syracuse and Abers, 2006). Quaternary
volcanism in Java has mainly generated basaltic andesite to andesite effusive
and explosive products (Whitford, 1975). Extinct, Quaternary volcanoes that
produced highly potassic, including leucititic, lavas lie to the north of the large
mafic-intermediate stratovolcanoes (Foden and Varne, 1980; Leterrier et al.,

2.2. Nusa Tenggara

Basement of Nusa Tenggara is less well known than Java because of less
exposure and greater challenges to access. Furthermore, considerable
portions of these islands are blanketed by Quaternary volcanic deposits. The
island of Sumba is a forearc section, uplifted where Australian continental
lithosphere has entered the trench (Harris et al., 2009, Fig. 1). Rigg and Hall
(2011) interpret Sumba as part of the East Java – West Sulawesi Block that
was accreted to Sundaland in the Cretaceous (Fig. 1). Other parts of Nusa
Tenggara could be constructed on similar basement. Further east Nusa
Tenggara may include different blocks of Gondwana-derived lithosphere,
accreted at a later date and/or newly formed arc crust representing
subduction products formed as the Java Trench propagated eastward in
response to a phase of rapid slab rollback initiated at around 15 Ma
(Spakman and Hall, 2010).

3. Methods

Previous studies have noted volcanoes distributed in linear segments in
several arcs (Marsh, 1979; Ranneft, 1979; Hughes et al., 1980; Bolge et al.,
Rather than “eyeballing” alignments we sought an objective method to identify such arrangement of volcanic structures. We considered multiscale trend analysis, in which a dataset is split into numerous smaller linear segments (Zaliapin et al., 2004), and random sample consensus, in which linear trends can be discovered in noisy datasets (Fischler and Bolles, 1981). However, these methods were ultimately rejected as they are not able to identify overlapping linear features, such as en echelon systems.

Volcanic arcs are already recognised as elongate arrangements of volcanic centres. Therefore, the aim of this study is to determine whether these centres are better modelled as small circles or great circles on a spherical surface i.e. are individual segments arcuate or linear. The Hough Transform method provides the most appropriate tool for this purpose.

3.1. The Hough Transform

The Hough Transform is applied to images to recognise geometric features that can be expressed mathematically, in this case lines. Modern applications are widespread, largely in physics and computer vision technology; however the technique has received relatively little application as a spatial analysis tool to detect geological structures (Wang and Howarth, 1990; Sæther et al., 1994; Karnieli et al., 1996; Cooper, 2006a and b; Yamaji et al., 2006; Jenkins et al., 2008). Some attempts have been made to identify volcanic alignment, mainly in monogenetic volcanic fields (Wadge and Cross, 1988; Connor, 1990; Connor et al., 1992). It is beyond the scope of this paper to present a detailed description of the mathematical concepts behind the Hough Transform, for which the reader is directed to Dunda and Hart (1971), Hart (2009) and
Any straight line in an image can be defined uniquely by two parameters related to the normal that passes through the origin of a Cartesian grid system (Fig. 3). The length of the normal is $\rho$ while $\theta$ is the angle it makes with the x-axis. For each point in the image, values of $\rho$ and $\theta$ are determined for straight lines with azimuths from $0^\circ$ to $359^\circ$ (Fig. 3a-b). A plot of $\rho$ versus $\theta$ produces a sinusoidal curve (Fig. 3c) for each point. This is repeated for all points. The sine curves for points which are aligned will include the same coupled $\rho$ - $\theta$ values because the normal will occur in the analysis of each point (e.g. normal 1 in Fig. 3a and normal 4 in Fig. 3b). Thus, intersection of sine curves in the $\rho$ - $\theta$ plot identifies alignment (Fig. 3c). For images containing multiple possible alignments, a threshold value is defined, as a percentage of the highest frequency $\rho$ - $\theta$ couple, to identify which further high frequency couples are either picked as potential alignments or disregarded. The $\rho$ – $\theta$ values of the recurring normals are then used to draw alignments back on the original image.

A map of Sunda Arc volcanic centres was produced as a greyscale image file in UTM projection (see below) to ensure equal x and y scales. Initially, each volcanic centre was represented by a circle of uniform size (Fig. 4a). A script was then constructed, exploiting in-built Hough Transform functions in MATLAB®, to perform the analysis on the image. The script is essentially composed of three components; the first produces a $\rho$ – $\theta$ parameter space plot, the second highlights and picks the highest frequency peaks from this plot, and the third projects the corresponding lines back onto the greyscale
image. It was necessary to specify two values manually. First, the minimum line length acceptable was set such that lines which only connected three or less data points were not accepted as significant alignments. Second, the maximum gap value was set such that lines could connect between volcanoes separated by ~100 km, which equates to 2-3 times the average separation of volcanoes in the arc.

A second map of centres was explored in which volcanoes had non-uniform size. Each volcano was scaled to a circle three quarters of the diameter at its base, as determined from geological maps and satellite images (Fig. 4b). This approach effectively weights the analysis toward larger volcanic systems. It also allows projection of linear trends between structures, even if their exact geometric centres are not aligned. This accommodates the fact that a volcanic structure may not lie directly above the main feeding conduit at depth. A three-quarter diameter scaling was chosen because circles scaled to the full size of centres would have resulted in overlap of many structures that clearly originate from different volcanic systems.

3.2. Volcano location database

The digital elevation model used to identify volcanic features is 3 arc second (~90 m) resolution NASA SRTM, version 4 of Jarvis et al. (2008) projected into UTM (Fig. 2). Great circles describe straight lines on gnomonic map projections. However, the area studied lies close to, and trends sub-parallel to, the equator therefore a UTM projection provides a suitable approximation in this case, such that any straight lines identified represent great circles.
A distribution dataset was created by plotting the locations of all volcanic centres identified on SRTM and was verified by reference to published geological maps (see Supplementary Material A). Many, but not all, of these centres are documented in the Smithsonian Global Volcanism Program (Siebert and Simkin, 2002). Such cross-referencing ensured that the centres identified are real volcanic features of the current arc. Many small topographic features, typically of 1-3 km diameter, remain ambiguous while others are clearly secondary parasitic structures. Thus, given the regional perspective of this study, volcanic structures with a basal diameter of <3 km are excluded.

All volcanic centres are recorded as a single discrete point/coordinate representing the underlying magmatic system. The geographic centres of volcanic cones/vents or summit craters, where these were discernible, were picked. If several small craters/conduits were observed on top of a single larger structure, an average position was chosen. The locations of all geologically validated volcanic centres from the Sunda Strait to central Flores are shown in Fig. 2 and listed in Supplementary Material B.

Some alignment of centres is immediately apparent but it is also clear that several lie north of the main arc front (yellow triangles in Fig. 2). In Java, these centres are older than the main arc (Letterier et al., 1990) and have erupted highly potassic lavas (Fig. 5). Gunung Muriah, its subsidiary cone Genuk, in central Java along with the Ringgit-Beser complex and Gunung Lurus in east Java all lie close to the northern coast of Java and erupted potassic and ultrapotassic leucititic suites that resemble intra-plate magmatism from Australia (Edwards et al., 1991; Edwards et al., 1994). None have been historically active and some are clearly extinct. Gunung Lasem has
a more arc-like calc-alkaline andesitic composition but is one of the oldest volcanic features in the arc and Leterrier et al. (1990) suggest that the location of this extinct centre, relative to the present margin, may not represent its position relative to the plate margin when it was active. Due to the distinction in age and/or origin of these centres we exclude them from the spatial analysis of the active arc.

Further to the east, Tambora, on the island of Sumbawa, and Sangeang Api, a small island NE of Sumbawa (Fig. 2), are also composed largely of potassic, nepheline normative trachybasalt-andesite (Foden and Varne, 1980; Foden, 1986). Therefore, these centres are also excluded from the distribution analysis. Sangenges volcano, in western Sumbawa, has erupted a silica undersaturated leucitic alkaline series but also produced typical, low-K, calc-alkaline andesites and dacites (Foden and Varne, 1980). For this reason Sangenges is included in the analysis.

4. Results

Several potential alignments of points were identified from the Hough Transform analysis of the uniform and weighted datasets (Fig. 4a and b). The length and number of points incorporated in each of these varies and several points are included in more than one segment. We focus on only the six segments that were common to both the uniform and weighted approaches. For each of these a coefficient of determination \((R^2)\) was calculated for the points lying closest to them, i.e. within the ellipses drawn on Fig. 4c.

The westernmost segment \((R^2 = 0.947)\) incorporates the same, unique set of points in both approaches and so we consider that these define a valid
geological feature. There are two possible segments through the easternmost
data but, since there is negligible difference between them, we regard these
as a single segment ($R^2 = 0.774$). In the central area there are three potential
segments. The shortest of these has the lowest $R^2$ value (0.917) and all of its
points can be accommodated in one of the other two possible segments in
this region. A potential segment covers the whole central area but, while $R^2$
for this is high (0.958), it only propagated across the gap between points A
and B because it has grazed the point at C (Fig. 4c). Terminating this
segment manually at point A gives a better constrained, east central segment
($R^2 = 0.974$), which complements the potential west central segment with $R^2$
of 0.964 (Fig. 4d).

Thus, an initial attempt at objective definition of alignment identifies four
segments (Fig. 4d). Firmer constraints on the validity of these as true arc
segments can be obtained by accounting for; 1) the different size of each
volcanic centre, and 2) the influence of local basement structures upon the
location of some volcanoes.

To address the sizes of volcanic systems a weighted regression was
performed in which the weighting factor applied to each data point was the
base diameter measured from the SRTM data (as recorded in Supplementary
Material B). This assumes the surface expression of a volcanic centre is
proportional to the significance of its underlying system. All of the centres are
of Quaternary age and lie at similar latitudes, experiencing similar climatic
conditions. Precipitation is high and so there is an opportunity for mass loss
through erosion and mass wasting. While a constant rate of erosion would
lead to a greater proportional loss from smaller edifices, we anticipate that
such differences will be negligible for centres above the cut-off diameter for the database (3 km). The greatest effect of this is to increase the $R^2$ value of the east segment, where a number of smaller volcanic centres are more scattered around the largest ones.

Local controls on distributions are suggested where volcanoes deviate systematically from the segments identified in Fig. 4d. This is particularly apparent at the overlap of the west and west central segments and in the middle of the west central segment, north of Merapi and Sumbing (centres shown as orange in Fig. 6). Geological mapping reveals that volcanoes in these areas coincide with several mesoscale structural features (10-100 km long) that cut through deformed Cenozoic basement and Quaternary deposits (Fig. 6). In the Bandung region, there are distinct structural ‘grains’ visible in the SRTM imagery sub-parallel to both the identified volcanic alignments (WNW - ESE) and the mapped basement mesoscale structures (NE – SW; Fig. 6b). Thus, several volcanoes appear to exploit extensional or strike-slip faults where the west and west central segments overlap. A study of basement structures in west Java by Carranza et al. (2008) also revealed numerous lineaments with similar trends to this grain. In central Java, Sundoro volcano and the Dieng Volcanic Complex trend northwest of Sumbing parallel to local lineaments (Fig. 2). Likewise, Merbabu, Telomoyo and Ungaran trend north-northwest of Merapi (Fig. 6a). The other outlying vent coinciding with mesoscale structure is the more unusual Pandan (Fig. 6c), which consists of a brecciated andesite plug of uncertain origin, emplaced across an apparent lateral offset in a Tertiary fold belt (Pringgoprawiro and Sukido, 1992).
We propose that the primary distribution of volcanism in the central Sunda Arc is four, en echelon linear segments, but that second order crustal mesoscale structures are also exploited to produce the overall observed distribution. This being the case, it is possible to remove such locally controlled vents (marked orange in Fig. 6a). Then, conducting the weighted regression analysis to account for vent size defines the four main volcanic segments with $R^2$ values ranging from 0.85 to 0.99 (Fig. 7).

**5. Discussion**

The central Sunda Arc does not fit well into recent global syntheses of arc geodynamics for two reasons. First, the volcano distribution is not well approximated by small circles, the fit to which England et al. (2004) quantified using the root mean square (RMS) of deviation. The RMS for Java (12) was one of the largest among the arcs examined (mean = 6.9 for 24 arcs). The “Bali/Lombok arc” (defined by Syracuse and Abers, 2006) deviates even further than Java from the systematics predicted by the generic model for “small circle” arcs (England and Katz, 2010). Second, Java displays the largest along strike variation in depth to slab of any arc (Syracuse and Abers, 2006).

RMS values for deviations from the best fit linear segment, or great circles (Fig. 7), in Java are 6.7 for the west segment, 6.1 for the west central segment and 7.5 for the east central segment. The linear segments could, instead, be fitted with similar RMS by small circles only slightly smaller than great circles. In this case, the improved fit might be attributed simply to the recognition of more segments. However, this would not eliminate the variation in depth to seismicity. Despite relatively constant dip and subduction velocity
from Java to central Flores (Section 2) there are significant variations in the depth to seismicity both between and within the segments (Fig. 8). Thus, our observations question both of the premises used to invoke the control of volcano distribution originating at depth within subduction zones.

Instead, both the linearity of segments and the variation in depth-to-slab within, and between, segments are more consistent with volcano distribution being controlled by the arc lithosphere. Upper plate control is also suggested by the overlap between the west and west central, and between the west central and east central segments (Fig. 7). Such overlap of linear features is a common attribute of tectonic failure in brittle plates. In the following section we discuss mechanisms by which the arc lithosphere could control the central Sunda Arc volcano distribution.

5.1. Upper plate control on distribution of volcanoes in the central Sunda Arc

The earliest observations of linear arc segmentation invoked linear zones of melting at or close to the slab–wedge interface (Carr et al., 1973; Stoiber and Carr, 1973; Marsh, 1979). Further observations in Central America, however, closely linked the distribution of volcanoes to lithospheric structures. This emphasised the role of arc lithosphere in controlling magma transport (Buckart and Self, 1985; Phipps Morgan et al., 2008; Bolge et al., 2009).

Unlike Central America, the central Sunda Arc segments are not clearly linked to large crustal blocks but the observed en echelon geometry is a characteristic feature of structural systems. Analogous examples, such as mineralised tension gashes and dyke swarms, show that en echelon structures are often important fluid transport pathways. Therefore, a plausible
interpretation of the central Sunda Arc is that magma is focused into volcanic systems by lithospheric scale linear structures. It may be argued that faults/fractures are rarely perfectly straight, but tectonic structural features are almost the sole cause of linear geological features on various scales. Indeed many examples of large linear faults exist and a stress-related interpretation is the most straightforward.

There are several kinematic scenarios that might generate the orientations and en echelon geometry of the central Sunda volcanic segments. Although each is considered separately in the following sections, given the complexity of the tectonics in the area it is unlikely any one scenario provides the sole causative mechanism.

5.1.1. Extension

En echelon geometries can be produced by laterally offset normal faults in which further extensional relays are developed within the zones of fault overlap (e.g. Peacock and Sanderson, 1991). There is little surface evidence for such faulting, however arc-normal extension has formed localised basins, such as the Bandung Basin and the Madura Sea (Dam et al., 1996; Kusumastuti et al., 2002). Slab rollback could cause long-term, arc-normal tension in the arc lithosphere (Macpherson and Hall, 2002) that may only intermittently become of sufficient magnitude to produce basin-scale subsidence. Alternatively, McCaffrey (1996) inferred sinistral motion of the Javan forearc from earthquake slip vectors, which could be reconciled with an extensional arc if the forearc was rotating anticlockwise with respect to Eurasia. The Roo Rise is currently being subducted beneath east Java,
potentially obstructing subduction there and providing an opportunity for more
effective slab rollback, and thus arc tension, further to the west (Fig. 2).

5.1.2. Strike-slip or oblique tectonics

Oblique convergence has been proposed for the central Sunda Arc
(McCaffrey, 1996; Simon et al., 2007) and has the potential to produce large
scale, en echelon features, which might focus magma into volcanic systems.
This part of the arc lacks obvious morphological features or the seismicity that
might be expected in such systems. However, the absence of well-developed
eamples of these features may reflect a weakly-developed or incipient
ystem, therefore we briefly outline transtensional and oblique tectonic
enarios consistent with the observed segmentation.

En echelon secondary structures are well-known within strike-slip shear zones
(Woodcock and Schubert, 1994). Assuming such a zone had boundaries sub-
parallel to the primary tectonic features, i.e. plate margin, the segments could
represent synthetic Riedel (R) shears in a dextral simple shear zone (cf. Fig.
9a and b) or a dextral transtensional system (Fig. 9c). Either scenario would
require an upper plate stress field with the principle compression direction
orientated oblique to the convergence vector between the Indo-Australian and
Eurasian Plates (cf. Fig. 2), which could result from slab rollback and/or
forearc rotation. However, geodetic data (Fig. 9a) and far field stress
indicators (Tingay et al., 2010) may be more consistent with contraction or
transpression across the arc (Fig. 9d). If this were the case then the en
echelon segments could represent arc-parallel shear zones created by
deformation partitioning along the axis of a sinistral deformation zone,
analogous to the situation in Sumatra (McCaffrey, 1996).
5.1.3. Arc lithosphere flexure

In a number of subduction zones the arc lithosphere is deflected downwards because of upper mantle flow above the subducting slab (Husson, 2006). Downward flexure would induce arc-normal stress in the arc lithosphere; compressive in the shallow lithosphere and tensional towards its base (c.f. Hieronymus and Becovici, 1999). This stress field would exist along the length of the margin and so could develop and sustain coherent segments. A tensional pattern of fracture segments in the lower lithosphere could act as a means to channel magma into volcanic systems that would reproduce the segmentation at the surface. Once established, such a stress field might be reinforced by the effects of volcanic loading on the arc lithosphere (Hieronymus and Becovici, 1999).

In summary, there are several mechanisms associated with tectonics and flexure of the arc lithosphere that could contribute to the en echelon alignment of central Sunda volcanic segments. It is beyond the scope of this work to determine the relative importance of these mechanisms but a combination of more than one is entirely feasible.

5.2. Stress in the Sunda Arc lithosphere

Špičák et al. (2005) attempted to resolve earthquakes originating in the Sunda Arc lithospheric mantle. Many of the events they located in Nusa Tenggara lie in E - W oriented zones to the north of the volcanic arc and may be associated with southward thrusting of lithosphere at the Flores Thrust (Widiyantoro et al., 2011). The remaining earthquakes occurred either in WNW – ESE oriented zones in western Java, sub-parallel to our west
segment, or in NE-SW oriented zones at various points along the arc (their Fig. 4). These two orientations are similar to the primary and secondary alignments we recognised west Java (Fig. 6b). Although the seismicity does not occur directly beneath the arc, we speculate that it reflects a similar overall stress regime throughout the central Sunda Arc.

To the west of our study area, the Great Sumatran Fault developed during the Cenozoic due to oblique, north-directed subduction of the Indo-Australian Plate (McCaffrey, 1996). In Sumatra, large calderas tend to occur close to, and are developed as a result of, lateral steps in the trace of the fault (Bellier and Sébrier, 1994). Stratovolcanoes erupting intermediate lavas and pyroclastic rocks are common close to well-developed segments of the fault. Sieh and Natawidjaja (2000) questioned this relationship because only 20% of the volcanoes lie within 2 km of the trace of the fault. However, this distance is considerably smaller than the diameter (or even the radius) of most volcanic centres and, therefore, must be considered too short to account for possible offsets of volcanic vents from main magma feeder zones. Furthermore, their treatment did not consider the possible complicating effect of secondary structures. Many Sumatran volcanoes lie to the southeast of the main fault along strong basement fabrics suggesting a secondary control, similar to our proposal for Java. Thus, we concur with Bellier and Sébrier (1994) and Gasparon (2005) that there is a strong relationship between the location of volcanoes and faulting in Sumatra.

To the east of our study area the margin becomes more complex where Australian continental lithosphere has collided with the arc (Fig. 1; Harris et al., 2009; Rigg and Hall, 2011). The islands there are constructed mainly of
Neogene to Quaternary volcanic products limiting opportunities to determine basement structures by direct observation. However, there is some evidence of a lithospheric control. First, early Quaternary, now extinct, volcanoes in the Pantar Strait (immediately west of Alor, Fig. 1) appear to have exploited NE–SW basement faulting (Elburg et al., 2002). Second, although there are no long, strong alignments (such as those identified in central Sunda), the shape of eastern Flores, Lomblen and Pantar islands and the volcanic centres of eastern Flores display a diffuse ENE–WSW en echelon, almost sigmoidal, alignment, sub-parallel to the Pantar Strait. The complex pattern of volcano distribution may reflect the stress field induced when the, possibly embayed, leading edge of Australian continental crust collided with the arc (Fig. 1).

5.3. Depth to Slab

Depths from arc volcanoes to the Wadati-Benioff Zone have been used to investigate the thermal structure and melting mechanisms in subduction zones (Syracuse and Abers, 2006; England and Katz, 2010). A subducted slab and dynamic mantle wedge is the zero-order requirement to generate the petrographic and geochemical characteristics of arc magmatism. However, volcano distributions throughout the Sunda Arc, like linear volcanic segments in several other arcs (Stoiber and Carr, 1973; Marsh, 1979; Ranneft, 1979; Hughes et al., 1980), are more plausibly explained by stress in the arc lithosphere than by processes operating either within the mantle wedge or close to its interface with the slab.

In the central Sunda Arc, west segment volcanoes have an average “depth to slab” ($H$) value of 91 ± 7 km while the average for the east central segment is 165 ± 8 km (Fig. 8). This brackets most of the range of average $H$ values for
arcs worldwide (c.f. England and Katz, 2010). A systematic variation along the west central segment also covers much of the global $H$ range but the variation is in the opposite sense to that expected for a gradual transition between the average values of the west segment and east central segment \textit{i.e.} $H$ increases towards the west, not towards the east (Fig. 8).

Convergence rate and slab dip both vary systematically along the central Sunda Arc but by less than 10\% (Section 2) and in opposing senses to one another, meaning their product varies by an even smaller amount (~5\%). These parameters, therefore, cannot be related to either the sense or magnitude of $H$ variation along the Sunda Arc. For other locations where $H$ varies significantly within individual arcs but slab geometry does not, Syracuse and Abers (2006) proposed that structures in the upper plate or thermal heterogeneity of the mantle wedge might provide local influences upon $H$. Such structures should, therefore, be a target for future exploration in the Sunda Arc. If, however, as we have inferred, the arc lithosphere exerts the primary control on volcano location then values of $H$ may have less relevance for the locus of melting than previously believed. Instead, the value of $H$ for any particular volcano may depend on the combination of the orientation of stresses in the arc lithosphere with the strike direction of the slab. Closer investigation of $H$ variation and segmentation within other arcs is required to resolve this issue.

6. Summary

Volcanoes of the central Sunda Arc, from Java to central Flores, occur in four, en echelon, linear segments each of 500 – 750km length. These are most likely to reflect stress-controlled weakness of arc lithosphere resulting from
tectonic forces generated close to the plate margin and/or arc lithosphere flexure. Deviations from the en echelon pattern in Java occur where other structures in the arc lithospheric allow magma transport. The segmentation identified in this study explains why approaches employing depth to slab have struggled to incorporate the central Sunda Arc.

East of central Flores, where Australian continental crust has been thrust beneath the fore arc, and west of the Sunda Strait, where highly oblique convergence has produced the Great Sumatran Fault, the stress regimes in the overriding plate change and volcano distributions diverge from the pattern of en echelon, linear segments in the central Sunda Arc. This empirical observation, in itself, points to an upper plate control on distribution of volcanoes throughout the Sunda Arc.

Acknowledgements

AP is grateful for the assistance of Michael McKimm (Geological Society of London) in obtaining geological maps. CGM acknowledges a period of research leave from Durham University, during which time this study was conceived. The SE Asia Research Group at University of London is thanked for funding work to understand volcanism in Java. Discussions with Robert Hall and Jeroen van Hunen were particularly helpful in developing these ideas. The editor and two anonymous reviewers are thanked for constructive comments that helped refine this contribution.
References


**Figure Captions**

Figure 1. Map of Indonesia showing the major islands and tectonic structures, modified from Macpherson and Hall (2002). Active subduction zones are thick lines with barbs on the overriding plate. Other solid lines represent inactive subduction zones or major strike-slip faults; GSF: Great Sumatran Fault. Black dotted line represents the estimated northern extent of Australian continental crust subducted at the Timor Trough (Harris et al., 2009). Grey dashed lines represent the estimated accretion ages of Gondwanan lithospheric terranes to Sundaland (Hall, 2011).

Figure 2. Relief of the central Sunda Arc produced from topographic (SRTM v.4) and bathymetric (SRTM30 Plus v.7 of Becker et al., 2009) base datasets. Black arrows showing convergence directions of the Indo-Australian Plate and Sundaland are labelled with convergence rates (Simons et al., 2007). Triangles represent all geologically validated Quaternary volcanic structures with a basal diameter >3 km. Seafloor colour coded for depth (cooler colours for greater depth). Volcanoes labelled are: Arjuno- Welirang (AW), Baluran (Bl), Batur (Bt), Galunggung (Gg), Kawi-Butak (KB), Krakatau (Kr), Lasem (La), Merapi (Me), Muriah (Mu), Papandan (Pa), Ringgit-Beser (Ri), Sangeang Api (SA), Sangenges (Sa), Semeru (Se), Slamet (Sl), Sumbing (Su), Tambora (Ta), Tankuban Prahu (TP), Tengger Caldera (TC) and Wilis (Wi). Yellow triangles represent centres omitted from outset due to petrological and/or geochronological differences to arc volcanics (see text for details).

Figure 3. Schematic illustration showing application of Hough Transform analysis to recognise alignment. Lines with all possible azimuths are passed through each point in a dataset. Grey lines in panels (a) and (b) illustrate two
such lines each for the square and the triangle, respectively. For lines of all azimuths the normal that passes through the origin (dashed lines) is identified and the length ($\rho$) and angle to the x-axis ($\theta$) are plotted against one another (parameter space plot) giving a sinusoidal trace for each point. This is illustrated in panel (c), where the open symbols are the examples shown in panels (a) and (b) and closed symbols represent normals to lines with other azimuths (omitted from (a) and (b) for clarity). Aligned points return the same coupled $\rho - \theta$ values (e.g. normals 1 and 4). Therefore, increased frequency of such pairs (effectively a third axis projecting out of the page) is a means of identifying alignments in datasets.

Figure 4. Hough Transform analysis of the (a) uniform, and (b) weighted volcanic datasets for the central Sunda Arc. All images are proportionate i.e. horizontal scale = vertical scale. Volcanic structures are represented by (a) filled circles of uniform size, and (b) circles three-quarters the measured basal diameter of the structure. Straight lines are the alignments identified by Hough Transform analysis. Varying shades and ornaments are used simply to aid distinction of potential alignments. (c) Alignments that occur in both the uniform and weighted datasets (labelled with $R^2$ values) for all circles that fall within the associated ellipses. (d) Four alignments (and $R^2$ values) identified by forcing circles to only lie in one alignment.

Figure 5. Plot of K$_2$O versus MgO for volcanic rocks from Java. Backarc volcanoes (Leterrier et al., 1990; Edwards et al., 1991; Edwards et al., 1994; Macpherson, 1994), plotted as discrete symbols, are significantly more potassic than the volcanic arc (Dempsey, 2013).
Figure 6. SRTM data for Java and Bali summarising significant structures from 1:100,000 scale geological mapping (Supplementary Material A). Triangles are volcanic centres included in the initial Hough Transform analysis (Fig. 4). Orange centres trend away from the segments identified in Fig. 4 but are aligned sub-parallel to other local structures. (b) Enlarged view of the Bandung area (white box in panel a) illustrating the distinct structural ‘grains’ which are approximated by the two black lines shown; the longer line is sub-parallel to the volcanic segments identified in Fig. 4. (c) Enlarged view of the black box in panel (a) showing that Pandan lies within a Tertiary fold belt, across which folded strata are apparently offset and warped.

Figure 7. Results of linear least squares regression for the central Sunda Arc weighted dataset after excluding those centres probably related to second order lithospheric control (see text and Fig. 6). Regression lines (solid) with $R^2$ values and 95% confidence interval (dashed lines). For clarity, the northing scale is exaggerated relative to the easting scale.

Figure 8. Latitude versus depth to the top of the Wadati-Benioff Zone ($H$) for Java, Bali and Lombok using data from Syracuse and Abers (2006), which provides little data for volcanoes from the east segment. Symbols are based on the alignments identified in this work (Fig. 7). Squares represent volcanoes excluded from our spatial analysis on the basis of petrography, geochemistry and possible secondary influence of mesoscale lithospheric structures (Section 5).

Figure 9. (a) The central Sunda Arc in UTM projection, with coordinates referring to UTM zone 48S; arrows represent GPS-derived movement vectors from GEODYSSEA stations with respect to the Sunda Plate (Socquet et al.,
Black lines show the volcanic segments identified in Fig. 7. (b) Plan view showing the orientation and sense of secondary structures in a dextral simple shear zone with respect to the principal stress axes. R and R’ are the synthetic and antithetic Riedel shears, respectively, T is tensile fracturing and P is P shearing (after Woodcock and Schubert, 1994). Zones of (c) dextral transtension, and (d) dexteral transpression in plan view showing the orientation and sense of structures with respect to the principal stress axes (Sanderson and Marchini, 1984). Strain ellipsoids also shown. Abbreviations as in (b) plus; TF - Thrust Fault, NF - Normal Fault, and F - Fold.
Outer margin of terranes accreted:
1 Pre-Cretaceous
2 Early Cretaceous
3 Mid Cretaceous
4 by Early Miocene

Figure 1
Figure 3
Figure 4

\[
R^2 = 0.947 \\
R^2 = 0.917 \\
R^2 = 0.958 \\
R^2 = 0.774 \\
R^2 = 0.964 \\
R^2 = 0.974 \\
\]

Northing (km; UTM Zone 48S)

Easting (km; UTM Zone 48S)
Figure 5
Figure 7

West Segment ($R^2 = 0.950$)

West Central Segment ($R^2 = 0.985$)

East Central Segment ($R^2 = 0.963$)

East Segment ($R^2 = 0.853$)
Figure 8
Figure 9
Supplementary Material A – Indonesian Maps

Maps used to verify volcanic features in Java, Bali and Flores, all published by the Geological Research and Development Centre in Bandung, Indonesia.

Djuri, 1995. Geological map of the Arjawinangun Quadrangle, Java (1:100,000).
Koesmono M, Kusnama, Suwarna N, 1996. Geological map of the Sindangbarang and Bandarwaru Quadrangles, Java (1:100,000).
Santosa S, Atmawinata S, 1992. Geological map of the Kediri Quadrangle, Java (1:100,000).
Sidarto, Suwarti T, Sudana D, 1993. Geological map of the Banyuwangi Quadrangle, Java (1:100,000).
Sudjatmiko, 1972. Geological map of the Cianjur Quadrangle, Java (1:100,000).
Suharsono, Suwarti T, 1992. Geological map of the Probolinggo Quadrangle, Java (1:100,000).
Sukamto R, 1975. Geological map of the Jampang and Balekambang Quadrangles, Java (1:100,000).
Supplementary Material B – Spatial Database of Volcanic Features

Details of all volcanic vents identified on SRTM data and verified by published geological maps (Supplementary Material A) as part of this study. Vents are listed from east to west along the Sunda Arc, and the largest approximate diameter of the topographic feature, as measured from SRTM, is given (note for asymmetric features an average diameter is used). Only those structures with a diameter >3 km and of Quaternary age are listed (see text for details). Any vent that did not have a unique name was given the name of the topographic high which it either forms or occurs upon or, if no such name could be found, is unnamed.

Notes:

1. These vents are known to be of differing chemistry/setting to the majority of volcanics, and the reference providing such information is given. They are discussed individually in section 3.2 of the main text.

2. Indicates vents discussed in section 5 of the main text.

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