1 **FIERCE: FInding volcanic ERuptive CEnters by a grid-searching algorithm in R.**

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6 **Roberto Carniel^{1,5,*}, Silvina Guzmán^{2,3}, Marco Neri⁴**

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8 ¹ Laboratorio di misure e trattamento dei segnali, Dipartimento Politecnico di Ingegneria e
9 Architettura (DPIA) - Università di Udine, Via delle Scienze, 206 - 33100 Udine, Friuli, Italy

10 ² Instituto de Bio y Geociencias del NOA (IBIGEO), UNSa, CONICET, 9 de Julio 14, 4405,
11 Rosario de Lerma, Salta, Argentina

12 ³ Institute of Earth Sciences Jaume Almera, ICTJA-CSIC, Lluís Solé i Sabarís s/n, 08028 Barcelona,
13 Spain

14 ⁴ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Osservatorio Etneo, Piazza
15 Roma 2, 95125 Catania, Italy

16 ⁵ Geognosis Project, ITMO University, Kronverksky Prospect, 49, St, Petersburg, Russian
17 Federation

18

19

20 * Corresponding author:

21 Roberto Carniel

22 Email: roberto.carniel@uniud.it

23 Telephone: +39 0432 558749

24 Fax: +39 0432 558700

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29 **Abstract**

30 Most eruptions are fed by dikes whose spatial distribution can provide important insights into the
31 positions of possible old eruptive centers that are no longer clearly identifiable in the field. Locating
32 these centers can in turn have further applications, e.g. in hazard assessment. We propose a purely
33 geometrical algorithm - implemented as an R open-source script – named FIERCE (FInding
34 volcanic ERuptive CEnters) based on the number of intersections of dikes identified within a grid of
35 rectangular cells overlain onto a given search region. The algorithm recognizes radial distributions,
36 tangential distributions, or combinations of both. We applied FIERCE to both well-known and less-
37 studied volcanic edifices, in different tectonic settings and having different evolution histories, ages
38 and compositions. At Summer Coon volcano, FIERCE demonstrated that a radial dike distribution
39 clearly indicates the position of the central vent. On Etna, it confirmed the position of the most
40 important ancient eruptive centers and allowed us to study effects of the structural alignments and
41 topography. On Stromboli, FIERCE enabled confirmation of some published locations of older
42 vents, but also identified possible vent areas not previously suggested. It also highlighted the
43 influence of the regional structural trend and the collapse scars. FIERCE demonstrated that the
44 dikes at the Somma-Vesuvius were emplaced before formation of Mt. Somma's caldera and
45 indicated a plausible location for the old volcanic crater of Mt. Somma which is compatible with
46 previous studies. At the Vicuña Pampa Volcanic Complex, FIERCE highlights the position of two
47 different vents of a highly degraded volcano.

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50 **Keywords:** Dikes, Eruptive centers, R, grid-searching algorithm, eroded volcanoes, open source

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58 **Introduction**

59

60 Understanding magma ascent dynamics and dike distributions provides crucial information for
61 assessment of volcanic hazard. Dikes usually have radial, tangential (circumferential) or regional
62 patterns (e.g., Chadwick and Howard 1991; Takada 1997; Acocella and Neri 2009). The radial
63 patterns suggest control by a local stress field caused by the load of the edifice, an effect that
64 increases with edifice height, while tangential dikes are often related to caldera collapses (McGuire
65 and Pullen 1989; Corbi et al. 2015). Distinguishing with certainty between radial and tangential
66 dikes is generally possible only if the vent position is known. Conversely, when eroded volcanoes
67 preserve dike segments, their orientations may prove highly useful for identifying the position of its
68 central or peripheral vents. Once we identify the vent's location we can then determine which dikes
69 are radial or tangential and hence understand the morphological and structural evolution of a
70 volcanic edifice, i.e. what caused its shape (Fiske and Jackson 1972). We can also identify evidence
71 for features like sector collapses, because the orientation of the dikes may be controlled by the
72 collapse scarps (e.g. McGuire and Pullen 1989; Acocella et al. 2006a, 2013; Neri et al. 2008;
73 Battaglia et al. 2011).

74 Unfortunately, in many cases the outcrops of dikes and feeding systems are partial and insufficient
75 for researchers to identify with certainty the location of volcanic centers from which dikes
76 originated. To this end, we have created an open source software package that performs the search
77 for (possibly multiple) vent locations in a mostly automated way. This software is designed to
78 identify the location of unknown (or not visible) old eruptive centers, using only the geometric data
79 of the feeding dikes. This approach can improve, in some cases, researchers' ability to reconstruct
80 the main eruptive axis of a volcano. The script is written in *R* (R Core Team 2016), an environment
81 in which several open source scripts related to volcanology and geochemistry are already available
82 (e.g., Janoušek 2006; Janoušek et al. 2006; Rittner et al. 2012; Guzmán et al. 2014; Janoušek et al.
83 2015; Vermeesch et al. 2016). The methodology can be used to improve understanding of the

evolution of eroded volcanoes, and also for hazard assessment, as recent dikes may indicate the possible locations of future eruptions. Indeed, the propagation of dikes feeding flank eruptions in central stratovolcanoes is one of the most dangerous types of event, since the eruptive vents may rapidly shift towards lower, densely-urbanized, slopes of volcanoes.

Methodology

The algorithm starts with a polyline shapefile, exported from a GIS, that contains a set of dikes $\{d_i\}$; it is essential to know their strike, which can also be derived directly by their graphic representation. There are no limitations on the minimum set of dikes or dike segments, but obviously the more dikes we have, the more reliable the results. It is worth noting that it is not necessary to know the age or composition of the different dike segments, although we can use this information to build more-homogenous datasets to be processed separately. We describe here the basic algorithm. Details of its implementation in the open source R script named FIERCE (FInding volcanic ERuptive CEnters) together with instructions on how to install and run the program are provided in the supplementary file Online Resource 1.

We first consider a very simple case, and assume that all $\{d_i\}$ dikes are radial with respect to their unknown eruptive center. In such an ideal case, the directions of all the dikes should intersect exactly in the eruptive center for which we are searching. To find such an intersection, we need to mathematically define the direction to which each of the dike segments d_i belongs. This is uniquely determined by the coefficients m_i and q_i of a line of equation

(1)

$$y = m_i x + q_i$$

108 These coefficients m_i and q_i can be calculated by setting the requirement that the corresponding
 109 line passes through two points $x_{i,1}, y_{i,1}$ and $x_{i,2}, y_{i,2}$, which in the easiest case can be taken to be the
 110 starting and ending point of each dike respectively. This leads (e.g., Larson 2014) to the well-
 111 known solution

112

113 (2)

$$m_i = (y_{i,2} - y_{i,1}) / (x_{i,2} - x_{i,1})$$

$$q_i = -x_{i,1} m_i + y_{i,1}$$

114

115 Once this procedure is carried out for each available dike, in the ideal case of all-perfectly-radial
 116 dikes we would just need to find mathematically (i.e. analytically) the intersection of these lines.
 117 Any pair of them would thus lead to exactly the same solution for the unknown eruptive center.
 118 With real data however, we have to look for a smarter, numerical solution, using a grid search
 119 approach. We define a search area in which the unknown eruptive center should reasonably be
 120 expected to lie. This, as we will see in detail, can be set slightly bigger than the area in which the
 121 dikes were recognized in the field.

122 We now divide it into a grid of sufficiently small rectangular elements and count how many of the
 123 direction lines we computed from the dike set pass through each of these grid elements. The
 124 element with the highest number of intersections will be our solution, i.e., will be the most probable
 125 location for the unknown eruptive center. Although this is the basic idea at the core of the FIERCE
 126 approach, some technical details enable fine-tuning and optimizing the results. One of these is the
 127 recognition that, as the dikes observed in the field are not perfectly radial, we should introduce
 128 some tolerance in determining the intersection between each dike direction and the elements of the
 129 grid. In practice, this means substituting the requirement that a line passes “through” a grid element
 130 with the more relaxed requirement that the distance of such a line from the center of the grid
 131 element is less than a given threshold. The threshold is expressed in the same unit as the coordinates

132 in the shapefile (typically meters, as in all the examples presented in this paper). The higher the
133 threshold, then the less strict the “radialness” requirement of each dike. The formula we need here is
134 the well-known “point-to-line distance” formula (e.g. Larson 2014):

135
136 (3)

$$137 \quad D = |y_0 - m_k x_0 - q_k| / \sqrt{1 + m_k^2}$$

138
139 Each time D is $< \text{Threshold}$ we assign a “hit” to the grid element, and increase its hit count by one.
140 In order to graphically present the results in a way that makes them independent of the number of
141 dike segments and - at least roughly - comparable between different datasets, we chose to normalize
142 the number of intersections (the hit count) by the maximum number of hits that any cell of the grid
143 gets. In this way, the results are expressed by an adimensional parameter ξ that can take values
144 between 0 (no intersections) to 1 (maximum number of intersections over the entire grid). The
145 graphical representation of the space distribution of this parameter can be further enhanced by the
146 choice of the color scale in a GIS, as shown in the examples below.

147 The hypothesis that we took for granted until now, namely that all the dikes are radial, is an ideal
148 premise. In reality, some dikes belong to the class of tangential dikes. If we use these dikes in the
149 previously described grid counting algorithm, these will actually do no harm, as their directions,
150 even if erroneously assumed as radial with respect to the eruptive center, basically become random,
151 i.e., will not contribute systematically to the appearance of a wrong solution in the grid. However,
152 instead of leaving them “neutral”, can we draw any information from these that actually help
153 determine the eruptive center? Indeed we can: if a dike is tangential, any section of it observed in
154 the field can be approximated by the line joining its ends. This line must be tangential to an
155 imaginary circle surrounding the eruptive center. We can then “draw” a perpendicular line that
156 passes through the midpoint (x_{c_i}, y_{c_i}) of this line. This line will have the following coefficients:

157

158 (4)

$$m_{i1} = -1/m_i$$

$$q_{i1} = (1/m_i) * xc_i + yc_i$$

159

160 The line will be now radial with respect to the eruptive center. We can therefore use it to determine
161 its direction, and use it to increase the numbers in the grid, exactly as before.

162 The third kind of dike belongs neither to the radial nor the tangential class, e.g., dikes whose
163 direction is determined mainly by the regional stress distribution. Although these cannot provide
164 information about the location of the eruptive center, within reason they will not bring about any
165 radial convergence to a wrong solution, therefore remaining completely “neutral” in the competition
166 between the different elements of the grid where we count the intersections. So, the important point
167 here is that we do not need to remove them manually from the dike dataset before executing the
168 software.

169 In the following, we present and discuss the application of the FIERCE software to different
170 volcanoes.

171

172 **Application examples**

173

174 **A case of regular radial dike pattern: Summer Coon**

175

176 Summer Coon is an eroded Oligocene, basaltic andesite to rhyolite, stratovolcano in southern
177 Colorado, USA (Lipman 1968). The cone has a basal diameter of 14 km, a summit elevation of
178 4,200 m and an average flank slope of 17° (Moats 1990). Poland et al. (2008) mapped 20 silicic
179 dikes that reach up to about 7 km in length and are formed by various offset segments. The dikes of
180 this volcano are almost perfectly radial, and they thicken with increasing radial distance. Offset
181 segments and fingers form along the upper peripheries of the intrusions. These dikes are interpreted

182 as feeding flank eruptions, but their radial distribution provides information about the location of
183 the main vent of the volcano (Poland et al. 2008).

184

185 The results of the execution of the FIERCE software to this dataset highlight that the dikes are
186 mostly radial. The solution obtained assuming that all the dikes are radial is shown in Fig. 1a in the
187 form generated directly by FIERCE within the R environment. This allows the user to test different
188 values of the parameters and quickly evaluate the results, without the complication of first
189 importing the output into a GIS program. The solution shown in Fig. 1a is in this case obviously the
190 correct one. However, it is noteworthy that the solution obtained by considering both the radial and
191 tangential dikes (see Fig. 1b) clearly also shows the central vent, although some spurious solutions
192 appear, but with considerably lower reliability (number of intersections). On the contrary, the
193 assumption that all the dikes are tangential does not lead to any reasonable solution - i.e.,
194 concentrated close to a single point - for the volcanic vent (see Fig. 1c).

195

196 **A more irregular radial dike pattern: Etna**

197

198 Etna stratovolcano, situated on the East coast of Sicily, is Europe's largest and most active volcano.
199 It has been active since the Middle Pleistocene and covers an area of ~1,250 km². Some 0.8 million
200 people live on or immediately adjacent to the volcanic edifice (Behncke et al. 2005). Massive debris
201 flows, associated with the formation of a large (4 x 6 km) and deep (up to 1 km) erosional
202 depression, the Valle del Bove (VdB in Fig. 2), occurred between ~15-4 ka (Coltelli et al. 1994).
203 This morphological depression is situated high on the eastern slope of the volcano and its scarps
204 show the relicts of ancient (up to ~110 ka) volcanic rocks. The present volcanic edifice, reaching a
205 height of ~3,330 m in 2010 (Behncke et al. 2016), has arisen from a succession of central
206 apparatuses and associated flank eruptions from parasitic cones roughly during the last 200 ka
207 (Corsaro et al. 2002; Branca et al. 2015).

208 The products and, in some cases, the general shape and the presumed position of the central vent of
209 the succession of these ancient volcanoes can be recognized along the VdB sides (Coltelli et al.
210 1994; Calvari et al. 1994, 2004; Branca et al. 2015). From East to West, they are: the Rocche
211 Centers (R in Fig. 2, which reached a maximum height of ~1,800 m, 110-101 ka); the Trifoglietto
212 Center (T, ~2,400 m, 107-99 ka); the Salifizio - Serra Giannicola Grande - Cuvigghiuni Centers
213 (~2,700 m, 85-65 ka, indicated as S-SG-C in Fig. 2, respectively); the Ellittico Center (E, ~3,800 m,
214 65-15 ka) and, finally, the present Mongibello (~3,330 m, < 15 ka). The Ellittico and Mongibello
215 volcanoes have the same central eruptive conduit.

216 A significant characteristic of the current magmatism is the prevalent lateral movement of magma
217 radially from the central conduit zone of the volcano along a distinctive series of rifts, aligned
218 broadly towards the NE, S, and W away from the summit area (Garduño et al. 1997; Neri et al.
219 2011; Cappello et al. 2012; Giammanco et al. 2016; Fig. 2a). They are fed by steeply dipping dike
220 systems. Exposures of these dikes, particularly in the walls of the Valle del Bove, display sub-
221 horizontal flow direction indicators consistent with radial movement of magma (Garduño et al.
222 1997; Acocella et al. 2009; Geshi and Neri 2014; Falsaperla and Neri 2015); in a few cases the
223 dikes are originated by plugs, corresponding to the conduits of the ancient eruptive centers (Ferrari
224 et al. 1991; Calvari et al. 1994).

225 At first we considered a total of 214 radial dike segments without distinguishing their relative ages,
226 but varying the threshold (see Methodology section) from 100 to 1,000 m (see Figure 2b-i). The
227 images are produced here by importing the FIERCE results in ENVI format into a QGIS project
228 (QGIS Development Team 2016). The main results highlight four main structural alignments,
229 oriented NW-SE, N-S, E-W, and NE-SW, respectively. These correspond to the main structural
230 alignments active today at Etna, frequently used by lateral dike intrusions during flank eruptions
231 (Neri et al. 2011). The supposed position of the previous volcanic centers (white circles in Fig. 2b-f)
232 are along these main axes. However, some of these centers are not located in the zones colored in
233 red-purple, i.e., the zones highlighting the major dike direction intersection. In detail, the positions

234 of Cuvigghiuni (C) and Serra Giannicola Grande (SG) are well centered in all the frames. The
235 Ellittico (E) is nearly centered for threshold of 500-1000 m (frames e-f in Fig. 2). Trifoglietto (T)
236 and Salifizio (S) appear slightly off center in almost every frame, even if they fall along the NW-SE
237 alignment. Finally, the Rocche centers (R) are not highlighted in any frame.

238 239 **Effect of structural regional trend and sector collapses: Stromboli**

240
241 The Aeolian Volcanic Arc (AVA) is made up of six islands and several seamounts located in the
242 southern Tyrrhenian basin, in Italy. The islands of Panarea and Stromboli are located at the eastern
243 margin of the AVA, which is aligned NE-SW. At Stromboli, the regional NNW-SSE extension
244 direction is dominant and is manifested by the NE-SW and E-W alignments of several morpho-
245 structural elements, i.e., summit vents, dikes, faults, and eruptive fractures (Pasquare` et al. 1993;
246 Tibaldi 2001; Acocella et al. 2006a; Tibaldi et al. 2009).

247 Today, Stromboli is characterized by a continuous strombolian activity, occasionally interrupted by
248 paroxysmal events (Jaquet and Carniel 2003). Morphologically, the most visible present-day feature
249 is the Sciara del Fuoco (SdF, ~5 ka old; Tibaldi 2001), a deep depression opened in the NW flank,
250 both above and below the sea level. But the history of the volcano is characterized by previous
251 several collapses that occurred in the last 13 ka (Tibaldi 2001; Tibaldi et al. 2009), often concurrent
252 with changes in the magma composition from calc-alkaline to potassic series, through high-K calc-
253 alkaline and shoshonitic ones (Francalanci et al. 1993).

254 On the basis of stratigraphic and morpho-structural unconformities and rock composition, the
255 volcanic succession of Stromboli has been divided into six major periods of activity, represented by
256 their lithosomes: Paleostromboli I (85-67 ka), Paleostromboli II (67-56 ka), Paleostromboli III (56-
257 26 ka), Vancori (16-13 ka), Neostromboli (13-5 ka), and Recent Stromboli (Pizzo lithosome and
258 present day activity; <5 ka) (Corazzato et al. 2008; Lucchi et al. 2013, and references therein). In

259 this article, we considered the position of the main vents of these ancient apparatuses as indicated in
 260 the Geological Map of Stromboli (Lucchi et al. 2013) and in Tibaldi et al. (2009).
 261 We have conducted different analyses using geometrical distributions of dikes previously published
 262 in the literature. In particular, we selected the geological map of Lucchi et al. (2013) and the data
 263 presented by Tibaldi et al. (2014). We built different dike datasets in the required shapefile format
 264 from both above mentioned papers. For comparison, we also included the position of the old vents
 265 inferred by Tibaldi et al. (2014) and separated the dikes from Lucchi et al. (2013) into different
 266 groups according to the different eruptive epochs suggested by the same authors. For the active
 267 crater zone we used an area, including all active vents, following results in both Lucchi et al. (2013)
 268 and Tibaldi et al. (2014). In Fig. 3 we present selected results from all the analyses made with
 269 FIERCE. Using all dikes of Tibaldi et al. (2014), we obtained the results presented in Fig. 3a. We
 270 interpret that these results highlight the NE-SW structural regional trend that characterizes this part
 271 of the Aeolian volcanic arc. In addition, at the NW part of the island, in coincidence with the Sciara
 272 del Fuoco, a marked WNW-ESE alignment is also evidenced, together with a less evident trend,
 273 approximately N-S. We interpret that the deviation of dikes from radially can be attributed to the
 274 presence of the Sciara del Fuoco scar, whose buried part acts as a barrier for dikes that reach very
 275 shallow depths (0-200 m), deviating them (Acocella and Neri 2003 and references therein). Most of
 276 the craters of the same age or younger than the eruptive epoch 3 proposed by Lucchi et al. (2013),
 277 i.e., ≤ 56 ka, as well as the active Stromboli craters, also lie on this NE-SW regional alignment.
 278 Only the older centers are not evidenced by this global analysis; this may be simply related to the
 279 relatively small number of older dikes available in comparison with the younger ones, as the older
 280 ones may be buried under younger units.
 281 Results using dikes derived from the Lucchi et al. (2013) map (Fig. 3b) are slightly different from
 282 the ones obtained using the Tibaldi et al. (2014) ones, even adopting the same 100 m threshold for
 283 both models. This gives an idea on the dependence of the results on the relatively small differences
 284 not only in the number of dikes segments ($n=94$ for Lucchi et al. 2013 and $n=105$ for Tibaldi et al.

285 2014), but especially in their geometrical distributions. The model based on Lucchi et al. (2013)
286 also shows the influence of the Sciara del Fuoco and the NE-SW structural trend, but the most
287 probable areas suggested by FIERCE for the location of the vents are concentrated in the SW part
288 of the island. These results might again be related to the smaller number of dikes located on the
289 eastern side of the volcano in the map of Lucchi et al. (2013), but we believe that this difference is
290 in fact dependent on the different dike orientations with respect to the map of Tibaldi et al. (2014).
291 We conducted additional analyses with the aim of trying to identify the position of the vents related
292 to the different volcanic epochs proposed by Lucchi et al. (2013). To carry out this investigation, we
293 therefore separated the dikes dataset of Lucchi et al. (2013) in different groups in relation to the
294 youngest volcanic units they intrude, in order to have a constraint on their possible relative age. The
295 reasoning here, which is evidently a simplification and just one possibility among many others - see
296 for instance the detailed studies by Corazzato et al. (2008) - is that dikes intruding a unit of age A
297 are younger than A and hence may indicate the position of coeval or younger volcanic vents. In
298 Figure 3c, we used only dikes intruding the lithosomes Paleostromboli I and Paleostromboli II, i.e.,
299 volcanic epochs 1 and 2. Finally, in Fig. 3d we show the results using all dikes by Lucchi et al.
300 (2013) which intrude the lithosomes of Paleostromboli III and younger ones (i.e., from volcanic
301 epoch 3 onwards).

302

303 **Reconstructing the position of the crater of a previous volcanic edifice: Vesuvius**

304

305 The Somma-Vesuvius (SV) volcanic complex, in Italy, is an active stratovolcano ~1,250 m high,
306 lying between NE-SW and NW-SE regional fault systems (Bruno et al. 1999 and references
307 therein). During the last ~30 ka, the SV erupted silica undersaturated and potassic basic products
308 (Scandone et al. 1993; Santacroce and Sbrana 2003). Vesuvius is the most recent volcano, active
309 during the last 2 ka. To the North, Vesuvius is bordered by the remnants of the Mt. Somma edifice
310 (~30-18 ka), which forms a scarp derived by a multi-stage caldera developed between ~18 ka and

311 79 AD; the scarp exposes a hundred dikes that are coeval with the Somma edifice and consequently
312 these dikes may not be representative of the present day feeding system of the Vesuvius cone (Cioni
313 et al. 1999; Acocella et al. 2006b; Porreca et al. 2006). The most recent activity occurred in 1944
314 (Cioni et al. 1999).

315 The dikes are all concentrated in the actual collapse scarp of Mt. Somma, to the north of the
316 Vesuvius active crater (Porreca et al. 2006). The absence of other dikes is probably the result of
317 their disappearance due to the collapse and/or to the burial under younger deposits.

318 We have carried out some analyses with FIERCE. The results are summarized in Fig. 4: in a first
319 case, dikes are forced to be interpreted as tangential (Fig. 4a); in the second case, we assumed that
320 all dikes are radial (See Fig. 4b). In this case, our analyses demonstrate that the dikes were
321 emplaced before the formation of the Mt. Somma's caldera.

322

323 **Recognizing vents in an intensely degraded volcano: Vicuña Pampa Volcanic Complex**

324

325 We now analyze the case of the Vicuña Pampa Volcanic Complex (VPVC), located at the SE
326 margin of the Altiplano-Puna plateau, in Argentina, for which we present some original data. The
327 VPVC was recently interpreted as a complex massif that underwent intense degradational processes
328 giving rise to a large (18 x 13 km) morphological depression (Guzmán et al. 2017). The VPVC is a
329 Middle Miocene volcano, formed by plugs and necks, lava flows, block and ash flow deposits and
330 ballistic fall-out tephra, whose composition mainly ranges from basaltic andesite to andesite.
331 Guzmán et al. (2017) interpreted that the VPVC had at least two stages of evolution separated by a
332 considerable time (enough for the erosion of the central depression). During the construction of the
333 VPVC, there were also multiple episodes of dike intrusions that today are mostly exposed at the
334 central and western parts of the eroded volcano (Fig. 5a).

335 Vertical and inclined sheets are seen all over the complex, but the densest concentration is
336 recognized in the western portion of the depression. We measured strike, dip and thickness of 33

dike segments. These are mostly vertical dikes, while moderate to low angle ($<60^\circ$) inclined sheets are less common. Dikes intrude different volcanic sequences of the VPVC, some being feeder dikes of small lava flows. Several intrusion episodes occurred during the construction of the main volcanic edifice and after the formation of the central depression (Guzmán et al. 2017). The orientation of the measured dikes intruding the younger deposits within VPVC is highly variable, with the maximum concentration striking N $351\text{--}360^\circ$ and dipping between 35° and 90° . Measured dikes intruding the older sequences, mainly located at the central western part of the depression, show main strikes varying from N $51\text{--}60^\circ$ and their dip varies between 62° and 90° . In the program, only the strike of the dikes segments is used for calculations.

We mapped all visible dikes from Landsat TM 7 satellite images, distinguishing the ones that intrude the units deposited previous to the formation of the central depression, i.e., <12 Ma (Fig. 5b), from those that intrude the interpreted younger deposits (Fig. 5c), i.e., those that were formed after the development of the central depression, of unknown age, possibly Late Miocene. We obtained a final set of more than 400 mapped dike segments.

We first analyzed all dikes (without distinguishing their relative ages) together. After choosing different thresholds, the results highlight two different areas that are shown for a threshold=500 m in Fig. 5a. The areas in red are to be considered the zones where most intersections are found. So, one zone coincides with the position of the interpreted roots of the eroded volcanic massif, and a second one may highlight the position of the center responsible for the post-erosional renewed volcanic event.

357

358 **Discussion**

359 The application of the FIERCE software to several case studies, corresponding to quite different
360 volcanic scenarios, allowed us first to verify - in simple and well-known cases - that the
361 implementation of the idea at the root of the method leads to results compatible to those previously
362 published. We therefore started with a case of very regular radial dike pattern, i.e. **Summer Coon**

363 volcano. Here the software provided solutions completely in line with what is expected when
364 assuming that all the dikes are radial (see Fig. 1a). Moreover, the flexibility of the software was
365 highlighted by the fact that the central conduit is clearly visible also if we assume that dikes could
366 be radial or tangential (see Fig. 1b). The hypothesis that all the dikes are tangential is also clearly
367 rejected by the lack of significative results provided by the software (see Fig. 1c).

368 Being confident of the capabilities of the software, we then proceeded with the analysis of non
369 trivial cases, the first of which is **Etna**. The results, shown in Fig. 2, may arise from various factors:

370 1) The most marked alignment is NW-SE, extending from the summit to the southern edge of
371 the VdB. The main eruptive axes of Ellittico (frames e-f in Fig. 2), Serra Giannicola Grande,
372 Trifoglietto and Salifizio (all frames in Fig. 2) are located along this alignment. This means that this
373 structural setting may have been constant during the last 85 ka. Further along this alignment, the
374 most recent summit cone, named New Southeast Crater, is growing (Acocella et al. 2016).

375 2) The N-S structural alignment is also well marked. It is located along the W side of the VdB
376 and may reflect the morphological conditioning exerted by the VdB depression on the younger
377 dikes (<15 ka). However, this alignment may also reflect an ancient (65-15 ka) morpho-structural
378 arrangement, i.e., the period when Ellittico overlapped the previous eruptive centers (Serra
379 Giannicola Grande, Cuvigghiuni, Trifoglietto and Salifizio; Coltelli et al. 1994).

380 3) The E-W alignment is evident between the summit area and the N side of the VdB. Many
381 dikes and some historical eruptive fissures follow this trend along the escarpment, but change
382 direction just over the edge of the valley, heading towards NE (Neri et al. 2011). This suggests a
383 strong morphological control exerted by topography.

384 4) An exception is the group of dikes located on the NE sector of the VdB. These dikes have
385 fed small volcanic centers dating back to ~100 ka (Coltelli et al. 1994). In this case, probably, the
386 small number of dikes does not allow the FIERCE software to locate the position of the main vents
387 of these centers.

388 Finally, we analyzed the possibility that the 214 dikes are either radial or tangential. The solutions
389 obtained for threshold values of 300, 500 and 1,000 m (Fig. 2g-i), respectively, correctly identified
390 the position of Trifoglietto and Salifizio (frame i) and Serra Giannicola Grande and Cuvigghiuni
391 (frames g-i), but they fail in the case of Ellittico and Rocche centers. This confirms that the dikes at
392 Etna are mainly radial, but the sector collapse affecting its eastern flank may have driven the
393 propagation of several dikes too.

394 The FIERCE application, therefore, is useful in confirming the position of the most important
395 ancient eruptive centers (T, SG, C), failing only in the case of the Ellittico (E) and Rocche (R)
396 centers, in the second case perhaps because of the small number of dikes, or of the fact that there
397 were several small centers (probably three, according to Coltelli et al. 1994), distributed in a not
398 well-defined area.

399 In the case of **Stromboli**, it is interesting in particular to discuss the results obtained by separating
400 the dikes dataset of Lucchi et al. (2013) in different groups according to their possible relative age.

401 In Fig. 3c, results are shown obtained using only dikes intruding the lithosomes Paleostromboli I
402 and Paleostromboli II, i.e., volcanic epochs 1 and 2. Following our reasoning, these may indicate
403 the position of craters of volcanic epochs 2 and 3 or, if we consider the results of Corazzato et al.
404 (2008) in terms of relative age of dikes (they found in almost all cases that compositions of dikes
405 are similar to the units they intrude, hence of similar age) this may indicate the position of craters
406 from epochs 1 and 2 of Lucchi et al. (2013). Our model matches only the interpreted position of
407 volcanic epoch 3 by Lucchi et al. (2013) and highlights two other possible vent areas that may point
408 to older vents. The divergence in the position of the older vents may once again be related to the
409 small amount of dikes, given their burial by younger deposits, or may effectively indicate the
410 position of those older vents. One interesting point to mention here is that even using only the older
411 dikes, the NE-SW structural regional alignment is already evidenced by that time.

412 The results obtained using dikes intruding the lithosomes of Paleostromboli III and younger ones
413 are shown in Fig. 3d. These still show how the dikes distribution are strongly influenced by the

414 geomorphological presence of the Sciara del Fuoco and by the regional structural trend evidenced
415 by the alignment of both the craters of volcanic epoch 3 and the active ones.

416 In the case of **Vesuvius**, our analyses with FIERCE demonstrate that the dikes were emplaced
417 before the formation of the Mt. Somma's caldera. In fact, if dikes are forced to be interpreted as
418 tangential, they highlight a hypothetical eruptive center located along the scarp of Mt. Somma (Fig.
419 4a), but no evidence of this eruptive center (i.e., necks, plugs and related volcanic products) crops
420 out there (Porreca et al. 2006). On the other hand, building other models with higher threshold
421 values (see Fig. 4b) and assuming the opposite hypothesis, i.e., that all the dikes are radial, the
422 location of a possible ancient main conduit clearly emerges. This model may indicate a plausible
423 location of the old volcanic crater of Mt. Somma, presumably located below the northern portion of
424 the Vesuvius cone. This result is compatible with the geometry of the Mt. Somma caldera rim, both
425 considering its northern part, which is still visible today, and its southern part, that is now buried by
426 younger volcanics. These results provide independent confirmation of previous studies based on
427 morphological survey (Santacroce 1987).

428 The case of **Vicuña Pampa Volcanic Complex** demonstrates well that the FIERCE software is
429 flexible enough to be able to process all dikes together without needing to "assign" them
430 beforehand to specific age- or vent- related subsets. The software can then process selected subsets
431 of the dataset in more detail if needed. Therefore, we applied FIERCE (not shown) separately for
432 dikes intruding the older volcanic sequence. In this case, with the same threshold=500 m, the
433 solution using radial dikes highlights only the older volcanic conduit (the northernmost in Fig. 5a),
434 which appears slightly enlarged or points to the existence of two neighboring vents. On the other
435 hand, when analyzing only dikes intruding the younger sequence we find that with different
436 thresholds (=150; 300; 500 and 700 m) the radial dikes indicate the presence of two possible vents,
437 while tangential and radial dikes together indicate two vents with small thresholds but a single
438 larger one with a threshold=700 m.

439

Conclusions

In this paper we present a new software package for automated detection of the possible position of the eruptive center related to a set of dikes. We also present a series of case studies in which the software is applied to different volcanoes. The software can be freely requested from the authors and, being open source, can not only be used to analyze other case studies, but also easily modified and improved. The software distribution file includes the shapefiles required to reproduce the examples illustrated in this paper, as described in Online Resource 1.

One of the advantages of the software is that more than one eruptive center can be determined at once. This implies that there is no strict need to separate a big dataset of dikes into subsets that are relatively homogeneous with respect to age, origin or location. On the contrary, this separation can be carried out *a posteriori* based on the first results from processing the full dataset. Alternatively, in well-studied volcanoes such as Stromboli, the knowledge of at least the relative age of dikes can be used for additional analyses of the different subsets.

In addition, the software enables researchers to obtain three output results separately, namely the best fit of intersections considering dikes to be all radial, considering all tangential or considering either of the two together. The use of these outputs separately may help the researcher better characterize the role of shallow magma transfer in collapse events. It is well known that tangential dikes are frequent along the sides of a number of calderas, in combination with radial dikes on the lower flanks of the volcanoes (Acocella and Neri 2009 and references therein). The presence of such a combination of tangential and radial dikes may be related to the presence of a shallow magma reservoir (Chadwick and Dieterich 1995) or of a caldera depression (Corbi et al. 2015).

Tangential dikes may also be observed at summit calderas or at volcanoes that underwent a sector collapse (e.g., McGuire and Pullen 1989; Fiske and Jackson 1972; Acocella and Tibaldi 2005). At Vesuvius, however, our analyses with FIERCE demonstrate that the dikes were emplaced before the formation of Mt. Somma's caldera. Also in the case of Stromboli, using only radial dikes for

466 modeling, the collapse scar of Sciara del Fuoco had an evident impact on dike orientations, whereas
 467 tangential dike tests were not useful for locating its ancient volcanic centers.

468 The FIERCE software may contribute to interpreting the stress conditions that acted during
 469 evolution of a volcanic edifice. A very good example of this is evident at Stromboli, where in all the
 470 models the NE-SW structural regional trend of the Aeolian Volcanic Arc is observed.

471 One limitation is the fact that in some cases the input shapefile can contain many different segments
 472 of the same dike. This could theoretically make the direction of that dike (and all the cells that this
 473 direction goes through) “weight” more than the direction of a well-exposed dike that counts as only
 474 one segment. Although this problem never arose in our examples, we advise paying attention to this
 475 possible bias in the results.

476 The results can be examined directly within the FIERCE software (Fig. 1), which is especially
 477 useful in the preliminary stages to modify the different parameters in order to find the best ones, but
 478 it is highly recommended to export and plot the final results using an external GIS program (Fig. 2,
 479 3, 4 and 5). Here, particular attention is needed on the choice of graphical normalization and color
 480 schemes, as this can be very important for highlighting the possible vents in the best way.

481 Although the software in its current version is based on a purely geometrical 2D description of the
 482 dike datasets, the results are already satisfactory. Future versions of the software will go in the
 483 direction of including the effect of the regional stress field and the topography.

484

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637

639 **Figure captions:**

640

641 **Fig. 1** Example of application of FIERCE to Summer Coon volcano's dike dataset. All the images
642 are generated inside R, without the need of a GIS program. (a) Output of the procedure under the
643 hypothesis that all the dikes are radial. (b) Output of the procedure under the hypothesis that the
644 dikes can be radial or tangential. (c) Output of the procedure under the hypothesis that all the dikes
645 are tangential. Threshold is fixed at 500 m for all the images shown. ξ : Likelihood of vent location
646 (see text for details). Coordinate system: WGS84/UTM Zone 13 N [EPSG: 32613]

647 **Fig. 2** Example of application of FIERCE to Etna volcano's dike dataset. a) Outcrops of dikes along
648 the Valle del Bove (VdB) walls, and presumed position of the central conduit feeding the previous
649 eruptive centers (from Rust and Neri, 1996): R = Rocche Centers, T = Trifoglietto Center, SG =
650 Serra Giannicola Grande Center, C = Cuvigghiuni Center, S = Salifizio Center, E = Ellittico Center.
651 The present-day central conduit is the same as that of the Ellittico Center. The Digital Elevation
652 Model (Bisson et al. 2016) also highlights the position of the rift zones. b-f) Application of FIERCE
653 considering radial dikes as radial only and varying the threshold from 100 m to 1000 m. g-i)
654 Application of FIERCE considering dikes as radial and tangential and varying the threshold from
655 300 m to 1000 m. ξ : Likelihood of vent location (see text for details). Coordinate system:
656 WGS84/UTM Zone 33 N [EPSG: 32633]

657 **Fig. 3** Example of application of FIERCE to Stromboli volcano; results are superimposed on a
658 Digital Elevation Model. Orange continuous line: Volcanic epochs 1, 2 and 3 craters interpreted by
659 Lucchi et al. (2013); Orange dashed-lines (old craters interpreted by Tibaldi et al. 2014), black
660 continuous lines: Volcanic epochs 4, 5a and 5b,c craters interpreted by Lucchi et al. (2013); violet
661 continuous line: area of active craters (Lucchi et al. 2013; Tibaldi et al. 2014). ξ : Likelihood of vent
662 location (see text for details). Coordinate system: Monte Mario/Italy zone 2 [EPSG: 3004]

663

664 **Fig. 4** Example of application of FIERCE to Vesuvius volcano; results are superimposed on a
665 Digital Elevation Model. a) Tangential dikes, b) Radial dikes. ξ : Likelihood of vent location (see
666 text for details). Coordinate system:

667 Monte Mario/Italy zone 2 [EPSG: 3004]

668 **Fig. 5** a) Example of application of FIERCE to the dataset of dikes in the Vicuña Pampa Volcanic
669 Complex (VPVC). Results were imported as an ENVI file into QGIS and superimposed on a
670 simplified geological map of the VPVC (detailed map in Guzmán et al. 2017). The solution
671 presented here shows the result of intersections assuming radial dikes only, considering all the dikes
672 that intrude the VPVC. With a 500 m threshold the resulting solution highlights the position of two
673 possible conduits. The more central one is interpreted as the one that formed the first volcanic cycle,
674 while the second, southernmost one, indicates the position of the conduit of the second volcanic
675 cycle. Coordinate system: WGS84/UTM Zone 19 S [EPSG: 32719], b) Rose diagram of dikes
676 intruding the first volcanic cycle rock units, c) Rose diagram of dikes intruding the second volcanic
677 cycle rock units.

678

679

680 Online Resources Captions:

681 Online Resource 1 - Details about the FIERCE software.

Figure 1

[Click here to download Figure Carniel et al Fig 2.jpg](#)

Figure 3

[Click here to download Figure Carniel et al Fig 3.jpg](#)

Figure 4

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Online Resource 1 of paper:

Title: “FIERCE: FInding volcanic ERuptive Centers by a grid-searching algorithm in R”

Journal: Bulletin of Volcanology

Authors: Roberto Carniel^{1,5,*}, Silvina Guzmán^{2,3}, Marco Neri⁴

¹ Laboratorio di misure e trattamento dei segnali, Dipartimento Politecnico di Ingegneria e Architettura (DPIA) - Università di Udine, Via delle Scienze, 206 - 33100 Udine, Friuli, Italy

² Instituto de Bio y Geociencias del NOA (IBIGEO), UNSa, CONICET, 9 de Julio 14, 4405, Rosario de Lerma, Salta, Argentina

³ Instituto de Ciencias de la Tierra “Jaume Almera”, CSIC, Sole i Sabaris s/n, 08028, Barcelona, Spain

⁴ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Osservatorio Etneo, Piazza Roma 2, 95125 Catania, Italy

⁵ Geognosis Project, ITMO University, Kronverksky Prospect, 49, St, Petersburg, Russian Federation

* Corresponding author:

Roberto Carniel

Email: roberto.carniel@uniud.it

Telephone: +39 0432 558749

Fax: +39 0432 558700

Online Resource Title: Details about the FIERCE software

1. Program requirements

The FIERCE software can run under Windows or Linux operating systems and requires the previous installation of the free R environment (R Core Team 2016). The availability of a GIS program like QGIS (QGIS Development Team 2016) is not required but strongly suggested to prepare the input files and better visualize the output files.

2. Program installation and execution

A copy of the software FIERCE (FInd ERuptive Centres) can be obtained by sending a request via email, with intended use, to the corresponding author.

The software consists of three scripts (FIERCE_Install_Packages.R, FIERCE_Main.R and FIERCE_Input_Data.R) all of which must be copied to the same directory of choice (e.g. C:\FIERCE under Windows, or /home/username/FIERCE under Linux).

This software runs within the free R program environment (R Core Team 2016), which must be installed first, if not already available on the system. Although input and output files can be exported/imported from a GIS program, this is not needed to run the R scripts presented here.

In order to install R, installation files can be freely downloaded from any of the CRAN mirrors (<http://cran.r-project.org/mirrors.html>). Supported operating systems are Linux, Mac OS X and Windows. R is also available as part of many Linux distributions, so the user should first check its availability within their distribution software manager, and download it from CRAN only if not available there.

Once R is installed, it must be executed. This is done in Linux by giving the command R in a terminal window, in Windows by clicking the corresponding program icon on the desktop. In Windows it is suggested to modify the properties of the icon in order to start the program from the same directory where the FIERCE scripts have been copied (e.g. C:\FIERCE). Similarly, in Linux, the user should change the current directory to that directory before executing R. Once R is executed, the R prompt is obtained:

>

The next step is to install the R packages that are needed to run the FIERCE program. This can be done executing the first script provided.

```
> source('FIERCE_Install_Packages.R')
```

If no package has been installed before in the same session, R asks to choose the preferred (closest and/or fastest) CRAN mirror from which to download the packages. An internet connection is therefore needed at this stage and clearly it is advisable to choose a mirror from your country. The packages that are needed and installed automatically by this script are 'rgdal' (Bivand et al. 2016) and 'raster' (Hijmans 2016). The package grid is also needed but it is automatically installed with R (R Core Team 2016). The script 'FIERCE_Install_Packages.R' needs executing only once after R installation, or possibly after an R upgrade.

An input file should be prepared before executing the main program. A file named FIERCE_Input_Data.R is included with the program script files. This is the only file that the user needs to modify and work with. The first paragraphs within this file are comments that describe how to use the file. A set of predefined examples follows, giving the user a more practical idea on how to implement his/her own processing.

In the R script language when # is present at the beginning of a line, the entire line is considered a comment, so that none of this information is used in the calculations. Conversely, when the line does not begin with a # symbol (see Fig. OR1.1), the line is interpreted as an R instruction. This allows the user to keep several alternative attempts in the input file and uncomment only one of them at a given time, ignoring the others without deleting them.

First, the user should choose which dike dataset to process. This is done by assigning a numerical value to the variable *DykesToAnalyze*. This number will be used to define and then access all parameters which apply specifically to this dataset (see below).

Although the minimum rectangular area into which all the dikes are contained is determined automatically (see Fig. OR1.2; Fig. 1), the user can specify how large the search area should be where the eruptive center can be determined. This is done by assigning a numerical value to the variable *outpercentage*. As the name says, this is expressed as a percentage, which increases the size of the automatically determined dike area (*xsizedykes* * *ysizedykes*) to get the search area (*xsearchdykes* * *ysearchdykes*) which is defined as

$$xsearchdykes = (1 + 2 * outpercentage/100) * xsizedykes$$
$$ysearchdykes = (1 + 2 * outpercentage/100) * y sizedykes$$

(see Fig. OR1.2). The search rectangle has lower and upper coordinates (*xmin*, *ymin*) and (*ymin*, *ymax*) respectively.

Then, the user should specify the number of boxes into which the grid search rectangle should be divided. This is done by assigning a numerical integer value to the two variables *nx* and *ny* (see Fig. OR1.2)

Next step is to choose the threshold below which we decide that a box is hit by a dike direction. This is done by assigning a numerical value to the variable *threshold*

Finally, the user can choose the directories which the program will use:

```
# Choose Program directory, where R scripts were installed
```

```
ProgramDir="C:/FIERCE"
```

```
# Choose Input directory, where input dikes shapefiles were copied
```

```
InputDir="C:/FIERCE/Input"
```

```
# Choose Output directory, where files are stored to be imported into GIS
```

```
OutputDir="C:/FIERCE/Output"
```

Here files with the results will be stored, ready to be imported into e.g. QGIS (QGIS Development Team 2016). Please note that the slashes separating directories in Windows should be indicated as “/” and not as “\”, i.e. R follows the Linux convention and not the Windows convention.

As mentioned, to keep the input file easy to read, each dike dataset is indicated with a numerical index *DykesToAnalyze*. All of its features are then assigned to the variable vectors with this index.

This also allows easily listing different, possibly alternative datasets for the same volcano (see Etna and Vicuña Pampa cases).

For each dike dataset we therefore choose a unique index, e.g. *m*, and assign the string variables *DykesFileDirs[m]* (Directory where the shapefile is located), *DykesFileNames[m]* (Filename, without extension, of the shapefile), *DykesTitle[m]* (The title for plots within R graphical windows). The shapefile format can be exported from the open source QGIS (QGIS Development Team 2016) or from many other commercial GIS packages. For a new, user-defined example, the easiest way is to copy an existing example and change the relevant parameters. It is essential that the new index chosen is unique, i.e. not used by existing examples.

Dikes are easily stored in a shapefile, a format originally proposed by ESRI, which stores non-topological geometry and attributes information for the spatial features in a data set, namely points, lines, and areas (ESRI 1998). It should be noted that an ESRI shapefile consists of several files: a main file (with extension *.shp*), an index file (with extension *.shx*) and a dBASE table (with extension *.dbf*). These three files are mandatory and must be in the same directory. In the main file - which is often, somehow incorrectly, named “shapefile” (*.shp*), each record describes a shape with a list of its vertices. However, this file is incomplete for distribution as the other supporting files are also required. Additional files are usually also present, such as *.prj* which stores the basic coordinate system and projection information and *.qpj* that stores a more complete set of parameters of the SR used by the QGIS software (QGIS Development Team 2016).

In order to analyse a new dike dataset at a given volcano, the user can simply export a shapefile with the dikes from the preferred GIS package, choose an index that has not been used before, and define the three variables indicated. Finally, s/he must assign, near the top of the *FIERCE_Input_Data.R* file, the newly chosen index value to the variable *DykesToAnalyze*.

When all the relevant choices have been made in the file *FIERCE_Input_Data.R*, the main program can be repeatedly executed by entering at the R prompt:

```
> source ('FIERCE_Main.R')
```

If syntax of all the statements in the file *FIERCE_Input_Data.R* is correct, execution starts and a first drawing is produced using as the plot area the search area with lower and upper coordinates (*xmin*, *ymin*) and (*ymin*, *ymax*). First, the dikes read from the shapefile are drawn as black segments. Second, their midpoints are calculated and drawn as red points. The program then draws all the directions that can be derived from the dikes assuming they are all radial; these are drawn as green lines. Finally, the software draws all the directions that can be derived from the dikes assuming they are all tangential; these are drawn as blue lines, perpendicular to the dikes and passing through their respective centers.

The software then proceeds with the grid search and plots its results. Three different plots are produced. In each graph, each grid cell is highlighted with a color scale that represents the normalized number of dikes that pass through it (with the tolerance given by the variable *threshold*). In the first plot, results are drawn assuming that the dikes can only be radial, while the second plot assumes that dikes can only be tangential. Finally, the third plot combines the previous two, assuming that each dike could be radial or tangential.

Apart from the plots that can be seen as R graphical windows during the execution of the program, the script *FIERCE_Main.R* also produces external image files in the TIFF format (TIFF 1992), which are stored in the folder specified by *OutputDir*.

The grid plots are a convenient way to rapidly show the solutions, i.e. the position of the potential eruptive centers suggested by the software, with respect to the position of the input dikes.

However, to precisely locate these potential eruptive centers it is essential to be able to import the solutions grid into a GIS environment, the same one from which the dikes shapefile was exported. To do so, the R script also produces raster images in a geo-referenced format known as ENVI (ENVI 2016), which can be easily imported into e.g. a QGIS project by adding a raster layer to be superimposed to the existing topography or map. This will show by default a different grayscale level for each grid cell depending on the number of dike direction intersections. However, better graphic results can be obtained by defining a suitable style, e.g. false color map that associates a blue-to-red color value similar to what is commonly used for temperatures. To compare different results it is advisable to map all values of ξ from 0 to 1.

3. Case studies presented in the paper

In order to process the Summer Coon dataset with the FIERCE software, we have to edit the FIERCE_Input_Data.R file and select it by assigning the corresponding variable:

DykesToAnalyze = 201;

In order to process the Etna dataset, we have to edit the FIERCE_Input_Data.R file and select it by assigning the corresponding variable:

DykesToAnalyze = 102;

In order to process the Vesuvius dataset, we have to edit the FIERCE_Input_Data.R file and select it by assigning the corresponding variable:

DykesToAnalyze = 301;

In order to process the Stromboli dataset, we have to edit the FIERCE_Input_Data.R file and select it by assigning the corresponding variable:

DykesToAnalyze=501; (we use all dikes from Lucchi et al. 2013)

DykesToAnalyze = 502; (we use all dikes from Tibaldi et al. 2014)

DykesToAnalyze= 514; (we use only dikes intruding the lithosomes Paleostromboli I and Paleostromboli II from Lucchi et al. 2013).

DykesToAnalyze= 515; (we use only dikes intruding the lithosomes of Paleostromboli III and younger ones ,i.e. from volcanic epoch 3 onwards, from Lucchi et al. 2013).

In order to process the Vicuña Pampa Volcanic Complex dataset, we have to edit the FIERCE_Input_Data.R file and select it by assigning the corresponding variable:

DykesToAnalyze = 001; (for the first analysis, where all the available dikes are used)

DykesToAnalyze = 002; (for the second analysis, where only dikes intruding the older volcanic sequence are used)

DykesToAnalyze = 003; (for the third analysis, where only dikes intruding the younger sequence are used)

Please note that any use of the dikes datasets is subject to the authorization of the respective data owners.

References for the Online Resource 1:

Bivand R, Keitt T, Rowlingson B (2016) rgdal: Bindings for the Geospatial Data Abstraction Library. URL <http://CRAN.R-project.org/package=rgdal>

ESRI (1998) ESRI Shapefile Technical Description, An ESRI White Paper—July 1998. <https://www.esri.com/library/whitepapers/pdfs/shapefile.pdf>

Hijmans RJ (2016) raster: Geographic data analysis and modeling. <http://CRAN.R-project.org/package=raster>

TIFF (1992) TIFF Revision 6.0 Final, <http://partners.adobe.com/public/developer/en/tiff/TIFF6.pdf>

Figure Captions in the Online Resource 1:

Figure OR1.1: Excerpt from the configuration file FIERCE_Input_Data.R. Lines beginning with the # symbol indicate comments and are not interpreted by the R program.

Figure OR1.2 : The minimum rectangular area that contains all the dikes is determined automatically and has size $x_{sizedykes} * y_{sizedykes}$. This is then expanded by a percentage factor *outpercentage* to determine the search area of size $x_{searchdykes} * y_{searchdykes}$. Finally, the search area is divided into a grid of $n_x * n_y$ search rectangles.

Figure OR1.1

```
## CONFIGURATION FILE FOR PROGRAM FIERCE - FInd ERuptive Centres
## User should choose the Dykes dataset to analyze and possibly other parameters here, as described below
## No compilation of this file is necessary, it is automatically loaded at each execution of FIERCE.

## CHOICE OF PARAMETERS BEFORE PROCESSING

# Choose Program directory, where R script were installed
ProgramDir="C:/FIERCE"
# Choose Input directory, where input dykes shapefiles were copied
InputDir="C:/FIERCE/Input"
# Choose Output directory, where files are stored to be imported into GIS
OutputDir="C:/FIERCE/Output"

# Choose Which Dykes to Analyze
DykesToAnalyze = 101;

# Choose percentage % of external search area outside the dykes, on each side (e.g. 10 for VP, 150 for Vesuvio)
outpercentage = 150

# Choose number of boxes to subdivide search for eruptive centre
nx=150
ny=150

# Choose threshold below which we decide that a box is hit by a dyke direction
threshold=300

## DEFINITION OF DYKES DATASETS: DIRECTORIES. FILENAMES, TITLE FOR PLOTS

#####
# Vicuña Pampa
# 001. Vicuña Pampa - All Dykes
DykesFileDirs[001]= paste(InputDir,"/VP",sep=")
DykesFileNames[001]="Estructura VP"
DykesTitle[001]="Vicuña Pampa - All dykes"

# 002. Vicuña Pampa - All dykes except Breccias II, III y IV
DykesFileDirs[002]= paste(InputDir,"/VP",sep=")
DykesFileNames[002]="Diques sin br II, III y IV"
DykesTitle[002]="Vicuña Pampa - All dykes outside Breccias"

# 003. Vicuña Pampa - Only dykes inside Breccias II, III y IV
DykesFileDirs[003]= paste(InputDir,"/VP",sep=")
DykesFileNames[003]="diques int br II, III y IV"
DykesTitle[003]="Vicuña Pampa - Dykes within Breccias"

#####
# Etna
# 101. Recent Etna Dykes
DykesFileDirs[101]=paste(InputDir,"/Etna",sep=")
DykesFileNames[101]="dicchi etna recenti"
DykesTitle[101]="Etna - Recent dykes"

# 102. All Etna Dykes
DykesFileDirs[102]=paste(InputDir,"/Etna",sep=")
DykesFileNames[102]="dicchi etna"
DykesTitle[102]="Etna - All dykes"

#####
# Summer Coon
# 201. Summer Coon Dykes
DykesFileDirs[201]=paste(InputDir,"/SummerCoon",sep=")
DykesFileNames[201]="summer coon dyke"
DykesTitle[201]="Summer Coon - All dykes"
```

Figure OR1.2