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FAULT CONTROL ON PATTERNS OF QUATERNARY MONOGENETIC VENTS IN THE ETHIOPIAN RIFT BETWEEN OMO AND TENDAHO

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ABSTRACT: Field and remote sensing data are used to examine the distribution of volcanism and fault geometry in the Ethiopian Rift between Omo-Chew Bahir rift and Tendaho graben during the Quaternary and evaluate their influence on the location and shape of individual vents as well as the development of alignments. The results of remote sensing, and field study of the total (2214) cone populations reveal that monogenetic vent alignments and the long axes of elongate cones are parallel to and spatially linked with mapped normal faults. This is consistent with the overall sub-latitudinal extension direction in the Quaternary deduced from fault slip analysis and earthquake focal mechanism solutions. Out of the rift axis, pre-existing faults were apparently reactivated and acted as conduits for magmatism to reach the surface, and hence vent clustering. On regional scales, vent clusters are located in Quaternary volcanic fields along the rift axis and in zones of reactivation of pre-Tertiary structures. Sixty two percent of the vents in the study area are part of nine regional vent alignments that vary in length from 48 to 68 km. On sub-regional scales, twelve clusters ranging in length from 10 to 30 km have been mapped. Locally, field structural data show that individual vents and short vent alignments, up to 10 km in length, occur along and adjacent to faults, particularly along fault segments, intersections, and bifurcations. The long axes of elongate volcanic cones also have trends generally parallel to the local faults.

Key words/phrases: Cluster, Ethiopian Rift, monogenetic vent, Quaternary, vent alignment

INTRODUCTION

Several investigations demonstrated that vents tend to cluster within cone fields, rather than being randomly distributed (Hasenaka and Carmichael, 1985; Connor, 1990; Connor *et al.*, 2000). Correlations between vent distribution and fault patterns in cinder cone fields have been noted in various volcanic fields (Settle, 1979; Hasenaka and Carmichael, 1985; Connor, 1990). The spatial distribution and alignment of vents can provide information about crustal structure and fracture systems at various scales. The faults had a detectable control on cinder-cone emplacement. Due to the regional nature of the work, morphometric analysis of the cone was not carried out.

Monogenetic vent distribution in the Ethiopian Rift is spatially and temporally clustered at various scales. As in many other basalt volcanic fields, structure clearly influences the distribution of small-volume eruptive centres. Alignments defined by multiple vents and the orientation of elongate volcanic cones can be attributed to subsurface feeder dikes aligned with the crustal stresses at the time of formation (Nakamura, 1977). Vent clusters and alignments in the Ethiopian Rift show spatial and temporal correlation with the localization of faulting and magmatism mainly in the axial zone of the Ethiopian Rift.

Rift localization in the Quaternary

The current study is focused on the region extending between the Omo-Chew Bahir rift and the Tendaho graben (Fig. 1). The Ethiopian Rift started to develop during the Miocene (Davidson and Rex, 1980; Gidey Wolde Gabriel *et al.*, 1990; Tadios Chernet *et al.*, 1998), following a broad doming centred on the present Afar depression (*e.g.,* Ebinger *et al.*, 1989). Accompanying the rift-ward younging of volcanism, the border faults became abandoned resulting in the localization of deformation and magmatism during the Quaternary in a narrow (15-20 km wide) axial zone (*e.g.,* Boccaletti *et al.*, 1998; Kendall *et al.*, 2005). The rift progressively deepened evolving through a sequence of strain localization marking the boundary between the Nubia and Somalia plates (Hayward and Ebinger, 1996). The rift is bounded by discontinuous boundary faults, some of them active from mid-Miocene (Gidey Woldegabriel *et al.*, 1990) and striking between NNE–SSW in the south and NE–SW in the north (Mohr, 1967; Mohr and Gouin, 1968; Meyer *et al.*, 1975; Boccaletti *et al.*, 1998; 1999; Acocella *et al.*, 2003, Tesfaye Korme *et al.*, 2004). Generally, stress states are thought to have rotated in the MER during the Quaternary (Bocaletti *et al.*, 1998) resulting in an axial rift zone called the Wonji Fault Belt where Quaternary magmatic and tectonic activities are going on. Despite the overall NE–SW trend of the MER, the rift axis is characterized by active NNE–SSW trending extension fractures and normal faults which collectively constitute a right-stepping *en échelon* fault array (Boccaletti *et al.*, 1998).

The increase in the volume of Quaternary basaltic volcanism in the rift axis can be attributed to the difference between the densities of magma and the surrounding crustal rocks (Glazner and Ussler, 1989). Basaltic dike intrusion must have increased during the Quaternary raising the overall crustal density. This, in turn, could have allowed more basaltic magma to rise due to buoyancy (Glazner and Ussler, 1989).

Kone and Boset acidic centres are exceptional in that they consist of abundant basaltic products right on the volcanic edifices. Gedemsa shows only a single basaltic vent in the caldera floor. Either the other acidic centres are devoid of basalts or basaltic flows are restricted to their flanks. This suggests along axis variation in magma localization, hence dike emplacement that influences vent clustering and development of alignments.

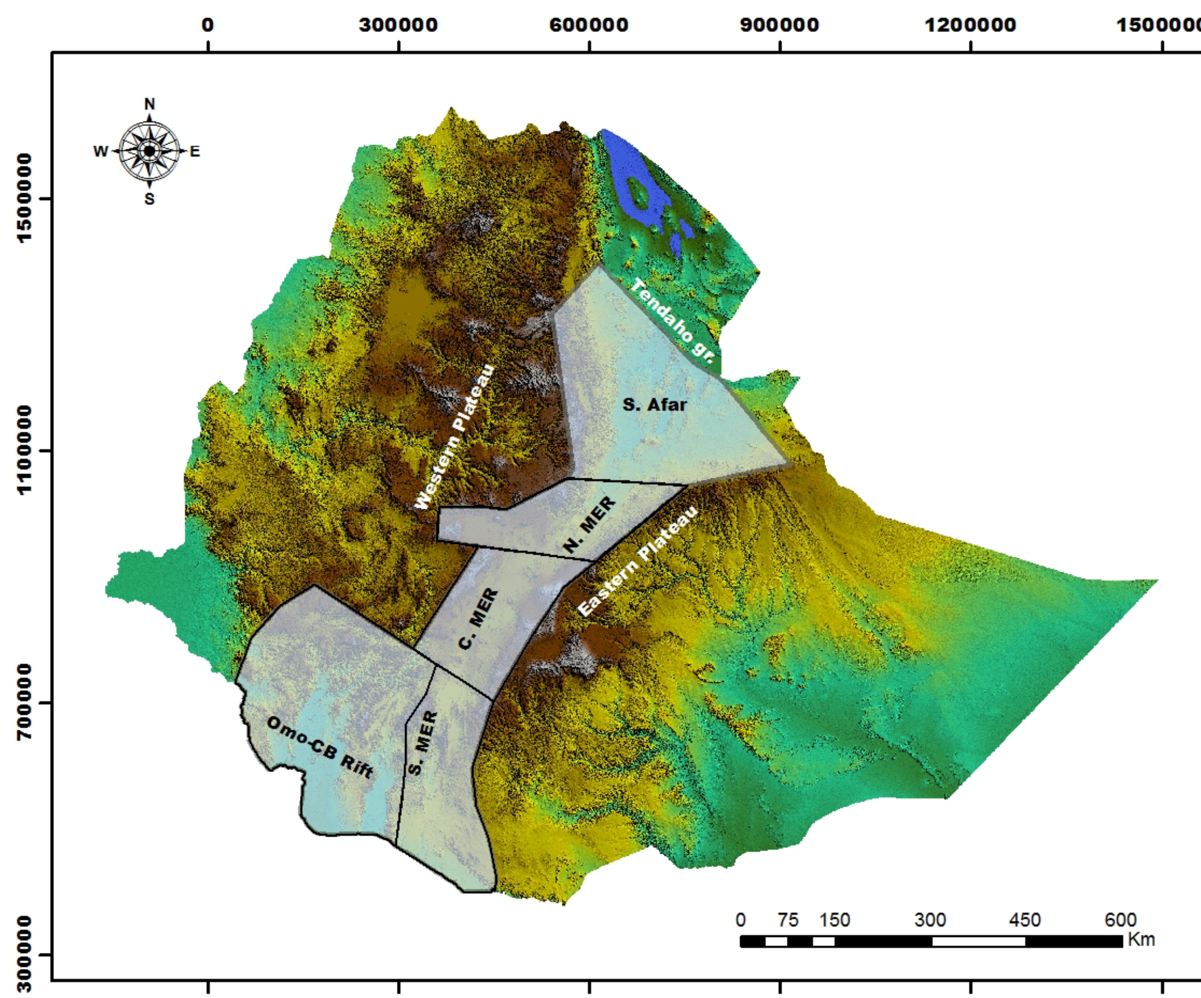


Figure 1. Location map of the study area showing the various rift sectors.

Most of the prominent regional and sub-regional cone alignments are developed on low, level ground of hanging walls and grabens/half grabens. This suggests that crustal density contrast between the hanging wall filled with loose pyroclastics and sediments and the footwall made of denser rocks determined the location of volcanic fields.

Quaternary volcanism is characterized by a bimodal basalt-rhyolite association (Peccerillo *et al.*, 2003) lacking intermediate products. This shift of the locus of magmatism towards the present rift axis was accompanied by increase in the proportion of basalts and by petrological and geochemical changes of the basalts (Table 1). High Cr and Ni content and elevated Mg-number in some of the axial basalts suggest that they may represent relatively primitive magmas (Trua *et al.*, 1999) due to rapid accent assisted by dense faulting.

This study encompasses the region between the Omo-Chew Bahir rift zone and the southern border fault of the Tendaho graben where the axis of the MER terminates. Quaternary volcanism is dominantly limited to the rift floor possibly as a result of partial melting of the lithosphere in response to extension across the Ethiopian Rift, even though there are minor off axis volcanic activities. The latter are related to new and reactivated structures of NE-SW and NW-SE orientations.

Table 1. Petrological and geochemical characteristics of basalts from the rift margin (Pliocene) and the axial rift zone (Pleistocene).

Unit	Eastern margin basalts	Axial basalts
Texture	Aphyric	Porphyritic
Olivine	Fo47-55	Fo74-79
Plagiocalse	An40-57	An60-74
MgO	3.9–4.8 wt. %	4.8–12.0 wt. %
CaO	7.1–7.7 wt. %	8.7–10.5 wt. %
Ni	5–14 ppm	15–64 ppm
Cr	4–56 ppm	32–376 ppm
Sr	532–875 ppm	425–675 ppm
Ba	410–547 ppm	183–494 ppm

Data source: Trua *et al.* (1999).

The axial rift zone is occupied by large silicic centres situated more or less regularly along the rift floor. Other volcanic forms include monogenetic centres. These are collections of cinder cones and craters. In this study, a group of vents situated within a volcanic field is considered as a vent cluster and preferentially aligned clusters are taken as cone alignment.

The general Quaternary volcano-tectonic setting of the MER is controlled by the *enéchelon* arrangement of the Wonji Fault Belt (Mohr, 1962). These NNE–NE Quaternary fault zones of the WFB form areas of active deformation obliquely cutting the MER rift floor (Fig. 2) The MER is a region characterized by east-west extension and NNE trending normal faults. Coupled with this overall pattern of crustal extension are numerous small-volume volcanic fields including cinder cones, maar vents and tuff rings with associated lava flows and pyroclastic deposits.

The objective of this study is to characterize basaltic vent clusters, alignments and their relationships to faulting at various scales. It is also intended to see how the interplay between fault geometry and regional as well as local states of stress influence the location of individual cones, their shapes and preferential orientation of cone clusters.

Mapping of faults and volcanoes is used to investigate the relationship between the distribution of basaltic cones and faults. At the regional scale, it appears that shifts in the locus of volcanism and faulting through time and the concentration of volcanic activity within specific areas of the Ethiopian Rift in response to extension determined the cluster zones.

During the Quaternary, volcanism and deformation became localized in the axial zone, which is characterized by more, or less regularly -spaced silicic volcanoes with or without calderas (Fig. 2). The silicic products comprise ignimbrites, tuffs, pumices, rhyolite-obsidian lava flows and domes. Concomitant with these is the em-placement of monogenetic cinder cones with highly concentrated discrete vent clusters and alignments. Each of these features of vent distribution is revisited in light of the structural and neo-tectonic setting of the volcanic fields. The increase in rate of vent formation in the Quaternary coincides with the time of shift in the locus of magmatism and faulting to the axial zone.

Most alignments of vents related to the volcanic activity during the Quaternary period correspond mainly to the NNE-NE oriented magmatic segments, similarly oriented extensional fault systems, and associated accommodation structures. They have orientations consistent with that of the regional stress (ca.

east-west extension). This strongly argues that structural control is a major factor in the development of vent alignments at regional, sub-regional and local levels. The location and elongation of individual cones is also strongly influenced by individual faults.

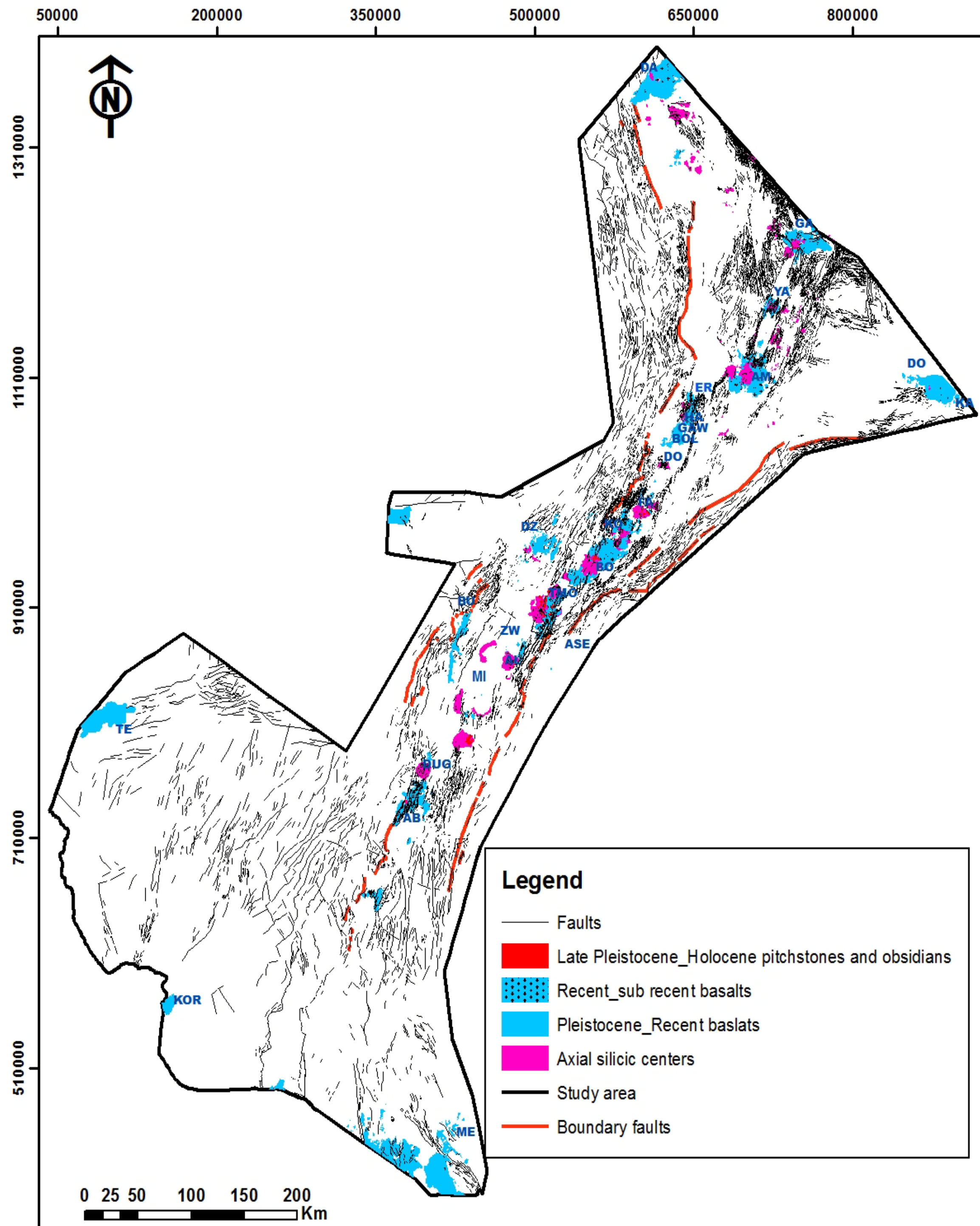


Figure 2. Quaternary volcanic zones and faulting in the Ethiopian Rift.

Notations in the Figure:

ME-Mega, KO-Korath, TE-Tepi, AB- Abaya, DUG-Duguna, MI-Mito, ZW-Zway, ASE-Asela, TMO-Tulu Moye - BO-Boset, DZ- Debre Zeit, KO-Kone, FA-Fantale DO-Dofan, BO-Bolhamo, GAW-Gawani, HA-Haledebi, ER-Ertele, AM-Amoissa, YA-Yangudi, GA_Gabilema, DO_Doba, KA-Kawdera, DA-Dabayra.

Cone clustering and alignment

Monogenetic cones show two distinct types of spatial arrangement within the rift floor and the adjacent margins. The most common distribution is expressed in the form of alignment parallel to faults indicating control of faults on their emplacement. Cone alignment is observed at the regional, sub-regional and local scales. Spatially, Quaternary basaltic cones in the Ethiopian Rift form nine regional, 12 sub-regional and numerous local alignments. The other type of cone distribution group is related to large eruptive centres where such cones show more or less radial clustering as signs of flank eruptions. In this study, cone alignments in excess of 30 km are considered as regional (Fig. 3). Such vent alignments of regional extent likely reflect linear zones of melt generation and magmatic localization. Shorter alignments extending between 10 and 30 km are taken as sub-regional and those smaller than ca. 10 km lengths are taken as local alignments.

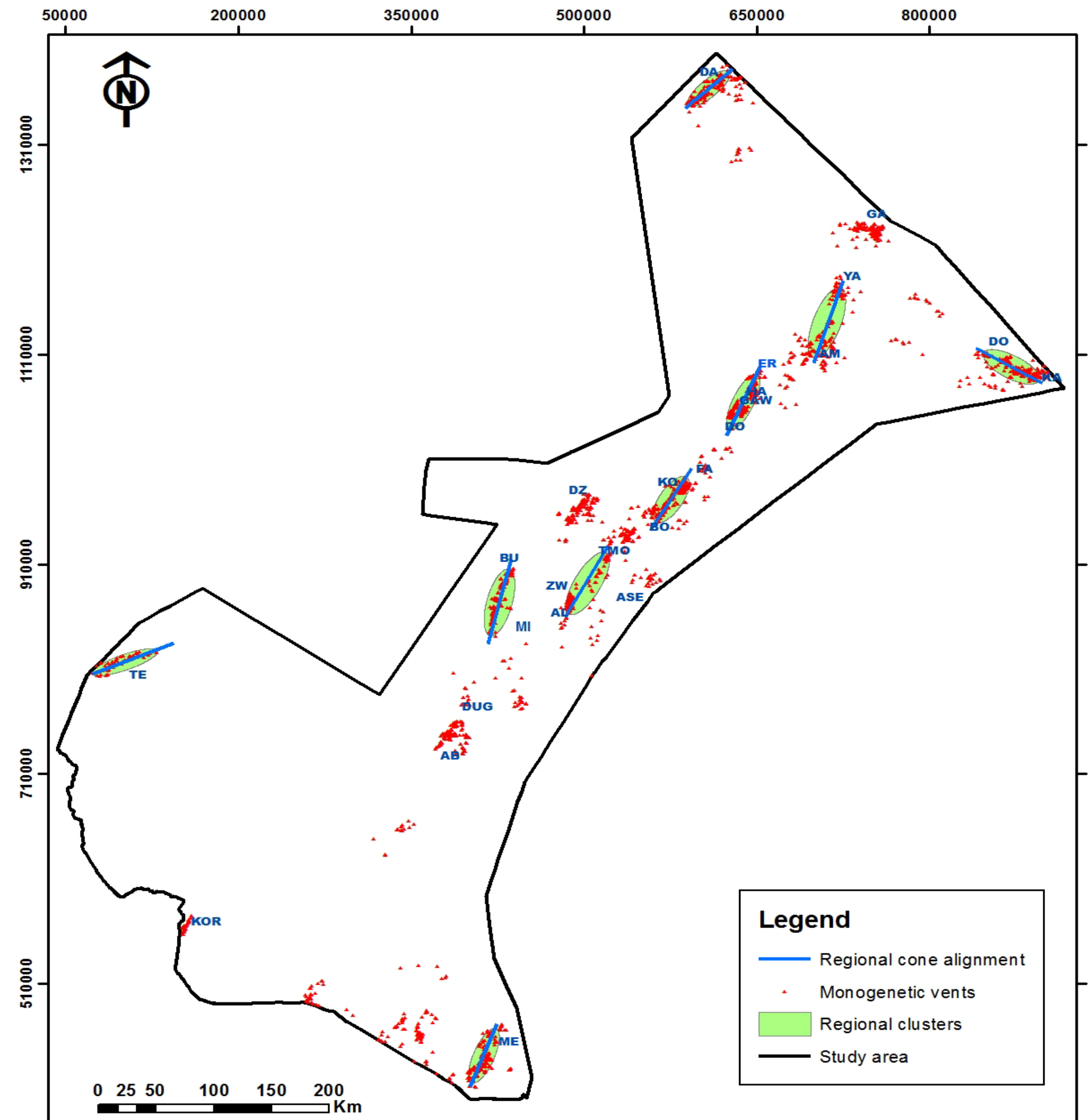


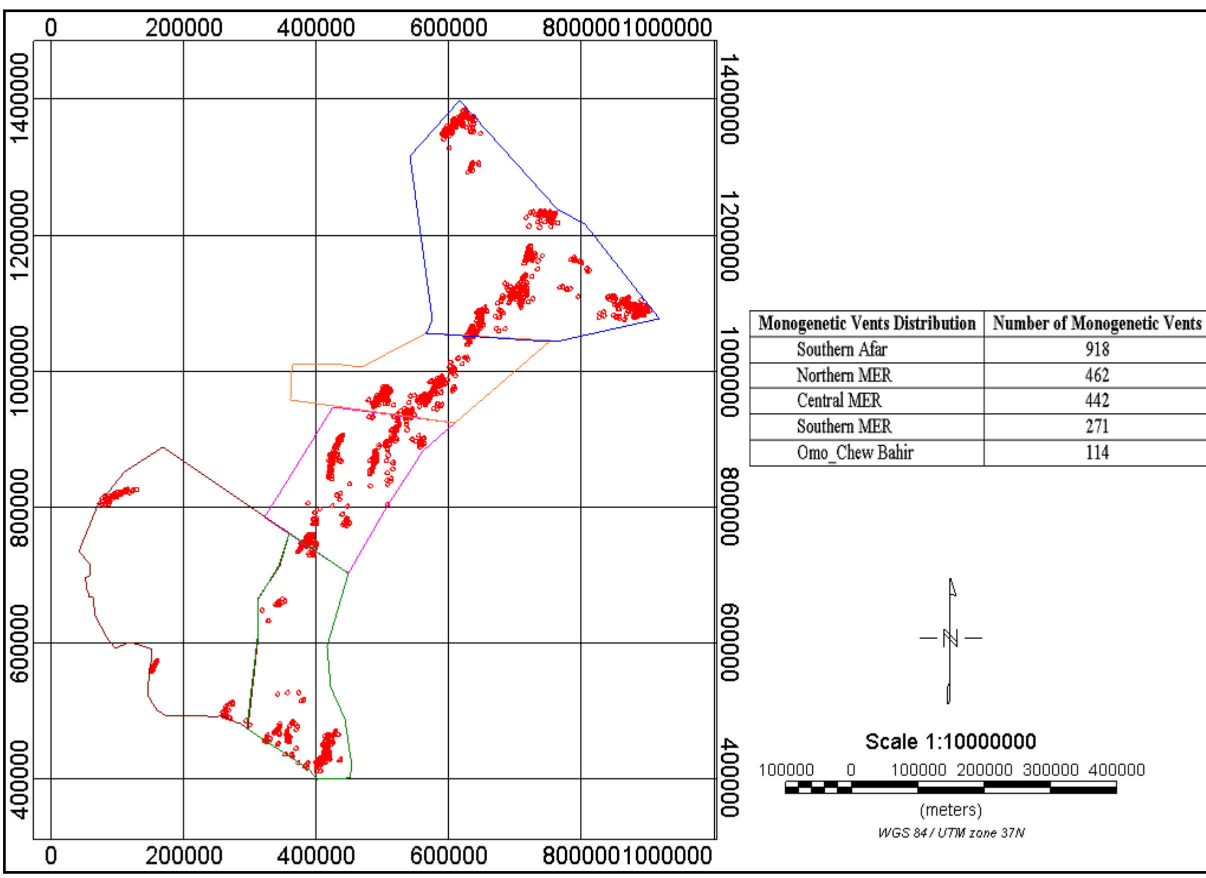
Figure 3. Regional cone clusters (green) and alignments (blue line) in the Ethiopian Rift.

Most cones develop mainly in areas where fault density is relatively low even within the same segment or sub-segment. This suggests that extension across such vent alignments is accommodated by dikes and blind faults striking parallel to surface faults. Trends in cone distribution and clustering thus appear to be dominantly related to active rift localization.

A total of 2214 monogenetic centres were mapped from topographic maps, satellite imageries and air photographs in conjunction with field observations. Detailed mapping indicates that a few cinder cones in monogenetic fields have had multiple eruptions, thus actually being polygenetic. In this study, such cones are considered as monogenetic if the successive eruptions occur on the same vent.

Following the rift axis, vent density increases northwards (Fig. 4) and clustering becomes more radial from Ayelu-Amoissa transfer zone to Gabilema. However, these flank clusters, too, constitute part of the northernmost regional alignment. South of this transfer zone, monogenetic vents form prominent regional and sub-regional alignments. Style of cone clustering shows a general variation between the Main Ethiopian Rift and southern Afar. In the Main Ethiopian Rift, the alignments parallel to associated faults are more prominent, whereas in southern Afar, they tend to be radially clustered. Averaged for the entire region, about 70 percent are members of regional and sub-regional alignments whereas 30 percent are outliers.

Plotting the distribution of the entire cone population reveals a dominant N10–25°E trend in regional alignments. This is in correspondence with the predominant fault trend along the rift axis that also defines a dominant N05–25°E strike. At the sub-regional scale, the most prevalent vent alignment is NNE-SSW parallel, except one NW-SE alignment at Gabilema volcano, to the faults bounding Tendaho graben.



Monogenetic Vents Distribution	Number of Monogenetic Vents
Southern Afar	918
Northern MER	462
Central MER	442
Southern MER	271
Omo_Chew Bahir	114

Figure 4. Distribution of monogenetic vents in the Ethiopian Rift showing a general increase in vent density from the Main Ethiopian Rift (MER) to Afar.

METHODOLOGY

A Land sat mosaic composed of six images with projected resolution of 28 m was used as a base map. In conjunction with this, 30 m resolution Digital Terrain Elevation Data (DTED) illuminated from different directions has been utilized to plot vents as point features and faults. Infrastructure, water bodies, lithologic contacts, faults and monogenetic vents were digitized on screen in ArcGIS 9.2 software. Shape files were created for all point, polyline and polygon features. Vent cluster density was calculated by dividing the area of each ellipse by the number of vents inscribed in it.

Owing to the near-perfect match between vent alignment and general fault trends, ellipses were constructed to represent aligned vent clusters with their long axes to the faults. Cone alignment polyline shape file was created in this manner. The long and short axes of the ellipses were constrained by leaving out peripheral point data sets, thus assuring the reliability and quality of the alignment at regional and sub-regional levels.

For the determination of the azimuth of vent long axes and local alignments, digitization was made on aerial photographs, and in the case of Boset area on Lidar (Light Detection And Ranging) images of 2 m resolution. Field verification was made to assert if individual vents are monogenetic or if they are built by multiple and coalescing eruptions.

The results of field observations and Remote sensing data were used to produce maps of regional, sub-regional and local vent alignments.

Regional scale cone alignments

On regional scales, small volume Quaternary volcano clusters are located in the actively extending axial rift zone and along reactivated old structural weaknesses. This preferential clustering of cones, in particular on faulted terrain is possibly related to the resulting density contrast between the rift floor and the adjacent plateaus, the former being characterized by low density sediments and loose pyroclastic rocks.

Mega vent alignment

One of the most prominent sub-regional clusters is the Mega alignment which is about 58 km in length and consists of 126 Quaternary basaltic vents resting on Miocene volcanic rocks of the southern Ethiopian Rift. The majority of this cone population falls along a N20°E trend cross cutting the NW-SE Precambrian structural fabric. The vent alignment is parallel to the axial rift of the MER but without any associated faulting suggesting the importance of magma-assisted rifting in this region. Quaternary basaltic volcanism occurs mainly on the low-lying area where the Gelana graben meets the northward propagating Kinu Sogo and Ririba rifts.

Tepi vent alignment

This Quaternary volcanic field occurs on the Eocene-Oligocene pre-rift basalts of southwestern Ethiopia. It consists of 55 basaltic cones spread along a 60 km distance. Nearly 90 percent of these cones form a N60°E alignment parallel to a system with similarly oriented faults defining the Tepi-Shebe Rift, which is orthogonal to the Main Ethiopian Rift (Fig. 5). The cone alignment marks Quaternary reactivation of this rift at its western tip.

Mito-Butajira alignment

The concentration of basaltic monogenetic cones between Mito and Butajira over a distance of 63 km forms a regional order alignment running parallel to the western rift margin of the Main Ethiopian Rift (Fig. 6). This cone field consists of 144 monogenetic cones 90 percent of which are preferentially aligned along common azimuthal direction of N10°E. The aligned cones are concentrated in a 2–3 km wide zone within the Mito-Butajira marginal graben indicating the control of structures on magmatism. Localization of volcanic activity within the 67 km graben, in turn controls concentration and alignment of monogenetic vents.

Aluto-Gedemsa alignment

The Aluto-Gedemsa basaltic filed consists of a cluster of 126 cones 87 percent of which form another major cluster with N25°E preferred vent alignment covering a distance of 66 km. This linear cone cluster runs from Aluto volcano to southern rim of Gedemsa caldera in close association with Quaternary basaltic lava flows occupying low-lying areas. Both the axial volcanic field and the regional vent alignment are perfectly parallel to .the local fault trend (NNE-SSW) indicating the role of faults on the emplacement and linear pattern of the cone locations.

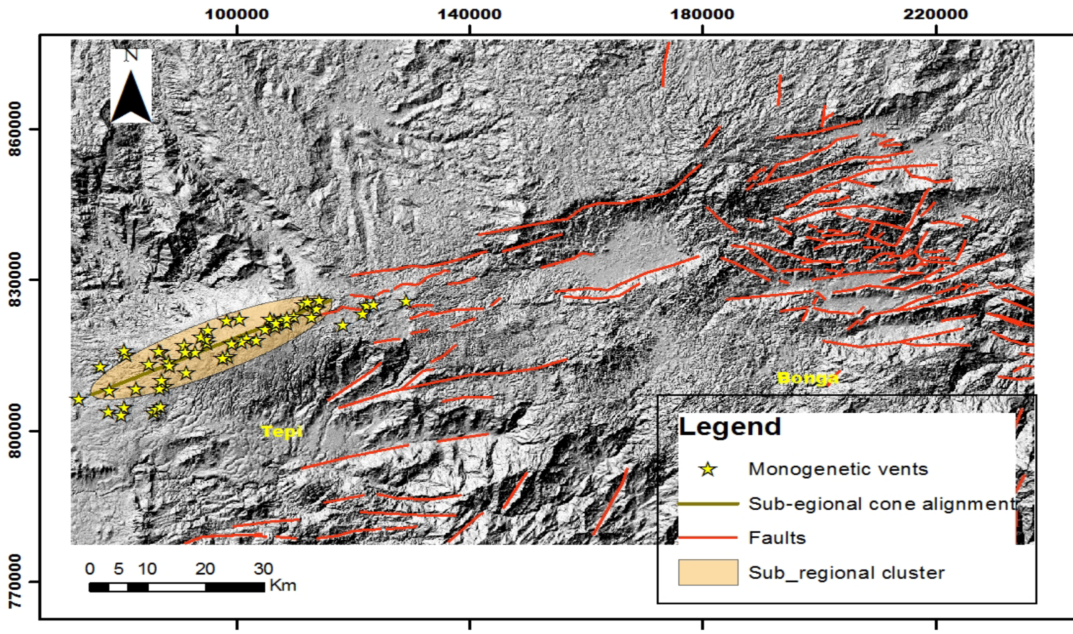


Figure 5. Tepi-Shebe Rift showing E-W trending faults and similarly aligned monogenetic vents on the western termination of the rift.

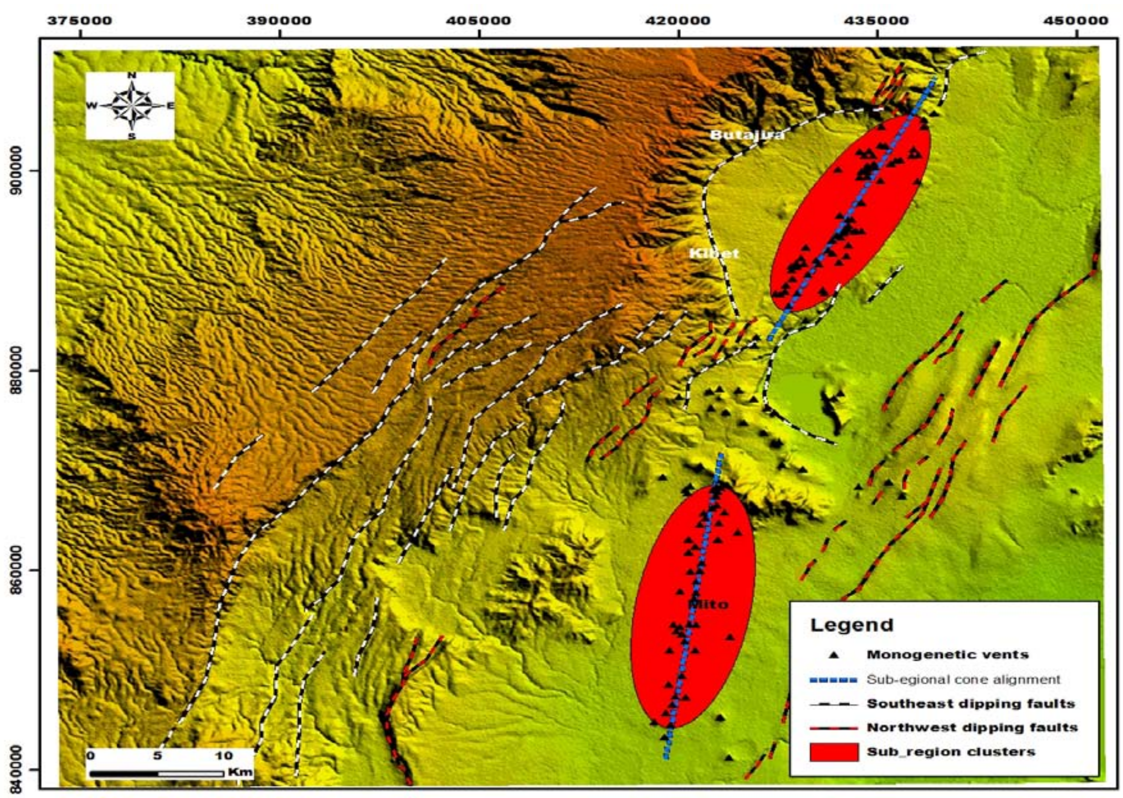


Figure 6. Butajira marginal graben on the western rift margin of the MER. The two ellipses: sub- regional clusters of Mito (southern) and Butajira (northern).

Boset-Fantale alignment

This vent alignment is 49 km long and oriented N35°E in the N40°E Boset-Fantale magmatic segment and oblique to the N05–10°E axial faults that cut the volcanic field (Fig. 7). Out of the total of 244 vents identified in this area, more than 80 percent form part of a general regional alignment. The majority of the vents are concentrated in areas of low fault density as compared to the flanking areas as clearly observed between Boset and Kone. The general vent cluster is restricted to the axial volcanic zone while the alignment runs parallel to the inner border fault of Melka Jilo. This suggests that the structure controlling the cone alignment is parallel to the faults flanking the rift axis but buried under the volcanic pile.

Dofan-Ertele

The Fantale-Dofan rift segment is characterized by sparse Quaternary volcanism and associated vents. A major regional vent alignment in this part of the Ethiopian Rift is the Dofan-Lake Ertele Quaternary monogenetic field consisting of 183 cinder cones with 90 percent of the cone population falling along a N20°E-trending alignment. The alignment is restricted to the axial volcanic field and extends for 57 km. Maximum cone concentration occurs in areas of low fault density adjacent to faults in the relatively low-lying level topography. The alignment of axial acidic centres and the localization of basaltic flows north of Nazreth town define a NE-SW trend whereas rift floor faults strike NNE-SSW. This regional cone alignment lies parallel to the alignment of the axial volcanoes, which is a zone of low faulting flanked by dense faults areas in the west and the east.

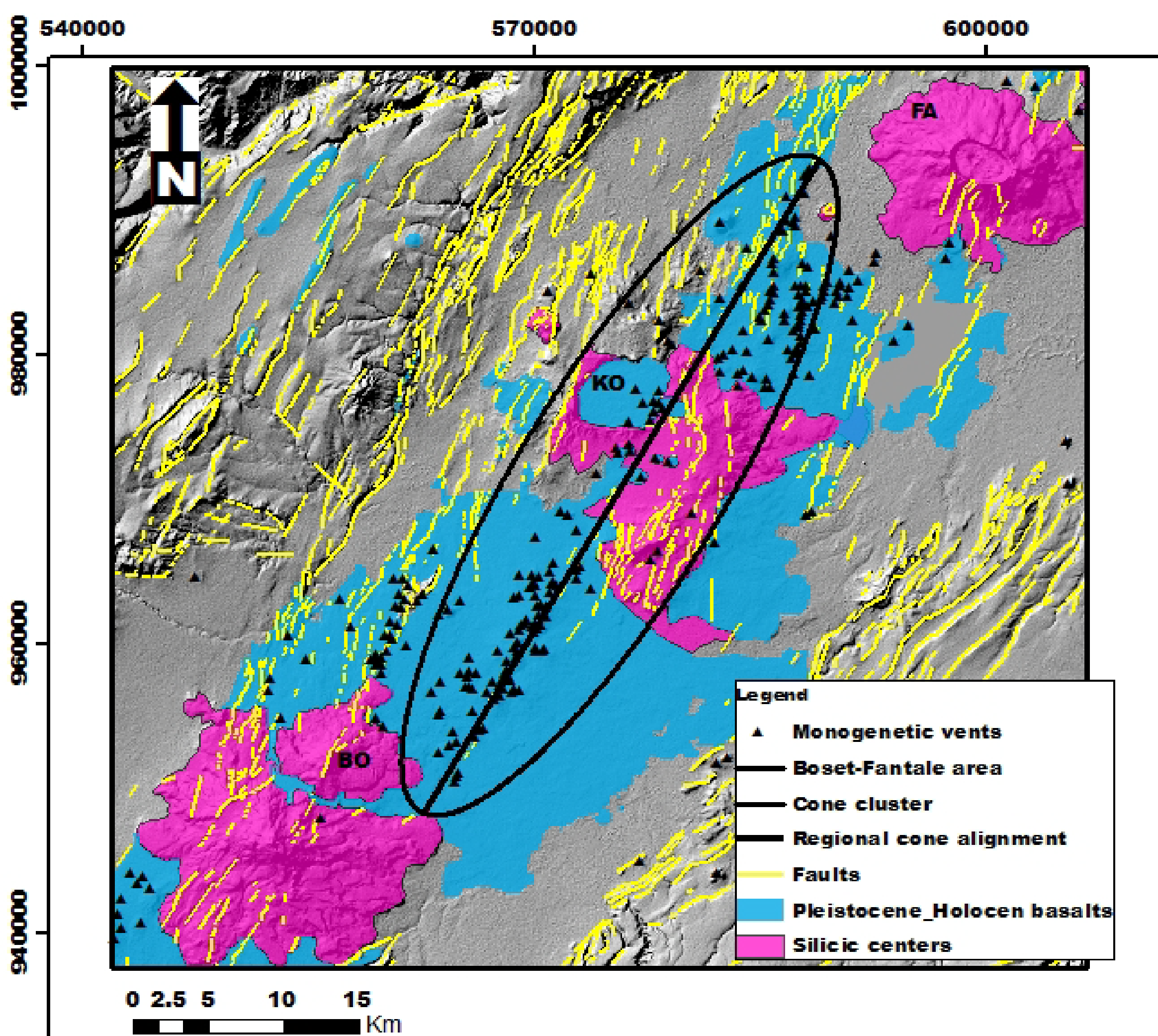


Figure 7. **Boset-Fantale NE-SW regional vent alignment .Vents are restricted to Quaternary basaltic fields, their alignment being slightly oblique to the local fault rend.**

Amoissa-Yangudi alignment

A right stepping *én échelon* configuration is observed between the Dofan-Ertele rift segment and the Amoissa-Yangudi (Dahwi Adda-Do) segment to the north. Basaltic cones in the latter segment show dominantly radial clustering around Amoissa and Yangudi volcanic centres. However, the majority of the 170 cones around the volcanoes and a small cluster in the middle of the graben form a continuous regional alignment 68 km in length and striking N15°E.

Kawdera-Doba alignment

Two hundred seven monogenetic vents have been mapped at the base of the southern Afar margin east of Dire Dawa town. One hundred sixty of these vents form a WNW-ESE alignment 55 km in length. The cones and associated basaltic flows are devoid of exposed faults and cover stratoid basalts, which are dissected by EW faults with small displacement. Some of the cones, which are peripheral to the cluster, are located on the stratoid basalts suggesting renewed volcanic activity through faults cutting the stratoid basalts. The N45°W alignment extends from Kawdera village through Doba and other smaller Upper Miocene acidic centres, parallel to faults on the stratoid basalts on the northern edge of the Shinile basin.

Dabayra alignment

The Quaternary Dabayra basaltic cone field consists of more than 170 monogenetic cones and associated flows at the base of the western Afar margin. This volcanic field lies west of the Dabahu-Manda Hararo rift segment where NW-SE striking Red Sea trend faults progressively swing to NS at Dabahu volcano. Ninety percent of the monogenetic cones distributed over a length of 48 km show a N45°E sub-regional alignment. The entire Quaternary volcanic field lies in an unfaulted terrain. The unique feature of this alignment is the fact that its orientation is not related to any fault trend in the surrounding area. It lies along the strike of the transfer zone between Alayta and Dabahu-Manda Hararo rift segments nearly orthogonal to the local rift trend. This also coincides with the zone of right step-over of the innermost faults of the western Afar margin. This and the N60°E Tepi alignment suggest reactivation of pre-Quaternary NE-SW structures.

Sub-regional vent alignments

Geologic field and remote sensing data are used to identify and map twelve sub-regional alignments of basaltic monogenetic cones ranging in length between 16 and 30 kilometres (Fig. 8; Table 2). All cone alignments except that of Gabilema along the rift axis are parallel to mapped normal faults (dominantly NNE-SSW); especially those with orientations that tend to cause them to dilate in response to extension. Around the Gabilema volcano, where the NW-SE Manda Hararo rift intersects with the NS to NNE MER, monogenetic cones show some degree of alignment parallel to the MER whereas the dominant preferential alignment is NW-SE. Even though the two fault sets mutually intersect (Acocella *et al*., 2011), the dominance of the NW-SE alignment probably suggests that the Manda Hararo Rift faults are more active than the MER faults.

Korath range

Korath is a volcanic ridge with a maximum summit elevation of 912 m located in the Omo basin. It is made up of Quaternary basaltic flows with N20°E aligned monogenetic cones mostly occupying the ridge crust. Nearly 90 percent of the 31 vents form a perfect alignment with the axial rift faults of the MER. Along the MER, Quaternary volcanism and faulting diminish southwards and terminate at Tossa Sucha between Abaya and Chamo Lakes. The widespread Quaternary activity in the Kenyan border indicates a northward propagation of the Kenyan Rift into southern MER.

Abaya-Duguna alignment

Another sub-regional vent alignment in the region is the 30 km long Abaya-Duguna alignment. This extends from the northwest edge of Lake Abaya to the southern foot slopes of Duguna volcano. This is one of the zones of dense, Quaternary faulting and volcanism in the MER. About 80 of the 122 cones within the Quaternary basaltic field in this area form a N20°E alignment parallel to the local trend of the border fault and the Quaternary faults suggesting that the emplacement of the volcanic cones is structurally controlled.

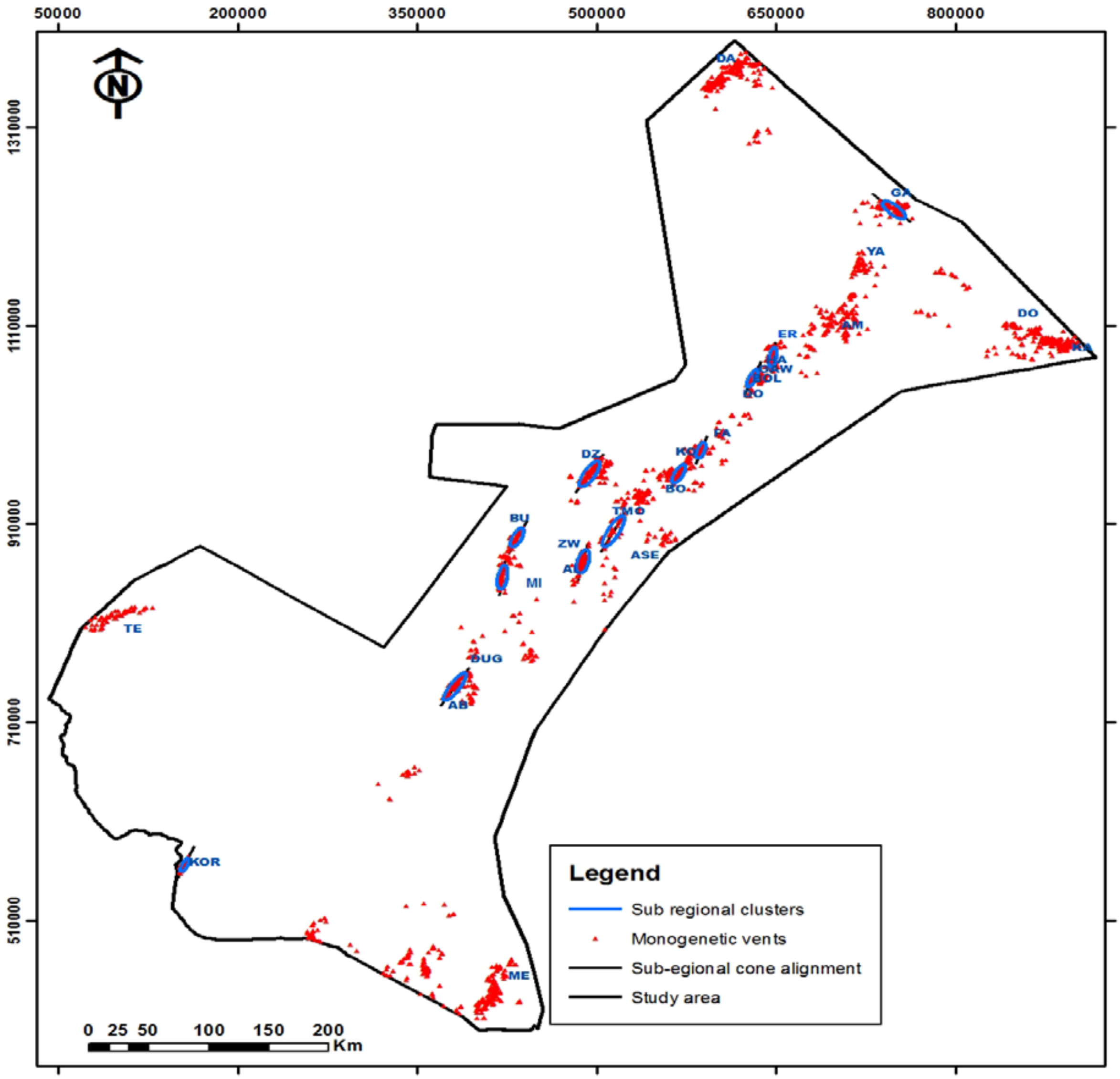


Figure 8. Sub-regional vent clusters and aligments.

Table 2. Sub- regional vent alignments with alignment lengths, number of aligned cones and cone density with approximate surface area of the cluster zone.

No.	Sub-regional alignment	Cone cluster area (km²)	Alignment length (km)	No. of vents in the alignment	Density/10 km²
1	Korath	64	18	28	4.44
2	Abaya-Duguna	256	30	84	3.28
3	Mito	160	24	47	2.90
4	Butajira	127	22	70	5.51
5	East Zway	114	18	79	6.12
6	Tulu Moye	160	21	21	1.31
7	Debre Zeit	210	25	56	2.67
8	Boset-Kone	136	20	85	6.25
9	Kone-Fantale	76	16	71	9.34
10	Bolhamo-Gawani	75	19	43	5.73
11	Haledebi-Ertele	118	21	60	5.08
12	Gabilema	158	21	77	4.87

Mito alignment

The Mito sub-regional alignment lies in the southern part of the Quaternary basaltic field situated in the ~68 km long Mito-Butajira marginal graben. It consists of 51 monogenetic cones more than 80 percent of which are aligned N5°E over a length of 24 km. The cone alignment is parallel to the NNE-SSW boundary faults of the graben.

The Butajira vent alignment is separated from the Mito alignment by a moderately faulted rhyolite centre and two NW-SE oriented local cone alignments with six and four cones each. These local alignments are parallel to the strike of Precambrian pegmatite veins exposed at Kella. Even though Quaternary deformation is accommodated mainly by NNE-SSW faults, the NW-SE cone alignments suggest reactivation of Pre-Tertiary weaknesses. The Butajira volcanic field lies in the northern half of the Mito-Butajira marginal graben and forms a 22 km long cone alignment oriented N20°E. The cluster consists of a group of 72 monogenetic cones some of which are associated with lava aprons. The difference between the Mito and Butajira alignment directions corresponds to the change in orientation of the bounding faults from nearly NS in the southern to NNE in the northern part of the graben.

East Zway

A sub-regional linear cone cluster comprising 88 basaltic vents is situated on the southern part of the Aluto-Gedemsa Quaternary magmatic segment east of Aluto and Lake Zway. The majority of faults in this magmatic segment are oriented N15–20°E becoming more northerly in the inner part of the fault zone. Most of the basaltic vents within this cluster form an18 km long sub-regional alignment oriented N07°E. The alignment coincides with the local fault trend that is oblique to the general fault trend. Cone concentration is limited to the 5 km wide basaltic field and the entire outer zone of the *ca*. 20 km wide fault zone in the Pleistocene ignimbrites is devoid of monogenetic vents. Most of the cones are located between faults while a small number of them fall on fault segments and tips.

Tulu Moye

In this part of the central MER, the zone of Quaternary faulting and volcanism deviates from the rift margin and cuts the rift floor obliquely. While the magmatic segment gives way to the north easterly Boset-Fantale segment, the faults cross the rift floor to the Kesem valley on the western margin. Due to dense faulting, most of the basaltic flows are emplaced in the form of fissural eruptions resulting in low cone density. Even though vents are sparse, 30 basaltic cones in the area are aligned N15°E, exactly parallel to the local fault orientation.

Debre Zeit cone alignment

The Debre Zeit cone field is uniquely situated with respect to the axial rift zone. A projection of the western margin border faults, which passes through Dukem and Yerer volcano, might be inferred as rift margin in this area. To the southwest, Quaternary faults of the Midre Kebd swing from NE-SW to N-S. The major active fault zones of the rift axis are situated east of this cluster zone. This volcanic field consisting of scoria cones, maars and tuff rings is characterized by absence of faults. About 70 percent of the 94 cones mapped from remote sensing and field observation in this area are members of a 25 km long sub-regional alignment striking N20°E. This is one of the two off axis Quaternary basaltic fields in the Main Ethiopian Rift, the other being the Mito-Butajira volcanic field close to the western margin. Besides being spatially isolated from the rift axis, the two basaltic fields are characterized by the absence of faults. Nonetheless, the cones in each field are strongly aligned parallel to the rift faults nearby suggesting structural control on their emplacement.

Boset-Kone alignment

The Boset-Kone sub-regional alignment occupies the southern part of the Boset-Fantale magmatic segment, which runs NE-SW, parallel to the Asela-Sire border fault. This segment is characterized by profuse basaltic volcanism compared to other segments. A total number of 131 vents are mapped in this cluster zone, which has no exposed faults. Nearly 80 percent of the vents form a 20 km long, N20°E alignment parallel to the local axial rift faults and oblique to the trend of the magmatic segment. Cone density in the linear cluster zone is 5 cones/10 km^2, one of the highest in the rift floor. The scarcity of faults and the abundance of monogenetic cones suggest that extension is accommodated mainly by dike intrusions and blind faults. In this magmatic segment, as in the others, cones are dominantly situated in fault free, low-lying areas adjacent to the faults.

Kone-Fantale

Another prominent vent alignment includes the Kone-Fantale area, the northern part of the Boset-Fantale magmatic segment. This is part of the regional-scale vent alignment extending between Bose and Fantale. The vents are densely concentrated in areas of sparse faulting. About 70 percent of the 97 vents between the two volcanic centres form a 16 km linear cluster with an average azimuth of N12°E that is parallel to the local rift floor faults. Average vent density is almost one vent/km^2.

Bolhamo-Gawani

The rift segment extending between Dofan and Lake Ertele is bounded to the east by NNE to NS striking, west dipping faults and to the west by eroded fault scarps of the western margin. The vents within this magmatic segment form one regional alignment, which, in turn consists of two sub-regional vent alignments with orientations varying according to the orientation of the flanking faults to the east.

The southern sub-regional alignment extends between Bolhamo and Gawani where ca. fifty percent of the 97 vents form a 19 km alignment with N15°E orientation. The second sub-regional alignment within this magmatic segment runs from Haledebi to Lake Ertele in the north. In this sub-sector of the rift, Quaternary volcanism and faulting are restricted to a 15 km wide graben flanked by faulted stratoid basalts. About 70 percent of the monogenetic vents identified form a N05°E alignment that imitates the strike of the local faults. The basaltic lava field is delimited by oppositely dipping faults of the graben indicating a structural control on both the distribution of young volcanic products and cone alignment.

Gabilema alignment

Gabilema volcano is situated at the intersection of the NS to NNE-SSW Main Ethiopian Rift faults with NW-SE faults of the Manda-Hararo rift trend. A dense cluster of monogenetic basaltic cones marks the flanks of the volcano. A striking feature of this cluster is that it forms a 29 km long, N50°W sub-regional alignment controlled by the NW-SE faults, a certain degree of radial clustering around the volcano summit and local alignments parallel to both sets of faults. Despite the mutual intersection between the two fault sets which testifies to their activity (Acocella *et al*., 2011), the trend of the alignment possibly indicates the NW-SE faults are more active than the MER faults. Hence, the volcano marks the northern termination of the influence of the MER, WHICH gives way to the Red Sea and Gulf of Aden fault systems.

Radial cone clusters

In addition to showing preferred alignments at various scales, numerous monogenetic vents also occur as radial clusters around the summits of some major volcanoes in the rift floor. This mode of clustering occurs around the summits of silicic centres of Amoissa and Yangudi on both ends of the Dahwi-Adda-Do basin.

Most of the acidic centres of the rift floor are characterized by an early phase eruption of rhyolitic lavas and pyroclastics, which construct the edifices. Upon cooling of the underlying magma chamber, faults start to dissect the centres and emit basaltic products (Van Wyk de Vries and Merle, 1996; Lahitte *et al*., 2003; Bekele Abebe *et al*., 2007). It appears that, in the absence of important faults to tap the magma, eruptions take the form of cones on the flanks of large central volcanoes.

Cone shapes, positions and local alignments

On the local scale, the relationship between individual as well as small groups of basaltic vents and faults is delineated based on geologic field data and interpretation of aerial photographs, high resolution DEMs and satellite imageries.

Virtually the majority of monogenetic cones in the rift have clearly defined relationships to faults. Faults appear to control the locations of vents on local scales regardless of whether vent alignments develop or not. Individual vents, at times develop in the vicinity of and on any part of a fault segment (at the tip or elsewhere) or at the intersections of varying fault trends which create high-dilation, hence additional space for ascending magma. Owing to these free surface effects, cinder cones are often located adjacent to faults suggesting that the distribution of high-dilation tendency faults may indicate where future volcanoes may erupt (Connor *et al*., 2000).

Within the Ethiopian Rift, fault distribution influences the development of local vent alignments ranging in length from 1 to 10 km, each consisting of 3 to 10 cones. The orientations of local cone alignments are consistently similar to the larger scale alignments. In this scale too, the majority of cone alignments are oriented NNE-SSW consistent with the dominant fault trend in the axial rift. Other alignments mimic localized weakness zones, reactivated in the Quaternary. These include mainly NW-SE and WNW-ESE local alignments around Mega, southern Afar (northeast of Dire Dawa) and Gabilema volcano. In southern Ethiopia, the local NW-SE striking cone alignments are influenced by the Precambrian weakness bearing this orientation whereas the co-existing NNE-SSW alignments follow the MER faults. There are also NW-SE vent alignments in the central and northern MER, WHICH are related to reactivation of Pre-Quaternary structural weaknesses. In southern Afar, northeast of Dire Dawa, NW to WNW local alignments follow the regional preferred alignment which is more or less parallel to the Pre-Cambrian structural fabric on the eastern plateau and the rift margin there.

Two sets of local vent alignments are developed on the Gabilema volcano at the intersection between NNE-SSW faults of the MER with the NW-SE faults of Tendaho graben. The NW-SE alignments are parallel to the later and to the prominent sub regional scale alignment. NNE-SSW vent alignments, on the other hand, are aligned with the northern termination of the MER axial faults.

Some monogenetic vents are located at fault terminations, along fault segments on relay ramps between stepping *en échelon* faults and intersections of faults of different orientations. Not only vent positions but also cone shapes are strongly influenced by faults. Monogenetic vents, which show preferred elongation, have their longer basal diameter dominantly parallel to the local fault trend (Fig. 9). The elliptical shape of monogenetic cones might be attributed to constriction of magma as pulses of small batches of magma exert pressure to ascend through the faults.

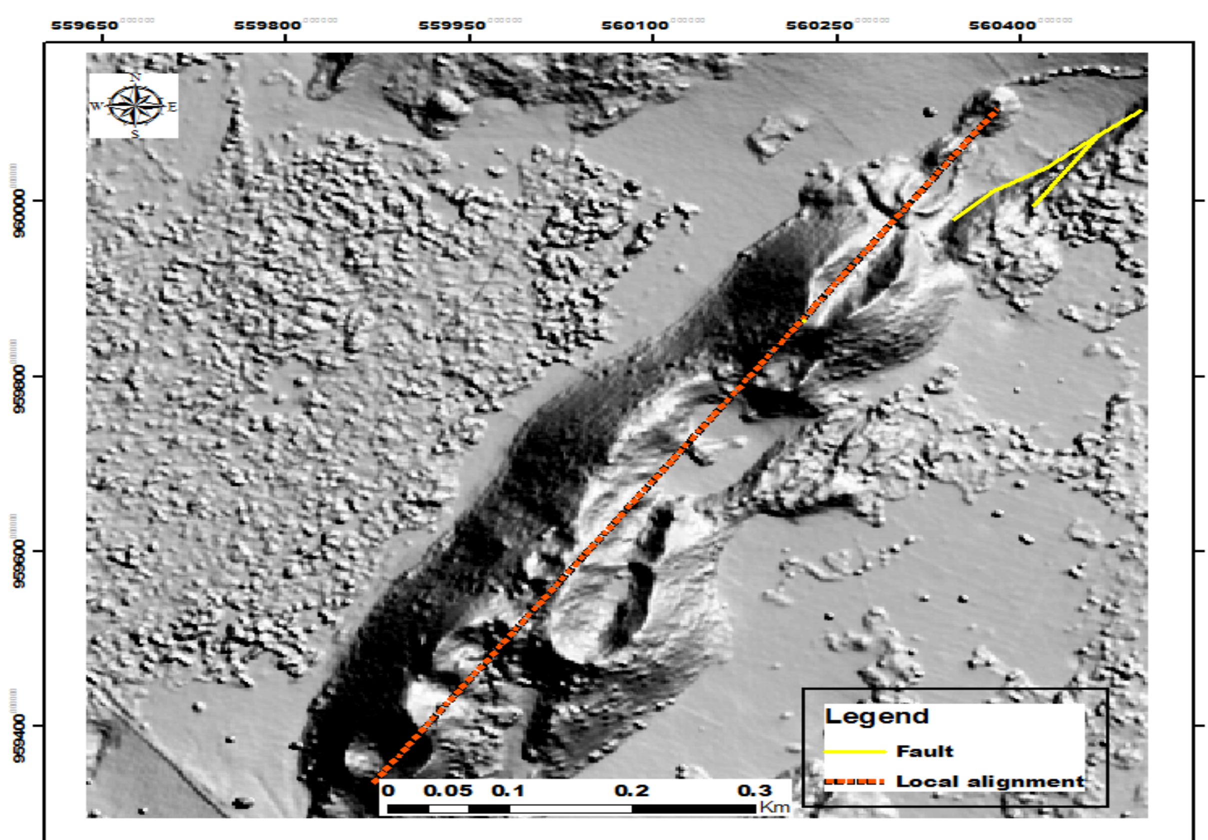


Figure 9. Local alignment of scoria cones north of Boset volcano; individual vents also show long basal diameter of vents parallel to local fault strike.

DISCUSSION

Localization of basaltic volcanism and faulting

The Quaternary geologic history of the Ethiopian Rift is marked by the abandonment of the border faults and the localization of basaltic magmatism and faulting towards the present rift axis during the Quaternary (Ebinger and Casey, 2001). This shift was accompanied by increase in the proportion of basalts and by petrological and geochemical changes in the basalts (Trua *et al*., 1999; Bekele Abebe *et al*., 2007). Along strike, variation in the volumes of extruded and intruded igneous rocks has been noted by Keir *et al*. (2015), especially in Plio-Pleistocene basalts, which increase in abundance from south to north.

Vent clustering and alignments

Geological evidences suggest that Quaternary faulting influences patterns of basaltic volcanic activity on regional, sub-regional and local scales as well as vent locations and shapes. Analysis of the distribution of faulting and basaltic volcanism in the Ethiopian Rift shows four major features characterizing Quaternary rifting. These include shifts in the locus of basaltic volcanism and faulting to the present axis, along strike variation in the volume of erupted basalts, vent clustering, and vent alignment. These features are revisited in light of the structural setting of the Quaternary volcanic fields and outlined in the preceding sections.

Mazzarini (2004) and Mazzarini *et al*. (2013) noted that vents in the Ethiopian Rift form statistically significant clusters. Remote sensing and field mapping of monogenetic vents in the Ethiopian Rift between the Kenyan border and Tendaho Graben clearly demonstrate structurally controlled clustering and vent alignments in all Quaternary volcanic fields.

At the regional level, vents are clustered within the Quaternary active rift zone and a few other off axis volcanic fields. Nine regional clusters, 46–68 km in alignment length have been identified in the entire region. Each vent cluster consists of 55–226 basaltic monogenetic cones, some of which are associated with lava aprons. Four of these regional clusters and alignments (Aluto-Gedemsa, Boset-Fantale, Dofan-Ertele and Amoissa-Yangudi clusters) lie along the rift axis in a right stepping *en échelon* arrangement. All four regional cone alignments fall within the magmatic segments and are parallel to the fault trends of the respective segment. However, the length of the alignments may be equal to or smaller than the length of the magmatic segment.

The Tepi vent cluster in the Omo-Chew Bahir rift sector is located on the western termination of the N60°E Tepi-Shebe Rift. All monogenetic vents developed on the western termination of the rift. The cone cluster which forms a 60 km long N60°E alignment takes over from the faults bounding the graben suggesting Quaternary reactivation of this rift in the form of aligned vents.

The Mega regional cluster forms a NNE-SSW striking vent alignment which is parallel to the Huri Hills cone alignment in northern Kenya. The linear arrangement of the vents is orthogonal to the prominent NW-SE structures of Anza Graben. This cone alignment possibly represents a northward propagation of the Kenyan Rift into southern MER.

The general orientation of the Mito-Butajira regional alignment is NNE-SSW and consists of two sub-regional alignments with slightly different orientations governed by the change in strike of the border faults. The cluster as well as the alignment follows the Quaternary volcanic field restricted to the marginal graben at the base of the western rift margin.

A unique vent cluster in the southern Afar margin, east of Dire Dawa forms a 55 km long regional alignment of N45°W orientation. One hundred thirty nine of the 207 vents in this part of the rift are part of the regional cluster orthogonal to the alignments of the axial rift zone. The alignment is sub-parallel to NW to NNW Precambrian structural fabric of the rift margin and basaltic dikes of Tertiary age. The E-W faults of the area, which dissect the Upper stratoid basalts, are interrupted by the obliquely oriented alignment implying post-stratoid reactivation of the northwesterly pre-Quaternary structural weaknesses.

The Dabayra alignment lies orthogonal to the local rift trend and along the strike of the transfer zone between Alayta and Dabahu-Manda Hararo rift segments. This also coincides with the zone of right step-over of the innermost faults of the western Afar margin. About 80 percent of the 209 vents form a regional alignment of N45°E strike. The cone cluster is localized in the post-stratoid volcanic field devoid of any surface faulting parallel to the vent alignment.

Twelve sub-regional preferentially aligned clusters have been identified in the study area. Among these, the Korath Range in the Omo area is possibly related to the northward propagation of the Kenyan Rift. Eight sub-regional clusters fall in four of the regional clusters and owe their existence to local change in fault orientation and branching within and close to the volcanic zones. The regional cluster consisting of the Mito and Butajira sub-regional alignments is situated in the marginal graben at the base of the western rift margin while the other three are within the axial rift. Another sub-regional alignment with high vent density is situated in the Quaternary volcanic field between Lake Abaya and Duguna volcano along one of the major fault zones which runs along the western margin. The Debre Zeit sub-regional alignment is uniquely located in an area without any exposed faults. Along strike projection of the faults to both the north and the south, pass through this Quaternary volcanic field. This suggests control of the vent emplacement and alignment by NNE-SSW oriented dikes.

The NW-SE Gabilema vent alignment is situated at the intersection between the NNE-SSW MER faults with the NW-SE Manda Hararo faults. Even though the two fault sets mutually intersect, the dominant vent alignment is controlled by the later.

CONCLUSIONS

Geologic structures control the distribution of Quaternary monogenetic vents at the regional, sub-regional and local scales. Regionally, vent clusters and alignments greater than 30 km are limited to Quaternary volcanic fields. Some of them coincide with the rift magmatic segments and the others are controlled by reactivated structures. While zones of high vent density may reflect zones of melt generation in the mantle, faults determine the locations of subsequent eruptions and cone emplacement. Sub-regional alignments, 10–30 km in length are restricted to the volcanic fields and they are dominantly controlled by the local fault trends of the rift axis and its margins. Local vent alignments with lengths of less than 10 km are controlled by faults of the same length. Individual and small groups of aligned vents lie on fault segments, intersections and bifurcations. Vents with preferred elongation show longer basal diameters parallel to local fault trends.

Vent alignments of all scales along the rift axis and the western margin are dominantly governed by NNE-SSW Quaternary faults. In the Omo-Chew Bahir and southern MER, they result from the propagation of the Kenyan Rift to the north (Fig. 10).

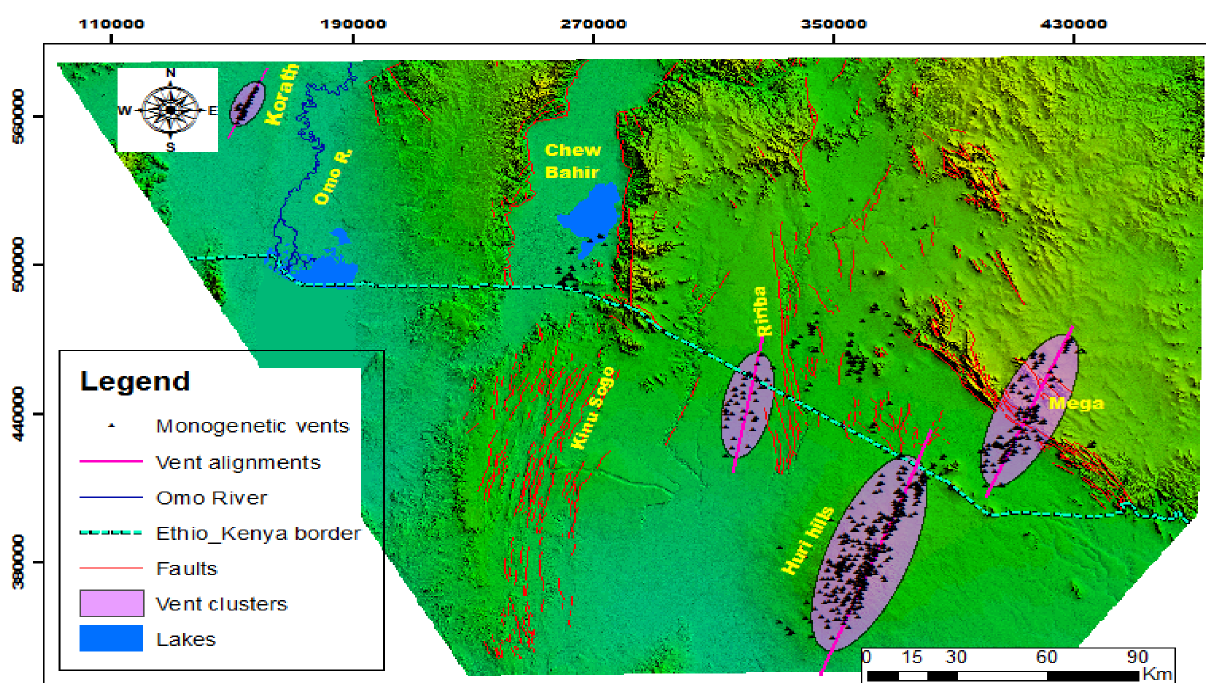


Figure 10. Monogenetic vent distribution in the Ethio-Kenyan border. The NS to NNE-SSW vent alignments show northward propagation of the Quaternary activity into the Ethiopian Rift.

In the Tepi area, vent alignments represent reactivation of the Tepi-Shebe Rift whereas in the southern Afar margin, vent alignments are due to reactivation of Precambrian weaknesses. Radial cone clusters are concentrated around the summits of a few central silicic volcanoes where faults are relatively sparse.

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