



# Is there a close spatial relationship between faults and plutons?

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## Abstract

Using spatial relationships between individual plutons and faults to support genetic correlations between faulting and magmatism is meaningless since even random magmatic or tectonic processes will result in some plutons adjacent to faults. Our initial analyses of populations of faults and Carboniferous plutons in the Armorican Massif, France and faults and Alleghanian plutons in the southern Appalachians, USA indicate that plutons have broad distributions with respect to faults but with a tendency for plutons to occur away from faults. Maxima of integrated pluton areas occur at 1/4 (Appalachians) and 1/2 (Armorican) of the distance between the average fault spacing in these orogens. Although there is a great need for statistical evaluations of relationships between populations of igneous bodies and structures in a wide variety of settings and crustal depths, our initial studies suggest that faults do not preferentially channel magma during ascent or emplacement and that these are relatively unfocused processes within orogenic belts. © 1999 Elsevier Science Ltd. All rights reserved.

## 1. Introduction

Plutons and faults of similar age invariably occur together in a variety of tectonic settings, an observation which has led to a growing perception that faults and plutons generally have a close spatial relationship (Hutton, 1988; Glazner, 1991; D'Lemos et al., 1992; Hutton and Reavy, 1992; Tikoff and Teyssier, 1992). Similar correlations have been made at surface levels between linear arrangements of volcanic centers and faults or fractures (Draper et al., 1994; Lutz and Gutmann, 1995) and at deeper crustal levels between igneous bodies and a variety of co-eval structures including faults (Hutton and Reavy, 1992; Brown et al., 1995; Collins and Sawyer, 1996). These relationships, typically based on qualitative observations of geological maps, are repeatedly cited as evidence that the ascent, emplacement, and sometimes the generation of magmas are controlled by faults (Strong and Hanmer, 1981; Hutton, 1988; D'Lemos et al., 1992). If these hypotheses are correct, then regional deformation, particularly faulting, plays a fundamental role

in magmatic processes at all crustal levels. This is such an important conclusion that its validity needs careful evaluation.

If indeed a causative relationship exists between faults and plutons, then the following should be demonstrable: (1) a strong spatial correlation; (2) a close geometric relationship; (3) a close temporal relationship; (4) compatible rates of faulting and plutonic processes; and (5) specific thermal–mechanical mechanism(s) by which magma is generated, ascended, and/or emplaced along faults. We suggest that even the first step of establishing and evaluating spatial relationships between faults and plutons is difficult at best. This is true for several reasons. First, devising useful methods for comparing spatial relationships between curvilinear faults and irregularly shaped plutons is not straightforward. Second, even in regions where previous authors have argued for a close spatial relationship between faults and plutons, there are invariably examples of plutons not in contact with, or adjacent to, faults. Thus, there is rarely, if ever, a simple one-to-one relationship between faults and plutons, emphasizing the need to quantitatively compare *populations* of plutons and faults rather than simply noting that one or more plutons lie along one or more

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faults. This step is necessary because even if faulting and plutonism are two independently operating processes, some plutons will invariably occur adjacent to faults. Finally, even if a close spatial relationship between populations of faults and plutons can be established, it may not indicate a causative link between faulting and magma ascent and emplacement. It is necessary to determine whether or not the established spatial relationship has a high probability of resulting from two independently operating processes, or requires a causative link.

Our goals in this paper are the following: (1) to explore issues that need consideration when evaluating spatial relationships between populations of faults and plutons; (2) to present an initial evaluation of two natural examples, Alleghanian plutons in the southern Appalachians, USA (Fig. 1), and Carboniferous plutons in the Armorican Massif, France (Fig. 2); and (3) to discuss the difficulties faced when attempting to determine if our results imply a genetic relationship between faulting and magma ascent and emplacement.

## 2. Establishing spatial relationships

Much of the literature pertaining to analysis of spatial relationships concerns establishing whether a distribution of a single type of object, typically represented by a pattern of points on a map, fits one of the following hypotheses (e.g. Boots and Getis, 1988): (1) complete spatial randomness in which all locations in the area studied have an equal chance of containing a point, and the location of one point in no way influences the location of another point; (2) a regular pattern in which points are distributed at uniform distances across the study area; or (3) a clustered pattern in which points are distributed in groups. Boots and Getis (1988) and Fry (1979) describe a number of methods employed to test these hypotheses. However, the analysis of spatial relationships between very dissimilar geometric objects in the natural world, particularly ones that are best represented by an area or volume, has received far less attention.

Both geological and analytical issues arise when trying to obtain and evaluate data for faults and plutons. Geologic issues include the following:

1. Geological maps contain inherent uncertainties including assumptions regarding the age of faults and plutons and whether or not the map is actually a representative example of a particular region of the Earth's crust. Typically our final picture of a region is only partial since areas will be obscured by other geographical features or more recent geological cover. This is important because, for instance, if

plutons actually continued beneath cover rocks but faults did not, then the determined spatial relationship would be stronger than appropriate.

2. All geological maps are constructed with some degree of interpretation, and not all contacts are located where shown on a map.
3. We can only measure parameters typically available from geological maps (i.e. two-dimensional space) such as the position of faults relative to plutons and the similarity of pluton spacing relative to fault spacing. In fact plutons and faults are complex three-dimensional objects. In a complete spatial analysis, spatial proximity should be examined along the full vertical extent of both faults and plutons. The only way to statistically address this problem is to consider multiple maps representing slices of crust at different crustal depths, a proposition typically difficult for any single area.
4. Plutons represent one snapshot of magma conduits which generally had a complicated history. For example, conduits may have changed shape or position through time. Some conduits may have had a much greater flux of magma than others. And some conduits, such as nested or zoned plutons, or plutons partially intruding other plutons, may now include only parts of several magma batches.

Analytical issues include the following:

1. It is difficult to determine methods of comparing faults with plutons, two distinctly different objects. Faults are curvilinear features which may vary at different scales from continuous singular discontinuities, to multiple, en échelon discontinuities, to broad zones of distributed deformation. Plutons are irregular shaped volumes ranging from sheets to spherical bodies. Because faults and plutons are geometrically very different, choosing parameters with which to analyze spatial relationships is not trivial. The parameters we choose may affect our success at testing different hypotheses. For example the percentage of pluton margins bounded by faults is a useful measure when evaluating emplacement models but provides no information about the distribution of plutons away from faults. However, the distance between faults and pluton centers may be more useful when evaluating the role during magma ascent of stress fields between active faults.
2. Our interpretation of spatial relationships may change depending on the scale at which we evaluate them. We illustrate this point with Fig. 1, a map from Speer et al. (1994) of faults and Alleghanian plutons in the southern Appalachians. As scale increases from Fig. 1(a–d) (i.e. the area covered decreases), resolution increases but population sizes decrease. The result is that we can more precisely evaluate spatial relationships between individual

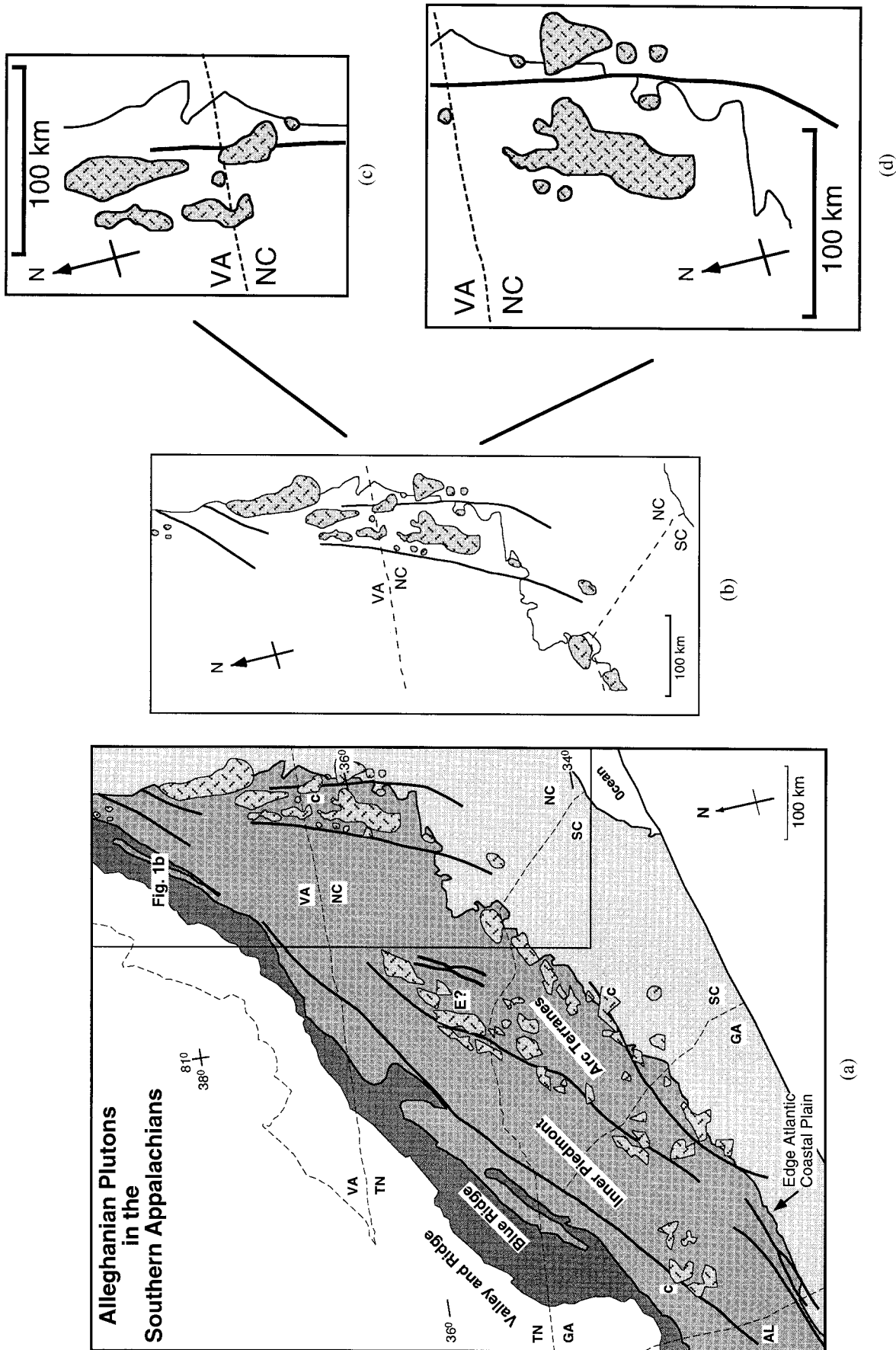
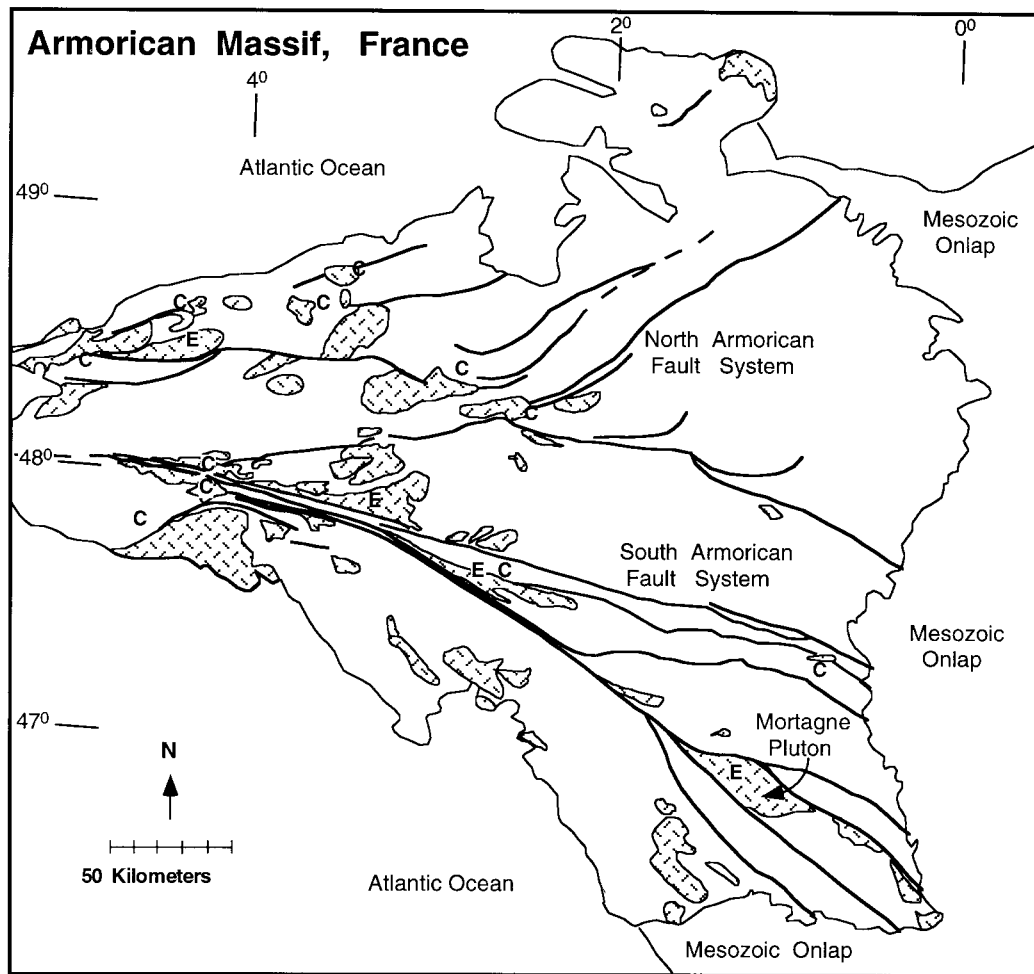
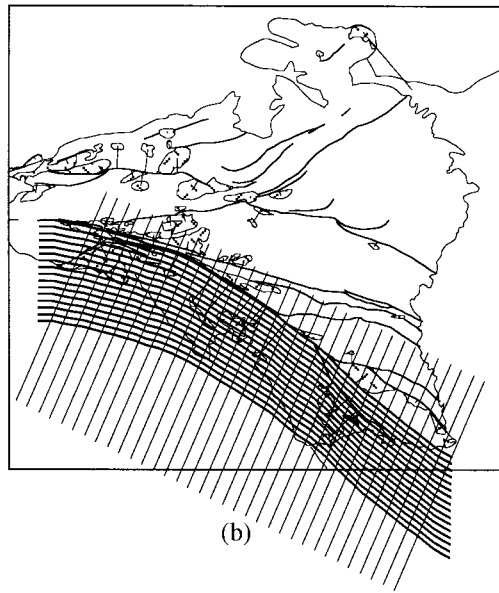


Fig. 1. (a) Sketch map of Alleghanian faults and plutons in the southern Appalachians, USA modified from Speer et al. (1994). States outlined with dashed lines: AL=Alabama, GA=Georgia, NC=North Carolina, SC=South Carolina, TN=Tennessee and VA=Virginia. C=plutons which discordantly cut faults, E=plutons where emplacement hypothetically could be controlled by faulting. (b)–(d) Enlargements of regions in (a). Comparison of (a)–(c) shows the effect on spatial relationships of increasing scale (decreasing area examined), and decreasing sample size. Comparison of (c) and (d) (both at same scale), shows the potential effect of sampling bias on inferred spatial relationships (e.g. these were drafted to exemplify the effect of only



(a)



(b)

Fig. 2. (a) Faults and plutons in the Armorican Massif, Brittany, France (redrafted from the 1996 BRGM map of France). C=plutons discordantly cutting faults, E=plutons where emplacement hypothetically could be controlled by faulting. See text for discussion. (b) measured pluton center to nearest fault distances shown for north Armorican fault system and a simplified example of one of the grids used to measure pluton area vs distance from nearest faults for the South Armorican fault system. Actual size of grid elements used during counting is 1/4 that shown.

objects, but have sample sizes potentially less representative of the relationships between the overall populations (e.g. compare Fig. 1c and d). Also note that whereas one may be tempted to argue for a close spatial relationship between faults and plutons in Fig. 1(a) (ignoring geological issues), such a hypothesis seems unlikely if only Fig. 1(d) is examined.

Furthermore, if a close spatial relationship exists, the scale at which the relationship is strongest may provide information about the scale at which a causative relationship operates. For example, if statistically significant spatial overlap between faults and plutons occurs at the scale of an entire orogen (100s of km; Fig. 1a), but not at the scale of individual faults and plutons (10 km; Fig. 1c), then it is inappropriate to evoke a causative mechanism such as pluton emplacement into fault step-overs. Rather, mechanisms such as control on magma generation sites or the overall stress regime across an arc might be more appropriate.

3. Finally, it is necessary to determine whether the measured spatial relationship could result (a) by chance from two randomly operating processes, (b) by two non-random but independently operating processes, or (c) by two interrelated processes.

A variety of measurements for evaluating spatial relationships between plutons and faults are possible: (1) pluton spacing relative to fault spacing; (2) distance from pluton margin to nearest fault; (3) pluton diameters relative to fault spacing; (4) area covered by plutons relative to the total map area; (5) the amount of overlap between separate plutons in nested plutonic complexes; (6) percent of fault-bounded pluton margins; (7) distance between the centers of mass of fault systems and magmatic belts normalized to the total area of the zones; and (8) area of the overlapping region between fault systems and magmatic belts normalized to the total area covered by these features.

In our preliminary analyses presented in the next section, we use several of these, but find that one of the most informative measurements is to determine the integrated area (in km<sup>2</sup>) of plutonic rock vs distance to the nearest fault (Fig. 3). These data are collected in the following manner. An approximately rectangular grid pattern is established with the average orientation of nearby faults used to establish one axis of the grid system and evenly spaced lines approximately perpendicular to the faults to establish the other axis (Fig. 2b). If fault geometries are heterogeneous (Fig. 2a) then multiple grid systems are established for different subdomains. The area of plutonic rock in each grid element is calculated and the distance between the grid element and nearest fault recorded. This process is repeated for each subdomain between faults and the

results are plotted on a histogram of integrated pluton area vs distance to the nearest fault (Fig. 3). One of the advantages of this procedure over, say, measuring distances from faults to pluton centers, is that it is independent of size, shape, and orientation effects of plutons. For example the distance-to-pluton-center measurements do not distinguish between differences in distribution of pluton area of an elliptical pluton oriented parallel to a fault, vs one oriented perpendicular to a fault.

### 3. Two examples

#### 3.1. Armorican Massif, France

One orogenic belt in which it has long been argued that faults and plutons are intimately related is the Armorican Massif, Brittany, France (Gapais and Le Corre, 1980; Strong and Hanmer, 1981; Guineberteau et al., 1987; Roman-Berdiel et al., 1997). Rocks of the Paleozoic Variscan orogen are cut by numerous strike-slip faults (Fig. 2), the most famous of which is the South Armorican shear zone. This region is of historical interest because it contains the shear zone in which *S–C* structures were first defined (Berthe et al., 1979) and the first non-sheeted pluton, the Mortagne pluton, for which it was proposed that magma emplacement occurred in a strike-slip fault step-over (Guineberteau et al., 1987; but see Roman-Berdiel et al., 1997).

In Fig. 2 we have shown all mapped regional faults along with plutons emplaced between 300 and 360 Ma (Hanmer et al., 1982; Le Corre et al., 1991). It is not our intent to discuss whether or not the mapping and age of plutons and faults is correct. Others far more familiar with the Armorican geology have used this same dataset to argue for a close spatial and thus genetic relationship between the two (Gapais and Le Corre, 1980; Strong and Hanmer, 1981; Guineberteau et al., 1987; Roman-Berdiel et al., 1997). We will therefore use this example to explore the validity of their conclusion.

Fifty-two plutons fall in the selected age range (300–360 Ma) and form 9% of the exposed area of the Armorican Massif. These plutons have length to width ratios ranging from 1.53 to 27.00 with a mean of  $\approx 4.00$ . Pluton areas range from 13 to  $\approx 1000$  km<sup>2</sup> with a mean of 159 km<sup>2</sup>. The plutons show a wide range of orientations, but there is a moderate tendency for those with the largest axial ratios to have their long axes at low angles to nearby faults. Twenty-seven fault segments define two fault systems—the NE-striking North Armorican and the SE-striking South Armorican fault systems, respectively (Gapais and Le Corre, 1980) along which shearing changed from sinistral (350–320) to dextral (320–300) (Faure, personal

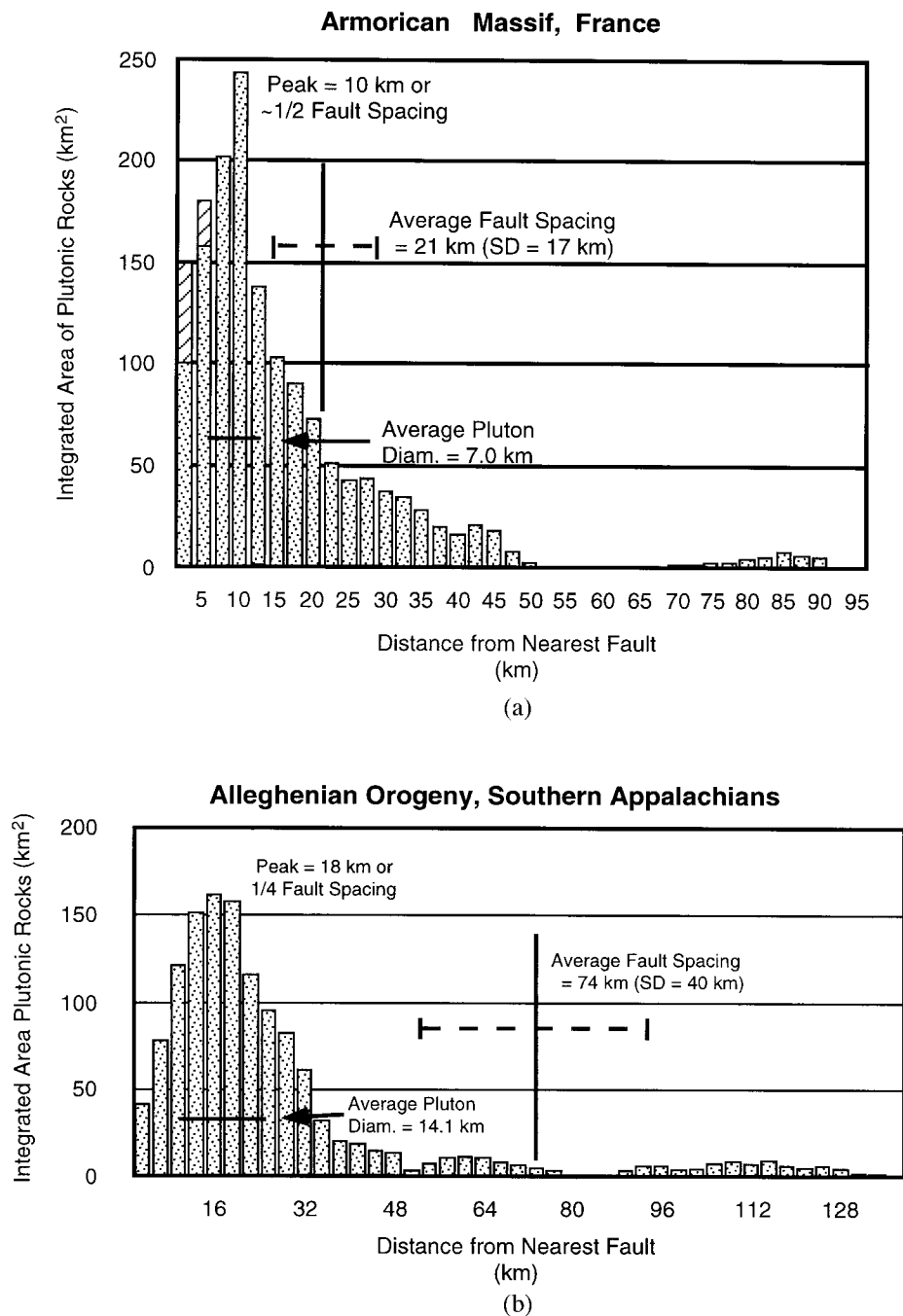


Fig. 3. Plot of integrated pluton area ( $\text{km}^2$ ) vs distance from nearest fault. See text for measurement technique. (a) Armorican Massif, France; (b) Alleghanian orogeny, southern Appalachians, USA. In (a), diagonal line pattern in columns = area of plutons believed to have been tectonically emplaced along faults. Note that in both (a) and (b), total pluton area decreases towards faults and that area maxima occur between average fault spacing. Asymmetry of plots is largely a function of the variability of fault spacing.

communication, 1998). Average fault spacing measured perpendicular to faults varies from 0 to over 80 km with a mean of 21 km and a standard deviation of 17 km. Surface traces of faults have trends that vary by over  $90^\circ$ .

Fig. 2 clearly indicates that there are numerous fault segments not intersected by or adjacent to plutons,

and many plutons not intersected by or adjacent to faults. Nine of the 27 fault segments do not intersect any plutons and 25 of the 52 plutons do not intersect a fault. An additional 14 of the 52 plutons intersect but cut discordantly across faults (labelled C on Fig. 2) and thus post-dated any significant movement on these faults (recent work by Michel Faure and col-

leagues may reduce this number). Another useful measurement with regards to evaluating emplacement models is to determine what percentage of a pluton's margin is bounded by faults. When making this calculation, if there was doubt as to whether a fault bounded a pluton, we included these margins in our total. Even with this liberal definition, 92.3% of pluton margins were not fault-bounded. We found only four examples where a pluton had >20% of its margin bounded by faults (labelled E on Fig. 2), the most impressive being the Mortagne Pluton with 56% of its margin fault-bounded (see, however, Roman-Berdiel et al., 1997).

The above observations alone indicate that in the Armorican Massif, pluton emplacement rarely if ever required faulting and faulting did not require pluton emplacement. Furthermore, Vigneresse (1995) used isostatic residual gravity anomalies to infer the location of the deepest parts of, or 'feeder zones' to plutons near the South Armorican fault zone and concluded that these feeder zones do not trend towards or connect with faults. Thus Vigneresse (1995) concluded that at least to depths of 2–6 km below exposed crustal levels magma did not preferentially ascend along these faults.

It remains important to statistically evaluate the spatial relationship between the populations of plutons and faults. One means of doing so is to measure distances between faults and plutons (Fig. 4) with distances determined by selecting the center of a pluton and measuring a perpendicular from this center to the nearest fault. Distances range from  $\approx 0$  to 65 km with a mean distance of 11.5 km; that is about half the mean spacing of faults and significantly greater than the average pluton diameter ( $\approx 7$  km). However, for reasons noted earlier, we find a more useful approach is to construct grids, measure pluton area vs nearest fault, and plot the integrated area ( $\text{km}^2$ ) of plutonic material vs distance to nearest fault (Fig. 3). This figure shows several interesting aspects:

1. The statistical distribution of pluton area significantly decreases in regions immediately surrounding faults. In fact during magma ascent and emplacement, cumulative pluton area may have been even lower near faults than indicated by this diagram. A few plutons near faults in this region were deformed by post-emplacement faulting, resulting in plutonic slivers along the fault and juxtaposition of new plutonic material with the fault. This process will increase the area of plutonic material along faults (Fig. 3).
2. A weak statistical maximum occurs at a distance of  $\approx 10$  km, that is approximately half the distance between the average fault spacing.
3. The average pluton diameter (7 km) is significantly

smaller than the average fault spacing and the width (or standard deviation) of the statistical maximum, indicating that the position of the statistical maximum and pluton locations are not strongly controlled by pluton width.

4. The statistical peak is asymmetric, emphasizing the effects of the large standard deviation of average fault spacing on the maximum distance that plutons can occur from the nearest fault.

### 3.2. Alleghenian orogen, southern Appalachians, USA

In the southern Appalachians, the Paleozoic suturing of Laurentia and Gondwana resulted in widespread deformation, faulting, and magmatism in an event called the Alleghenian orogeny (Gates et al., 1988; Hatcher, 1989). Speer et al. (1994) concluded that the plutons emplaced during this orogeny were spatially associated with dextral strike-slip faults and that the generation, segregation, ascent, and emplacement of plutons were linked to this faulting. Again, we will not defend the accuracy of the dataset shown in Fig. 1 since this same dataset has been used by others to argue for a genetic link between magmatism and faulting (e.g. Speer et al., 1994).

In the Alleghenian example, 60 plutons range in age from 327 to 266 Ma and make up only  $\approx 5\%$  of the region. Pluton length to width ratios range from 1.0 to 5.0 with a mean of 2.0. Pluton area ranges from 24 to 2930  $\text{km}^2$  with a mean area of 397  $\text{km}^2$ . As with the Armorican example, Alleghenian plutons show a wide range of orientations of long axes, but with a tendency for plutons with the largest axial ratios to be subparallel to closest faults.

Twelve major fault segments occur in this region with fault activity overlapping in age with the plutons (Speer et al., 1994). Averaged fault spacing varies from 14 to 185 km with a mean of 74 km and a standard deviation of 40 km. Surface traces of faults vary in trend by up to 57°. An examination of Fig. 1 shows that few faults actually intersect or border plutons. Seven of the 12 fault segments do not intersect plutons and only 12 of the 60 plutons are intersected by a fault or are close enough to a fault (<5 km) to assume that the pluton is partially bounded by the fault. Even when faults <5 km away from plutons are assumed to bound plutons, over 99% of pluton margins are not fault-bounded.

Statistical measures of the spatial relationship between faults and plutons in the Alleghenian orogeny show a similar lack of significant correlation. Measurements of the distance from pluton centers to nearest fault show a large range of values (0.8–133 km) with an average of 27 km (Fig. 4). Integrated

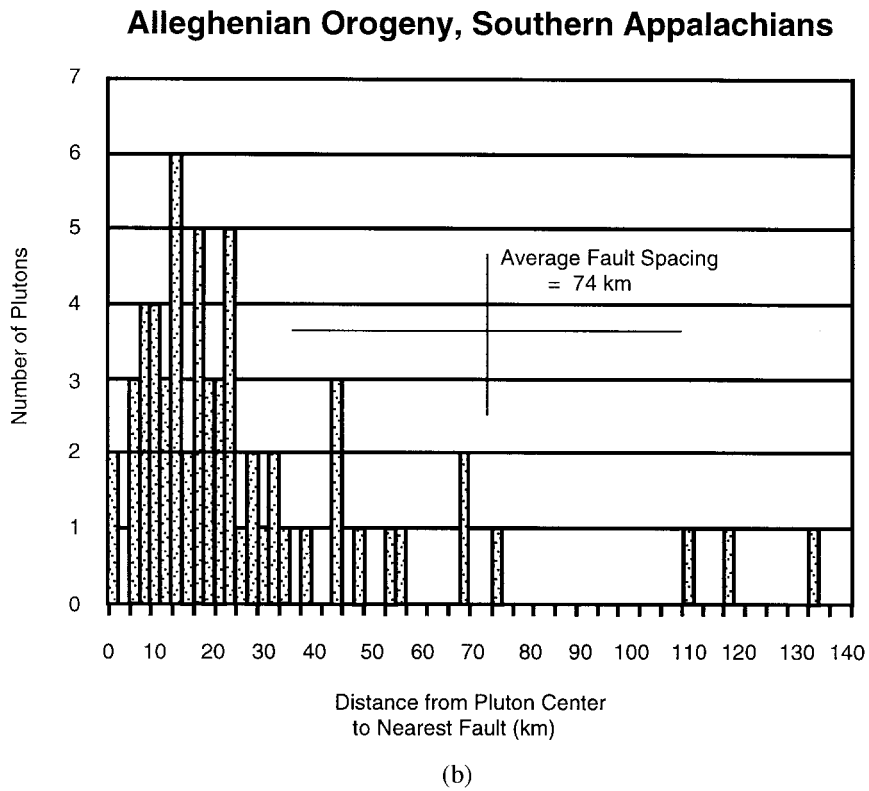
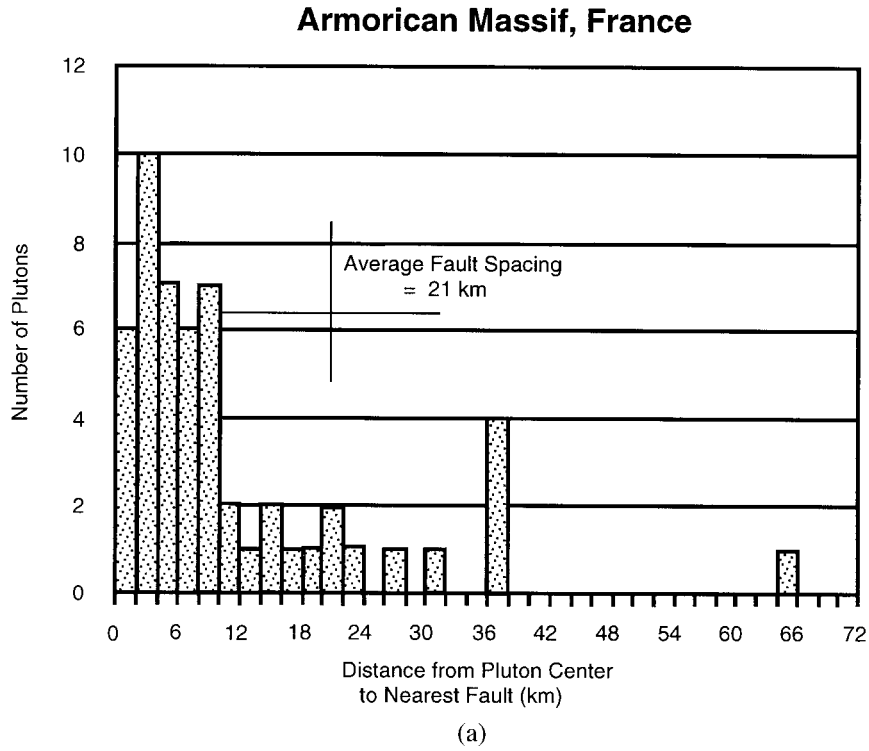


Fig. 4. Plots of distances measured from pluton centers perpendicular to nearest fault for (a) Armorican example and (b) Alleghanian example. Note that the maxima and asymmetry of plots are largely a function of fault spacing and do not suggest an increase of plutons towards faults.



pluton area vs distance to nearest fault (Fig. 3) produces an asymmetrical bell-shaped curve with a maxima lying approximately 18 km from nearest faults. Integrated pluton area falls off dramatically to statistically insignificant levels near faults. In contrast to the Armorican example, the peak of this curve falls closer to the nearest fault, that is 1/4 instead of 1/2 the distance between averaged fault spacing.

#### 4. Discussion

We emphasize that the above measurements help to characterize the spatial relationship between pluton and fault populations, but do not by themselves establish the significance of these relationships. To do so we need to evaluate whether it is statistically likely that two independently operating processes (in our case faulting or the existence of non-active faults and pluton emplacement) develop datasets such as those determined earlier, or whether it is likely that these datasets require some dependency between the processes.

In a subsequent paper, we will use modeling results to better constrain the significance of data presented in the previous section. Here we briefly explore, in a qualitative manner, the interpretation of integrated pluton area plots (Figs. 3 and 5) in order to emphasize parameters which affect these spatial analyses.

Fig. 5 shows four different curves, each of which represents an idealized combination of fault and pluton populations within a square box. If plutons are uniformly distributed throughout an area in which a single fault exists, then (ignoring boundary effects), plots of integrated pluton area will result in a subhorizontal line (curve #1). If two or more faults exist, then

there is a maximum distance at which plutons can occur from faults. If plutons remain uniformly distributed, then an asymmetrical curve results with a flat maxima centered on the nearest fault (Fig. 5, curve #2). If multiple faults exist and plutons are not uniformly distributed, then asymmetrical, bell-shaped curves result. The peak of these curves occur at zero distance from nearest faults if plutons statistically have a close spatial relationship to faults (curve #3), or 1/2 way between the average fault spacing if plutons statistically cluster as far from faults as possible (curve #4). The peak, standard deviation, and skewness of these curves reflect an interplay between the degree of clustering of the plutons, the average and standard deviation of pluton diameters and orientation, and the average and standard deviation of fault spacing.

A comparison of these curves to the Armorican and Alleghanian plots indicates that plutons are not uniformly distributed and do not preferentially fall along faults. Instead they form weak maxima (with large standard deviations) at 1/4 (Alleghanian) to 1/2 (Armorican) the distance between average fault spacing. The Armorican example approaches the case where plutons are statistically located as far from faults as possible, but again only with a weak peak. Thus these data indicate that in these two orogens, plutons are relatively uniformly distributed but with weak tendencies to cluster at some distance from faults.

These data indicate that there *is* a spatial relationship between faults and plutons but not the close spatial relationship so often assumed in the literature. Instead plutons show a weak tendency to occur away from faults, a conclusion previously reached by Vigneresse (1995) for the South Armorican plutons. As

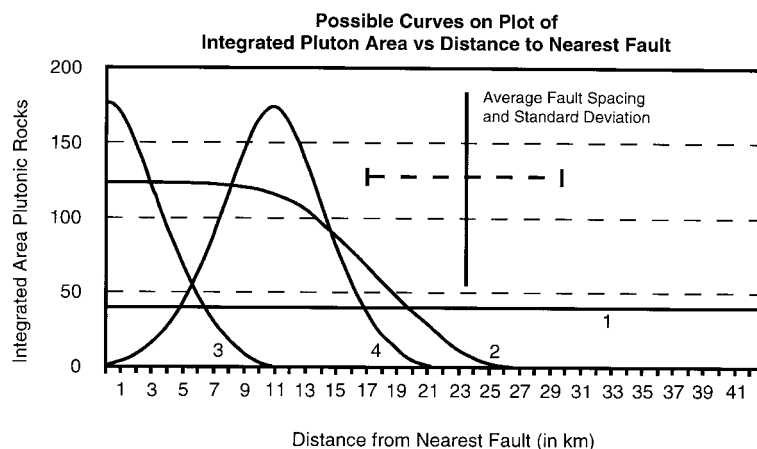


Fig. 5. Cartoon of integrated pluton area vs distance from nearest fault, exemplifying shapes of curves resulting from different fault and pluton populations. Curve #1 = random plutons and 1 fault in analyzed domain (ignoring boundary effects). Curve #2 = random plutons and 2 or more faults. Curve #3 = non-random plutons which statistically occur along faults. Curve #4 = non-random plutons which statistically occur as far from faults as possible. See text for further discussion.

noted by Vigneresse (1995), this relationship suggests that stress fields between faults may somehow influence the location of magma ascent and emplacement, a conclusion compatible with our results. We emphasize, however, that the effect is weak since plutons in these two orogens are not strongly clustered. We also emphasize that these maxima may not be statistically significant. For example, if fault–pluton relationships in 20 orogens were analyzed (instead of two) and weakly developed maxima varied from zero distance to nearest faults (curve #3 in Fig. 5) to 1/2 the distance between average fault spacing (curve #4 in Fig. 5), then these data could be interpreted to imply that magma ascent is a relatively random process and that just by chance a small amount of clustering of plutons occurs at different locations in different orogens.

The above analysis strictly considers spatial relationships. We speculate that one reason that others have concluded that faults and plutons are intimately related is because of observed temporal and/or geometrical relationships. We agree that existing data in many orogens support a close temporal relationship between active faulting and magmatism, but note that magmatic systems typically transfer mass at rates faster (to orders of magnitude faster), than faulting (Paterson and Tobisch, 1992), which suggests that a close temporal relationship does not require a strong coupling between these two processes.

Our initial analysis does indicate a weak geometric similarity between fault and pluton orientations. Plutons with the largest axial ratios tend to be subparallel to nearest faults (but note exceptions in both Figs. 1 and 2). Furthermore, linear arrays of plutons (Fig. 1) tend to form parallel to nearby fault traces. The latter observation can be rigorously tested using procedures outlined by Lutz and Gutmann (1995) for evaluating linear alignment of volcanoes. However, we again caution that a geometrical similarity does not require a direct genetic link. This is particularly true in orogens, where fault and pluton orientations are also commonly subparallel to other host rock anisotropies, subduction zones, principal planes in regional stress fields, continental margins, and inferred orientations of magma source regions. Determining which of these, if any, control pluton shapes and orientations is a challenging proposition.

These results indicate that it would be useful to apply similar statistical and geometrical analyses to migmatites and other intrusive bodies at deep crustal levels and to volcanoes and subvolcanic intrusions at near surface levels before drawing conclusions about the spatial relationship between magmatic systems and various structures. For example, there are many examples at deep crustal levels of plutonic material residing in low stress sites (Hutton and Reavy, 1992; Brown et al., 1995; Collins and Sawyer, 1996).

However, this does not imply that magma was preferentially channeled up these zones unless one of two possibilities can be demonstrated. It must be demonstrated that either more plutonic material resides in these sites than in regions between these sites, or that a larger volume of magma moved through igneous bodies preserved in low stress sites than in igneous bodies preserved between these sites. The latter possibility is difficult to test, but the former can be tested using the statistical approach described earlier.

It is our impression, from looking at maps and based on our initial statistical analyses, that in many orogenic belts magma ascent and emplacement, at all crustal levels, is a relatively unfocused process. We suspect that crustal anisotropies and local and regional stress fields may have a weak focusing effect, but see no evidence that magma is preferentially channeled along faults. In fact, our data from two orogens indicate that magmatic bodies show a weak tendency to cluster away from faults.

## 5. Conclusions

When evaluating relationships between magmatism and deformation in orogenic belts, we suggest that it is important to consider ways of testing a variety of contrasting hypotheses such as whether faulting and magmatism are closely linked *or* whether there is no relationship between faulting and magmatism except that both occur in orogenic belts with restricted areal extent. More specifically we can ask whether: (1) the production of magma is triggered by faulting *or* magma-induced fracturing triggers faults, *or* faults nucleate on plutons in thermally weakened crust; (2) magma ascent is controlled by faulting because faults provide anisotropic control, and/or favorable stress gradients, and/or thermally heated pathways, and/or the necessary displacement of host rock, *or* the magma ascent process is dominated by buoyantly driven, vertical transport and is relatively independent of the above controls; (3) magma emplacement is controlled by faults because faulting displaces host rock and traps magma from further ascent *or* magma emplacement is independent of faulting and thus populations of faults and plutons will have a wide range of spatial relationships; and (4) regional deformation makes space for magma emplacement *or* magma emplacement causes or accommodates regional deformation.

In attempting to evaluate the above hypotheses, we believe it is important to seek ways of quantifying spatial, geometrical, and temporal relationships. Our work to date supports the following conclusions:

1. Using qualitative spatial relationships between indi-

vidual plutons and faults to reach conclusions about relationships between faulting (or faults) and magmatism is meaningless since even random magmatic processes will result in some plutons adjacent to faults.

2. Evaluating spatial relationships between populations of faults and plutons is a function of scale, sampling biases, and measurement parameters.
3. Pluton populations in the Armorican Massif and southern Appalachians are roughly uniformly distributed with a weak tendency for plutons to occur away from faults. Maxima of integrated pluton areas occur at a distance of 1/4 (Appalachians) and 1/2 (Armorican) the average fault spacing in these orogens.
4. Average spacing between fault segments controls the maximum distance that plutons can occur from faults. Thus as fault spacing decreases, (and/or more faults are discovered), a closer spatial relationship results regardless of whether or not magmatic processes are related to faulting.
5. There is a great need for statistical evaluations of spatial and geometrical relationships between populations of igneous bodies and structures in a wide variety of settings and crustal depths before inferences can be made about the relationship between magmatic and tectonic processes.
6. However, our initial studies indicate that magma ascent and emplacement are relatively unfocused processes in orogenic belts and that faults do not preferentially channel magma during ascent or emplacement.

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