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The relationship between length and width of plutons within the crustal-scale Cobequid Shear Zone, northern Appalachians, Canada

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Abstract The lengths and widths have been measured for 69 component bodies of composite plutons along the Cobequid Shear Zone. Plutons on major fault strands, those with mylonite zones >0.1 km wide, exhibit evidence of multiple intrusion of magma batches. Small plutons along short faults in stepover zones appear related to rapid emplacement of magma in bodies 1.5–4 km long by 0.1–2 km wide. Such small plutons show low enrichment in incompatible elements in older component bodies, but increasing amounts in younger bodies as a result of progressive magma expulsion from crystal mush during crystallization and shear-enhanced compaction in fault zones. Wider plutons generally occur along longer fault strands accommodating more strain and penetrating deeper into the crust and show enrichment in incompatible elements. The width of the mylonitic fault zone is about 15% of the width of these plutons. The length-to-width ratio of component bodies and composite plutons varies between 2 and 11. The best-fit line describing these data has a slope of 1.056, which implies scaling behavior between plutonism and tectonic processes. Scalar properties of plutonic bodies are similar to those of faults, but scalar relationships observed in component bodies do not apply to composite plutons.

Keywords Shear zone plutons · Scalar properties · Cobequid fault · Canada

Introduction

Field-based structural and geochemical analyses of exhumed fault zones can be used to constrain compositional and deformational processes with fault zones. The evolution of fault zones is a complex process that is governed by a series of factors. Current questions in fault zones and hosted plutons that can be addressed by field-based geologic investigations include the following: (a) The role of fault segments for pluton segregation. (b) What effects do lateral changes of composition have on the distribution of deformation along a fault zone? (c) How do the fault complexities or discrete fault strands affect magma draining? Is the fault deformation tied with fault zone composition? Is the magma segregation related to its composition?

Many plutons appear to have been emplaced in fault zones with the probable intrusion mechanism being the “dyke to pluton construction” of Hutton and Reavy (1992) and Hutton (1997) apparently applicable for plutons within the Cobequid Shear Zone (Pe-Piper and Piper 2003).

In this study, we have taken the opportunity provided by detailed mapping in the crustal scale Cobequid Shear Zone of southeastern Canada, active during Devonian—Carboniferous time, to investigate the plan-form geometry of high-level magmatic bodies (Fig. 1). We use length and width relationships to draw conclusions about the processes that control the pluton evolution. In particular, the purpose is the analysis of geometrically regular relationship between the dimensions of small-scale intrusions, component bodies of plutons, and plutons themselves. The relationship between pluton width and the width of the deformation zone across the associated fault strand is also investigated. This analysis leads to a better understanding of the relationship

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distance along the Cobequid Shear Zone (Figs. 3, 5)

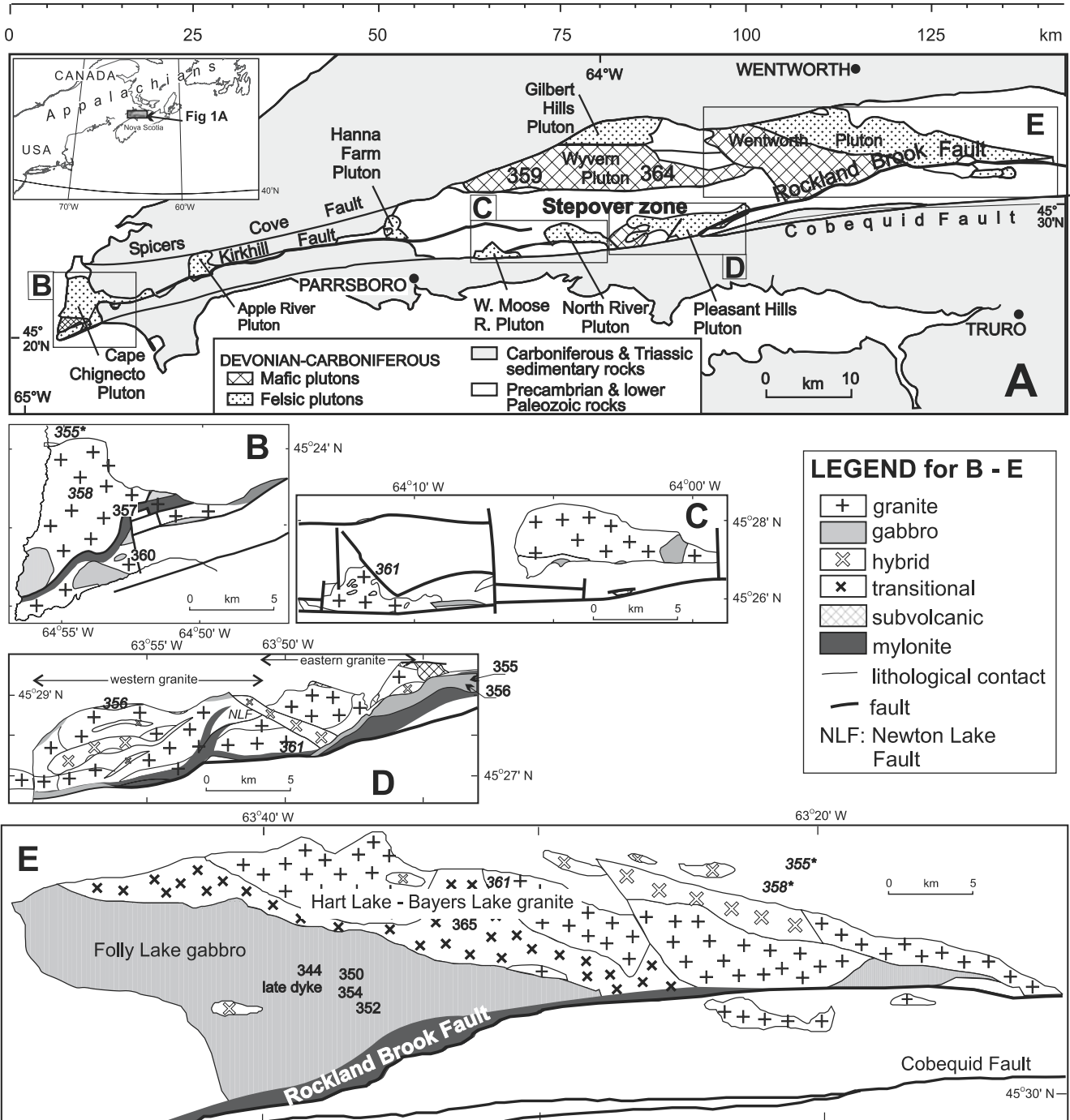


Fig. 1 a Summary geological map showing the plutonic rocks of the Cobequid Shear Zone and major fault zones. Inset shows the location of the study area within the Appalachians. **b-d** More detailed maps showing component bodies of plutons and mylonite zones based on detailed field mapping reported by Koukouvelas et al. (1996, 2002), Pe-Piper et al. (1998) and Pe-Piper and Piper

(2005). Radiometric ages interpreted to date igneous events are shown, based on U-Pb dates on zircon by Doig et al. (1996) and Dunning et al. (2002) (shown in *italic font*) and Ar-Ar dating principally of amphibole by Pe-Piper et al. (2004) (shown in regular font). * Indicates ages of coeval volcanic rocks

between faulting and pluton emplacement within a crustal scale shear zone. The end result of this work is the notion that pluton length and width resemble fault length and displacement and that deformation plays a crucial role in the build-up of large plutons.

General problems of fault control on pluton emplacement

Although the weight of field evidence, modeling and thermal efficiency indicate dyke ascent of most magmas

(Clemens 1998), and this concomitantly attests to fault control on the ascent and emplacement of plutons, several problems remain regarding the concept of faults and plutons (Vigneresse 1995; Cruden 1998). Three modes of plutons can be defined within shear zones at obliquely collided margins: plutons closely related to faults, unrelated to faults, and plutons interacting with faults. This interaction with faulting may involve faulting that follows magma intrusion or faulting that predates magma intrusion, such as the Tertiary plutons in the Alps (Rosenberg et al. 1995; Rosenberg 2004; Steenken et al. 2000), and the Carboniferous plutons in the Cobequid Shear Zone (Koukouvelas et al. 2002). Thermal weakening of the crust by plutons can interact both spatially and temporally with faults, e.g., the Adamello pluton (Stipp et al. 2004). Apparently not related to faults are a series of plutons in French Massif Central (Améglio et al. 1997).

At a small scale, dynamic permeability and supralithostatic melt pressure cause melt-enhanced embrittlement and ductile or brittle opening-mode fracture (d'Alessio and Martel 2005). At a larger scale, fault slip facilitates the tectonic extrusion of blocks (Pe-Piper et al. 1998; Xypolias et al. 2003; Wang et al. 2005). Fault zone permeability has an important influence on magma transport, which can take place along large scale faults, through permeable fault strands within damage zones, or from percolation between grains within the fault zone (Petford et al. 1993; Brown and Solar 1998; Cox 1999; Cruden and McCaffrey 2001; Rosenberg 2004), or from melt flow above the solidus (Leitch and Weinberg 2002). However, in general it remains obscure how the magma penetrates the crust (Brown 1994, 2001; Clemens 1998; Petford 2003).

Laccolithic intrusions have been shown to obey empirical scaling laws between their length on maps and thickness in cross-section, implying that the pluton thicknesses are having a scale-dependent relationship (McCaffrey and Petford 1997; Petford et al. 2000; Cruden and McCaffrey 2001; Vigneresse 2005). This concept of self-affine birth and inflation is also well understood for quartz veins (Stowell et al. 1999).

Geological setting of the plutons in Cobequid Shear Zone

The Cobequid Shear Zone is a family of faults active during pluton intrusion immediately to the north of the dextral strike-slip Meguma-Avalon terrane boundary of the Canadian Appalachians (Fig. 1). Well exposed plutons occur along two right-stepping fault strands and their stepover zone in the southern part of the Cobequid Shear Zone (Fig. 1a). The 60 km long Kirkhill Fault strand, which is truncated in the west by Triassic basin margin faults, bounds the large Cape Chignecto pluton (Fig. 1b) and a series of smaller plutons (Fig. 1a). The 60-km-long Rockland Brook Fault strand (Miller et al. 1995), bounds the large Wentworth pluton and the smaller Pleasant Hills pluton (Fig. 1d). Between these

two prominent faults, in their stepover zone, the deformation was accommodated by several faults including the Newton Lake shear zone within the western Pleasant Hills Pluton (NLF in Fig. 1d), a fault along the southern margin of the North River Pluton, and the fault along the southern margin of the West Moose River Pluton (Fig. 1c). The poorly exposed Wyvern and Gilbert Hills plutons (Fig. 1a) are probably composite plutons developed north of major faults parallel to the Kirkhill Fault, including the Spicers Cove fault, but outcrop in this part of the Cobequid Shear Zone is extremely poor. Apart from their total area (defined with the assistance of geophysical data), they have not been included in our analysis.

Geochronology indicates that predominantly ductile deformation along the Cobequid Shear zone lasted at least 30 million years, from 363 to 333 Ma (Pe-Piper et al. 2004). Almost all pluton emplacement may have taken place over a period of < 5 Ma from 363 to 358 Ma, based on reported dates that have standard errors of ± 2 –4 Ma (Doig et al. 1996; Pe-Piper et al. 2004) (Table 1), although the precision of dating means that pluton emplacement might have extended over as much as 10 Ma. The only exceptions are the late gabbro in the southwestern Wentworth pluton (Fig. 1e), which was emplaced at about 354–350 Ma, and a few small-volume late phases in other plutons (e.g., a small intrusive rhyolite dating at 356 ± 2 in the Pleasant Hills pluton). All plutons were emplaced in the upper crust in greenschist facies rocks.

Geological parameters, such as the present day crustal thickness, are constant all along the shear zone. Pluton geochemistry is also uniform, with Fe-rich olivine gabbros related to regional rifting (Dessureau et al. 2000) and A-type granites resulting from partial melting of anhydrous lower crust (Pe-Piper et al. 1991) of relatively uniform Nd isotopic composition (Pe-Piper and Piper 1998). The sole exception is the likely thermal effect of the 5–10 million year younger large gabbro body in the southwestern Wentworth pluton, which caused substantial melting of older granite bodies within the pluton (Koukouvelas et al. 2002). Based on these data, pluton length and width, as well as the relationship between thickness of mylonites and width of plutons, are principally the result of plutonism and tectonism.

Description of the plutons

The Cobequid Shear Zone plutons show apparently vertical boundaries in map view and inward inclined but steep contacts with host rocks in cross-section, indicating an overall southward dipping pluton floor. Furthermore, vertical mineral lineations near the main Rockland Brook fault of the Cobequid Shear Zone suggest that the fault acted as a magma conduit (Koukouvelas et al. 2002). The general scarcity of vertical plunging lineations is interpreted to imply significant horizontal magma flow away feeding zones (see also

Table 1 Geochronology of plutons in the Cobequid shear zone

Pluton	Rock	Method	Age (Ma)	References
Cape Chignecto	Granite	U-Pb zircon	361 ± 2	Doig et al. (1996)
	Granodiorite	Ar-Ar hornblende	357 ± 4	Pe-Piper et al. (2004)
West Moose River Pleasant Hills	Diorite	Ar-Ar hornblende	360 ± 2	Pe-Piper et al. (2004)
	Granite	U-Pb zircon	361 + 5/-3.5	Dunning et al. (2002)
	Granite	U-Pb zircon	358 ± 2	Doig et al. (1996)
	Granodiorite	Ar-Ar hornblende	355 ± 4	Pe-Piper et al. (2004)
	Granodiorite	Ar-Ar hornblende	356 ± 4	Pe-Piper et al. (2004)
Wyvern	Late granite	U-Pb zircon	356 ± 2	Dunning et al. (2002)
	Granodiorite	Ar-Ar hornblende	359 ± 3	Pe-Piper et al. (2004)
Wentworth (old)	Granodiorite	Ar-Ar hornblende	364 ± 3	Pe-Piper et al. (2004)
	Granite	U-Pb zircon	362 ± 2	Doig et al. (1996)
Wentworth (young)	Granite	Ar-Ar sodic amph.	365 ± 4	Pe-Piper et al. (2004)
	Gabbro	Ar-Ar biotite	352 ± 2	Pe-Piper et al. (2004)
	Gabbro	Ar-Ar biotite	350 ± 2	Pe-Piper et al. (2004)
	Granodiorite	Ar-Ar hornblende	354 ± 4	Pe-Piper et al. (2004)
Equivalent volcanic rocks (all U-Pb on zircon from rhyolite by Dunning et al. 2002)				
	Top Byers Brook Fm = end of old Wentworth granite		358 ± 1	
	Mid-Diamond Brook Fm = Wentworth late gabbro		355 ± 3	
	Fountain Lake Gp near West Moose River pluton		356 ± 2	
	Fountain Lake Gp near Cape Chignecto pluton		355 ± 2	

Améglie et al. 1997). All plutons are asymmetric, developed within the north fault block of the Cobequid Shear Zone (*sensu* Cruden 1998, his Fig. 5). Where the width of the pluton (measured orthogonal to the shear zone) is more than 2 km, magmatic foliation is of low angle (Waldron et al. 1989; Koukouvelas et al. 1996). The thicknesses of plutons are not defined either in natural sections of tilted plutons or unambiguously from gravity and other geophysical data: their 3D geometry is thus unknown. However, structural data within the plutons and their rims indicate that they translate their host in a ductile manner and penetrate crustal rocks by one or more conduits or root zones. All structural data within the plutons indicates that these bodies are almost tabular with a southward dipping floor (e.g., Cruden 1998), suggesting a cantilever shape and carrot-like roots (Pe-Piper et al. 1998). Within the plutons, contacts between different lithologies are typically moderately inclined and genetically related with the faults, which have apparently acted in some cases as magma conduits. Equivalent volcanic rocks show several eruptive episodes with evidence of magma chamber fractionation, estimated to have a periodicity of the order of 10^6 years, suggesting that magma segregation was also episodic (Koukouvelas et al. 2002).

Data

We have recently mapped the Cobequid Shear Zone at a scale of 1:10 000, enabling the recognition of major component bodies within plutons (Pe-Piper and Piper 2005), as summarized in Fig. 1. Most plutons and their component bodies (dimensions in km) are elongate subparallel to the Cobequid Shear Zone. Several samples for whole rock geochemical analysis have been taken from each plutonic body.

We have measured the long and short axes of entire plutons and those component bodies whose dimensions can be reliably mapped, as indicated in Fig. 1b–e. The well exposed Pleasant Hills and Wentworth plutons have provided most of the data on the shapes of component bodies within plutons. Fewer data are available from the western Cobequid Highlands, where pluton shape is obscured by onlapping younger strata or by thick glacial till (Pe-Piper and Piper 2005). Representative mesoscopic bodies (dimensions in m) within plutons and adjacent country rock have also been measured from areas of good outcrop, principally from glacially eroded pavements within the Wentworth pluton and from river gorges that cut the southern margin of the Pleasant Hills pluton, but parallel sided dykes have been excluded. Representative small granite lenses (dimensions in cm) within the gabbro of the Wentworth pluton were measured from photographs to evaluate the full-scale range of component bodies.

We also measured the width of highly deformed zones both at the margins of plutons and where they continue into basement rocks. These zones consist of strongly foliated rocks separated by true mylonite and locally ultramylonite. These zones are well exposed in river sections and some road sections at the southern margin of most plutons (Pe-Piper et al. 1998, their Fig. 3; Koukouvelas et al. 2002, their Figs. 7, 12) and in coastal sections in the Cape Chignecto pluton (Koukouvelas et al. 1996, their Figs. 9, 10).

In areas of good outcrop, positions are good to ± 10 m and boundaries are good to ± 20 m. Where outcrop is poor, aeromagnetic data (Kiss et al. 1989) allow positioning of boundaries of major bodies to ± 200 m. Thus for bodies > 2 km in length, the error in estimates of pluton width and length is less than 10%. In general, smaller bodies have been mapped only in areas of good outcrop and the positioning of their boundaries

is also estimated to be $< 10\%$. Good estimates of width of highly deformed zones are spaced more widely than observations on pluton width, generally along rivers or roads. Errors along these sections are $< 5\%$ and lateral extrapolation along the shear zone is probably within 10% .

Whole-rock geochemical data from the plutons has been presented in previous publications (Pe-Piper et al. 1991, 1998) and is interpreted here only in as much as it constrains the structural evolution of the plutons. All analyses have been carried out using the same laboratory methods, X-ray fluorescence for major and trace elements and INAA for REE.

Results

Aspect ratio of plutonic bodies

A plot of length against width of plutonic bodies (Fig. 2) shows that most have an aspect ratio (width:length) of between 1:1.2 and 1:11 (thus extending over an order of magnitude), with a cluster around 1:3 ($\approx 33\%$ of the data). To analyze differences between length and width in component bodies and entire plutons we calculated the slope of width in relation to length using bivariate reduced major axis (RMA) models on log transformed data. We used RMA models because both axes are equally subjected to error (Sokal and Rohlf 1995). RMA regression was performed with RMA software for RMA regression (Bohonak 2004), available at the website $< \text{http://www.bio.sdu.edu/pub/andy/rma.html} >$. RMA regression of the data shows an increased width of component bodies or plutons with length, best characterized by a power law of the form $W = 0.252L^{1.056}$, where 0.252 is a constant and the power law exponent (a) = $1.056 + 0.039/-0.036$, and a y axis intercept of -0.05979 . The slope of the best-fit line on a log-log plot is 1.056 (correlation coefficient, $R^2 = 0.97$) (Fig. 2). Small gabbro bodies in basement rocks and entire plutons have an aspect ratio of 1:2.5 to 1:4, whereas component bodies within plutons show a much greater range in aspect ratio, clustering in a length range of 1.5–4 km and with a proportionally greater range of widths from 0.1 to 2 km. Variation in aspect ratio along the strike of the fault zone (Fig. 3) indicates that more than 50% of the ratios exceed 3.5, with the most elongate component bodies concentrated along the Kirkhill fault, the stepover zone, and the eastern half of the Rockland Brook fault. This analysis suggests that the component bodies within the plutons are commonly elongate. However, as shown by previously published field data from the Pleasant Hills pluton (Pe-Piper et al. 1998) and Wentworth pluton (Koukouvelas et al. 2002), the strongest magmatic and solid-state deformation structures occur within elongate plutons. The lithology of component bodies appears to have limited influence on the aspect ratio, which has a mean

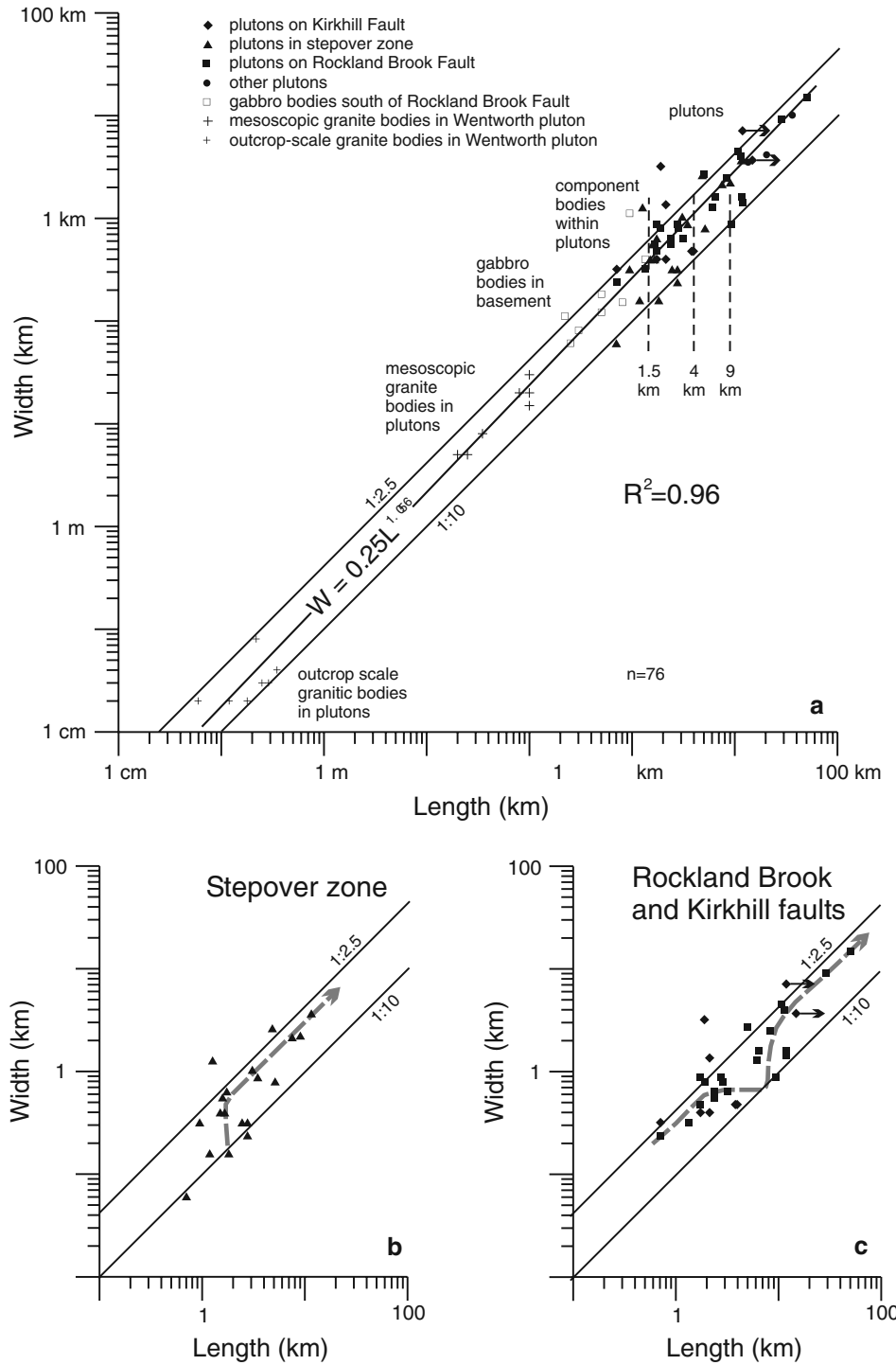
value of ≈ 4.6 for gabbro and ≈ 3.5 for granite. In the Wentworth pluton, the aspect ratio is lower near the large late gabbro intrusion, even though deformation in the area is high. All these data suggest that the dimensions of the component bodies, their length and width, are governed by the equation $L = 4W$. Note the similarity with the relationship between fault displacement against their length which varies only over different length scales (see Kim and Sanderson 2005, their Fig. 5c).

A log-log plot of the ranking of width and length against absolute width and length for plutonic bodies > 0.1 km long can be resolved into three segments with abrupt inflection points between them (Fig. 4). Bodies < 1 km in length show a rather flat distribution, those 1–9 km in length show a steeper straight-line distribution, and component plutons or entire plutons from > 10 to 11 km in length show a much steeper distribution. We do not know whether the break of slope at 1 km represents either the resolution limit of the mapping [or more generally the resolution limit of the measurement technique (Jackson and Sanderson 1992)] or is a natural characteristic of the pluton population. Plutonic bodies < 1 km in length were easily obscured by glacial till so that it is likely that not all of them were recorded. However, if small plutonic bodies have been under-sampled, this affects only the relationships in Fig. 4; in other plots, only the data density would be affected. Component bodies with length 1–9 km yield a scaling relationship $\log(N) = -0.65 \times \log(L) + 4$ and plutons or component bodies with lengths 9–50 km define a second linear segment with $\log(N) = -1.42 \times \log(L) + 5.6$. Data on pluton body width show a pattern similar to that seen in length distribution (Fig. 4). Component bodies with width 0.3–3 km yield a scaling law $\log(N) = -0.62 \times \log(w) + 3.2$ and plutons or component bodies with widths > 3 km define a second linear segment with $\log(N) = -1.28 \times \log(w) + 3.7$.

Faults, deformation and plutons

Irregular dykes cutting more deformed plutonic rocks are increasingly abundant towards the Kirkhill and Rockland Brook fault zones, suggesting that the faults on the southern margins of plutons were the major magma pathways (Koukouvelas et al. 1996). Therefore, we have concentrated our attention on these faults, the plutons which they bound, and deformation associated with them. The width of the highly deformed mylonitic zone in any cross-section of the Kirkhill and Rockland Brook faults is generally proportional to the width of the pluton to the north (Fig. 5). Most plutons are widest at their western end and progressively narrow eastward, which along with the existence of subvolcanic lithologies at the east ends of the plutons (Fig. 1) suggest that this outcrop pattern corresponds to deeper structural levels at the western ends. In the Wentworth and Pleasant Hills plutons, the width of the mylonite zone also decreases

Fig. 2 a Plot of length to width for plutonic bodies. Insets show detail of **b** stepover zone only and **c** plutons along the Rockland Brook and Kirkhill faults only



eastward. In the stepover zone, mylonites are generally thin or absent (Fig. 5). Along the Kirkhill Fault, in the few cases where the full width of the pluton is well exposed, dimensions are similar to those at the eastern end of the Rockland Brook Fault.

Anomalously high widths of the deformed zone are found in the western Wentworth pluton and the eastern Pleasant Hills pluton, close to the younger Wentworth pluton gabbro (Figs. 5, 6). Except for this, along the

Rockland Brook fault, for plutons > 4 km wide, width of the highly deformed zone shows a linear relationship to pluton width. The ratio of width of mylonite to width of pluton is 1:7 (correlation coefficient, $R^2 = 0.89$) (Fig. 6) and similar sized plutons along the Kirkhill Fault show a similar relationship. In contrast, mylonites and plutons in the stepover zone show a similar ratio of 1:7 for all sizes of plutons (with a poorer correlation coefficient, $R^2 = 0.60$).

Fig. 3 Variation in aspect ratio (length:width) along the length of the Cobequid Shear Zone. Distances are indicated in Fig. 1

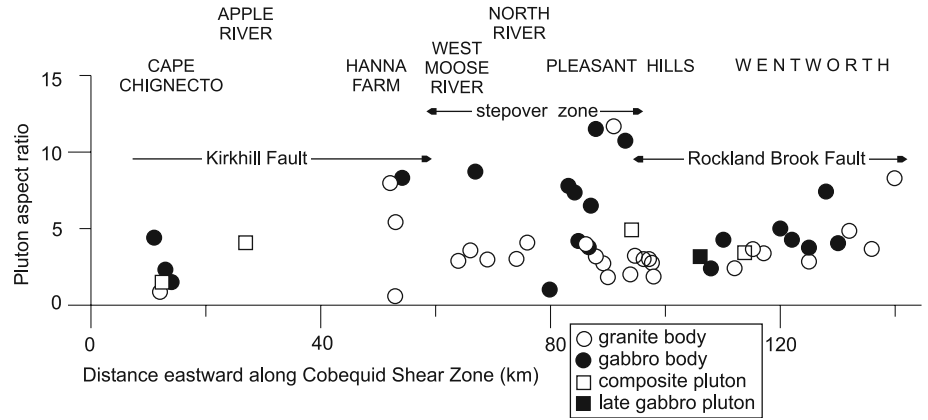


Fig. 4 Cumulative number versus plutonic body length and width plots in logarithmic scales. Both length and width distributions fit linear functions (for explanations, see the text)

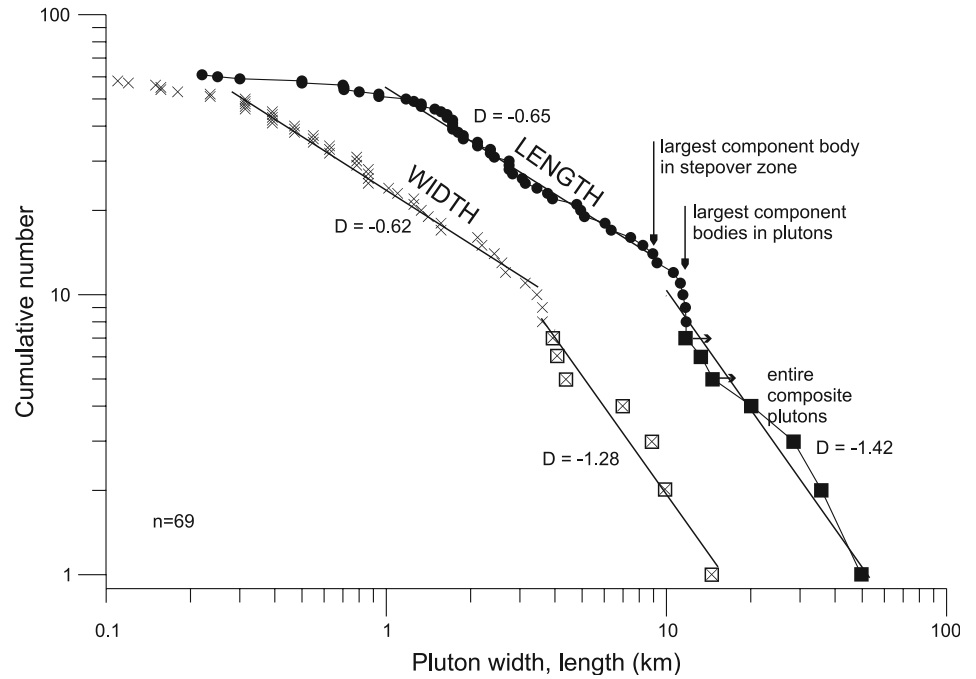


Fig. 5 Variations in width of deformed zone and width of pluton to the north along the length of the Cobequid Shear Zone. Distances are indicated in Fig. 1

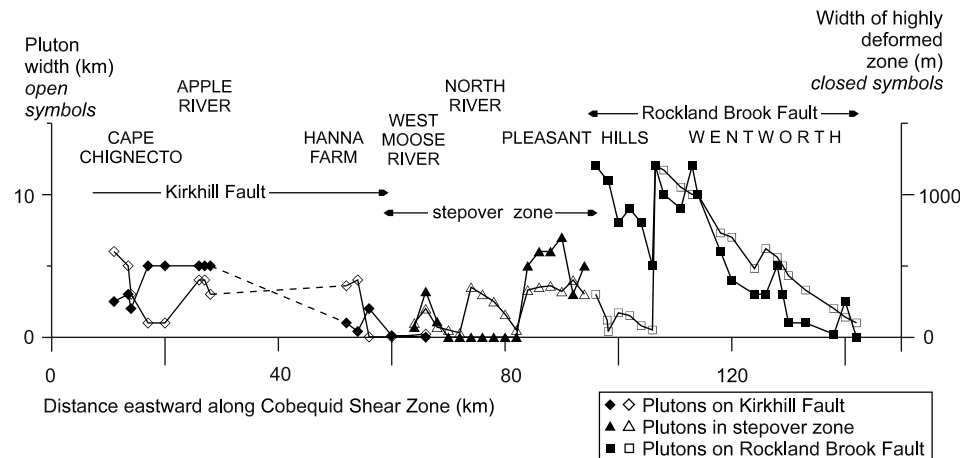
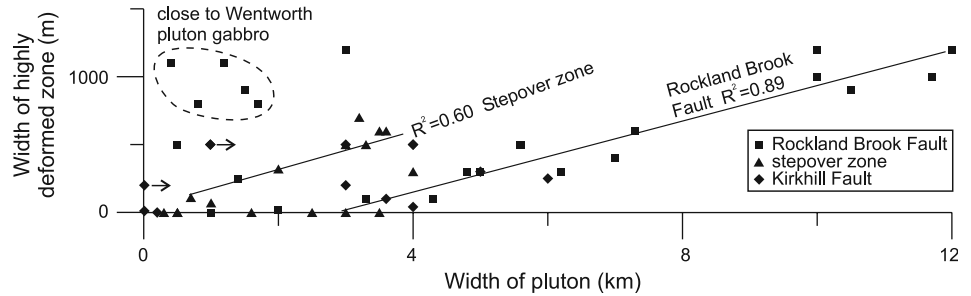


Fig. 6 Plot of width of highly deformed zone against the width of pluton



Relationship of geochemistry of plutonic bodies to faulting

Variations in the geochemical character of magma in shear zones has been interpreted by previous authors (e.g., Vigneresse et al. 1996; Hecht et al. 1997) to be a consequence of (a) the nature of the partial melting in the source area, (b) chemical evolution including fractional crystallization and assimilation during magma ascent, and (c) local magma expulsion from a crystal mush by shear-enhanced compaction in shear zones. In the Cobequid Highlands, granites with SiO₂ contents >70% (Fig. 7), unlike most granodiorites, generally show no evidence of having mixed with gabbroic magma. Previous work has shown that variations in several trace elements, including Nb and Zn (Fig. 8), are related to variations in the conditions under which partial melting took place (Pe-Piper et al. 1991) and are there-

fore not discussed further here. Chemical evolution during magma ascent, including fractionation of water, and magma expulsion by shear-enhanced compaction both result in chemical segregation of incompatible large-ion lithophile elements such as Rb and Th (Fig. 8). Regionally, plutons developed north of the Kirkhill and Rockland Brook faults have high Rb content, whereas low Rb is found in the plutons in the stepover zone: the western Pleasant Hills, West Moose River and North River plutons (Fig. 7c). The exceptions are that low Rb also occurs in some late granites of the Wentworth pluton, which have a complex history involving remelting of older granite by the late gabbro body (Koukouvelas et al. 2002), and high Rb is found in the late granites of the western Pleasant Hills pluton. A similar variation is shown by Th, which is lowest in the early rocks of the western Pleasant Hills pluton (Fig. 8b) and in some rocks of the North River and West Moose River

Fig. 7 Plots showing variation of Rb with SiO₂ for granites of the Cobequid Shear zone. Dashed line shows lower limit of Rb content of plutons along the Kirkhill and Rockland Brook faults

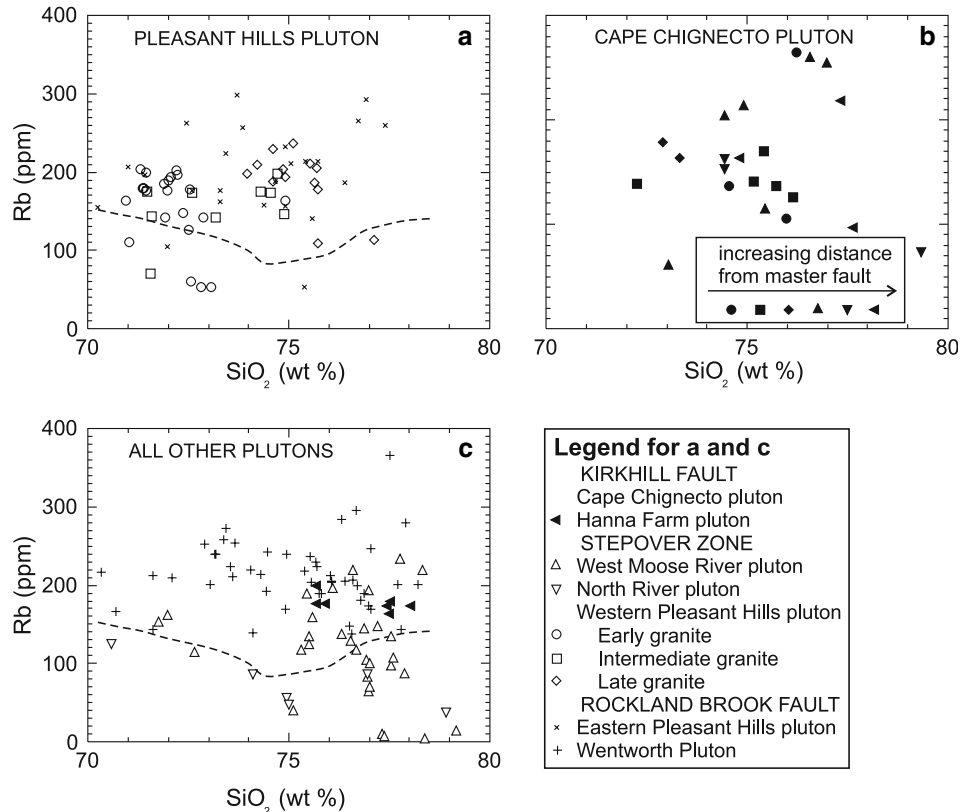
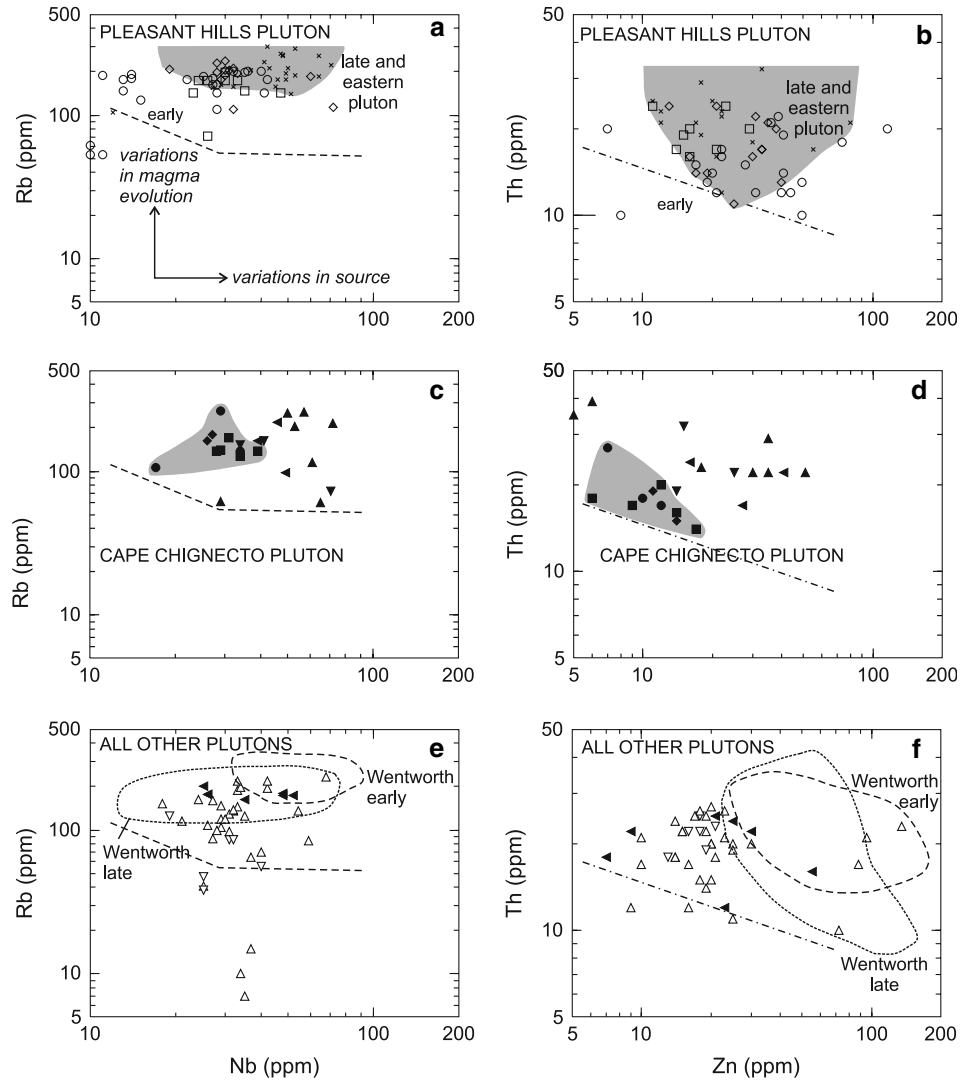


Fig. 8 Element plots showing effects of variation in magma source and variations in magma evolution. Legend as in Fig. 7. *Dashed line* shows lower limit of Rb and Th content of plutons along the Kirkhill and Rockland Brook faults. **a, b** Plot of Rb against Nb and Th against Zn for the Pleasant Hills pluton, where the relative ages of component bodies are well known (Pe-Piper et al. 1998), showing relative ages for the western part of the pluton. Variations in Nb and Zn (a proxy for F) are a consequence of source partial melting conditions (Pe-Piper et al. 1991). *Shaded area* emphasizes late bodies and those of the eastern pluton. **c, d** Plot of Rb against Nb and Th against Zn for granites of the Cape Chignecto pluton, showing variation with distance from the southern master fault. *Shaded area* emphasizes those samples nearer the master fault. **e, f** Plot of Rb against Nb and Th against Zn for all other plutons in the Cobequid Shear Zone (fields for Wentworth pluton; data points for other plutons)



plutons (Fig. 8f). In the Cape Chignecto pluton, where many samples are available at varying distances from the master fault zone, those farther from the master fault zone tend to have higher Th (Fig. 8d) and less systematically, higher Rb (Fig. 7b, 8c). The abundances of Rb (Fig. 7) and Th (not illustrated) show no systematic trend with increasing SiO_2 content (Fig. 7). The high Rb in the plutons along the major fault strands is thus not a result of processes leading to high Si content, but rather it is likely due to concentration of elements in hydrous magma expelled from crystal mush in shear zones (Vigneresse et al. 1996). On the other hand, in the North River pluton Th, but not Rb, shows a systematic decrease away from the southern margin fault (Fig. 9), indicating that the granite emplaced at a greater distance from the magma pathway is more fractionated, as observed by Hecht et al. (1997) in the Fichtelgebirge granites. A similar dichotomy in the variation of Rb and Th with distance from the southern margin fault is seen in the Cape Chignecto pluton (Fig. 7c).

Discussion

Research over the last decade suggests that directly or indirectly, fault-related emplacement is the most robust process for pluton formation. This model shows two end modes: those plutons that evolved by vertical accretion (i.e., Cruden 1998) and those that evolved by horizontal accretion perpendicular to an active fault that also acted as magma conduit (as in this study). Our contribution sheds light on how horizontal accretion is built-up from component bodies within plutons.

The third dimension of the plutons

As discussed above, thickness of the plutons is unknown. However, the larger of analyzed plutons show strong evidence for dyke-to-pluton development. They have carrot like roots along their southern rim inferred

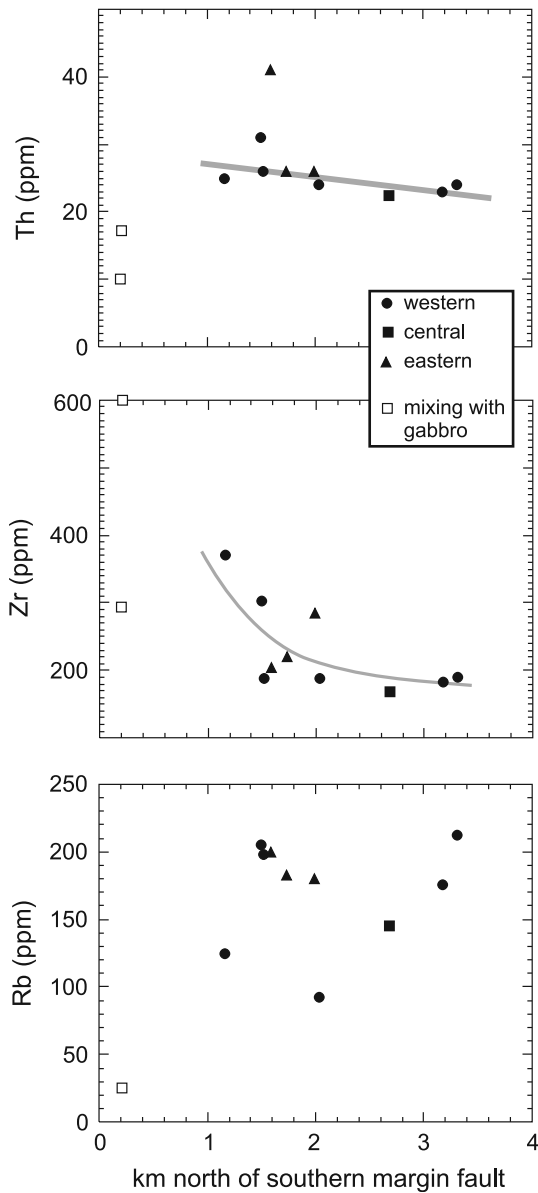


Fig. 9 Plots of Th, Zr and Rb against distance from southern margin fault in the North River pluton

from gravity data and internal structural patterns (Koukouvelas et al. 2002). Geochemically, less evolved granite and the greatest abundance of gabbro is found along the southern rim. All these suggest that the thickness dimension of the pluton is set at the early beginning along the magma conduit of the pluton and the subsequent pluton evolution has a greater impact on the map view of the pluton. The consistency of the morphometric analysis of centimeter-scale dykes to kilometer-scale plutons suggests that cm-scale dykes are located at the propagating edge of early formed component bodies, with a height within the crust much longer than any other dimension. Thickness in horizontally accreted plutons, such as the Cobequid Shear

Zone plutons, may not contain much information, but rather is a consequence of the brittle–ductile transition or some other kinds of mechanical barrier of the crust at the time of pluton intrusion (Cruden 1998 and references therein). We also note that information on component bodies and structural interpretation is widely available on geological maps, and therefore our empirical power laws can be tested also for other horizontally accreted plutons.

Larger plutons bounded by the Kirkhill and Rockland Brook faults

Large, elongated granitic plutons along the two major fault strands are made up of multiple bodies generally subparallel to the fault trend and show evidence of construction from a series of component bodies, as summarized in Fig. 1. The multiple component bodies of the large plutons, with a length to width ratio of about 1:3, have distinctive geochemical characteristics suggesting that they comprise different magma batches (Pe-Piper et al. 1998). As argued above, all show elevated amounts of incompatible elements such as Rb resulting from segregation of hydrous magma from crystal mush in shear zones (Hecht et al. 1997). The southern boundary of each large pluton was a broad shear zone in which mylonites formed during the progressive deformation that is evidenced by cross-cutting igneous phases (Pe-Piper et al. 1998; Koukouvelas et al. 2002). Primarily this shear zone, as well as splays off this zone, were the site for emplacement of new magma and thus contributed to the growth of the pluton. Repeated injections of magma in the highly deformed zones would maintain elevated temperatures over a longer period. Strongly elongated bodies are most common within the highly deformed zones and may reach length to width ratios of 1:11. This flattening may in part be the result of solid-state deformation, since mafic enclaves show flattening of 1:5 within the highly deformed zones, with the degree of flattening decreasing northward (Koukouvelas et al. 2002). Such flattened bodies, however, make up less than 5% of the total data set.

All plutons >2 km wide along the Kirkhill and Rockland Brook faults have mylonite zones >100 m wide at their southern margin. For the Rockland Brook Fault, width of the highly deformed zone correlates well with the width of the pluton ($R^2=0.89$). This correlation is interpreted to be a result of the regional migration of melt into high-strain zones (Brown and Solar 1998). The lack of precise correlation between high deformation areas (Fig. 5) with pluton aspect ratio (Fig. 3) implies that the relationship between magmatism and deformation is complex (see also Petford 2003). The variation in pluton size shows that the rate of magma delivery varied along the major faults. Space for magma was created by fault slip, but not all fault slip resulted in pluton emplacement.

Smaller plutons of the stepover zone

In contrast to the large composite plutons along the Kirkhill and Rockland Brook faults, the plutons in the stepover zone tend to be smaller and internally more homogenous (West Moose River, North River and western Pleasant Hills plutons)(Fig. 1). In the stepover zone, displacement was taken up on numerous smaller faults, some of which have an extensional component relative to the major dextral strike-slip faults.

Earlier plutonic bodies in the stepover zone do not show strong enrichment in incompatible elements (Figs. 7, 8). Later plutonic bodies show the same enrichment similar to that seen in plutons north of wide mylonite zones. The small amount of deformation in the West Moose River and North River plutons (Kokouvelas et al. 1996) probably suggests that these plutons were emplaced rapidly compared with the total time of deformation in the Cobequid Shear Zone, although radiometric age data are insufficient to confirm this (Table 1). In the case of the North River pluton, which shows neither significant mylonite (Fig. 5) nor strong enrichment in incompatible elements (Figs. 8, 9), the fault segment may have locked after magmatism.

We therefore conclude that plutonic bodies < 2 km wide and < 4 km long may be emplaced rapidly, without significant mylonitic deformation, along short fault segments. Field observations in the stepover zone suggest that such fault segments were 5–10 km in length. The highly variable width (0.1–1 km) of the 1.5–4 km long plutons suggests that the amount of magma drained towards faults during the emplacement of the plutons was highly variable. Therefore, component bodies of these dimensions were likely located on minor faults at the propagated end of larger faults, rather than on the master Rockland Brook and Kirkhill faults. This is also indicated by the presence of country rock within the Pleasant Hills pluton (Pe-Piper et al. 1998). Some minor faults could have later served as the locus for development of longer fault strands during the evolution of the fault zone, in the manner described by d'Alessio and Martel (2005).

Fault influence on growth of larger plutons

The distribution of pluton sizes suggests that at the time of magma emplacement, the Kirkhill and Rockland Brooks faults were both major faults of a scale different from that of the faults of the stepover zone. The Rockland Brook Fault appears to be made up of three or four discrete linear fault segments each 12–18 km in length (Pe-Piper and Piper 2005). Fault segments of this length also bound the syn-tectonic basins in this part of the shear zone (Piper and Pe-Piper 2001). The fault segments appear to have coalesced to form a 60-km-long fault that acted as a major conduit for magma. The scaling properties and the mechanics of faulting (see discussion in chapter 3 of Scholz 2002) suggests that the

thickness of fault rocks is proportional to the fault displacement which is in turn in direct proportionality to fault length (Kim and Sanderson 2005). The width of the mylonite zone along the Rockland Brook Fault compared with the mylonites in the stepover zone suggests that motion along the fault continued over a prolonged time. Such a 60-km-long fault would have taken up a significant amount of motion on the Cobequid Shear Zone and would have extended deep into the crust, at least to the brittle–ductile transition zone. In the stepover zone, the ratio of fault segments length to pluton length is approximately 2:1. An analogous relationship to fault segment length on the larger faults might explain the inflection in the rank–length relationship at 9 km length (Fig. 4).

Since our data show that faults play an important role in localizing plutonic bodies, then plots of fault-strike length against fault displacement (Jackson and Sanderson 1992; Davison 1994; Marrett et al. 1999; Kim and Sanderson 2005) can be considered analogous to plots of pluton body length against width (Fig. 2). Fault dimensions show a linear pattern on a logarithmic plot, but with a steeper gradient than that shown by pluton length and width (Fig. 10). However, for lengths of 1–100 km, the two trends are close. Small plutonic bodies show a length–width trend that is similar to small faults (Davison 1994), gashes (Hippertt and Massucatto

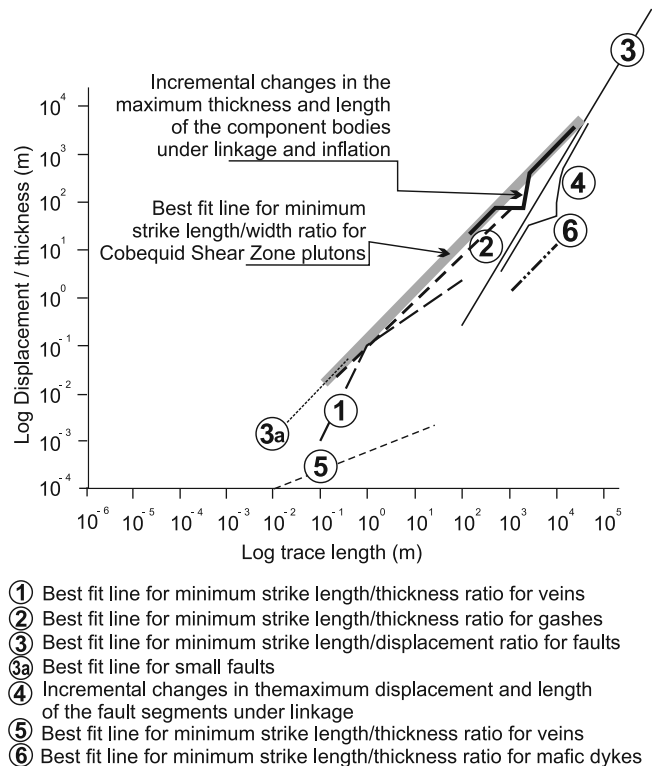


Fig. 10 Fit lines in log–log space showing displacement of faults (3)–(3a), thickness for veins (1) and (5), gashes (2), and mafic dykes (6) as a function of their length. Fit line (4) shows how linkage of faults creates variation in the length–displacement variation

1998), and some reported measurements of veins (Johnston and McCaffrey 1996). In contrast, dykes and many veins (Vermilye and Scholz 1995; Johnston and McCaffrey 1996; Stowell et al. 1999) show a length–width relationship with a much lower gradient, with dyke width increasing only slightly with increasing length. This observation confirms that the “dyke to pluton” construction takes place through a process involving slip or deformation along faults. Pluton experience far more complex evolution than veins, because of the local effects of magma segregation during emplacement (Vigneresse 1995, 1999).

Natural associations of fault segments commonly show departures from linearity in a plot of log displacement against log length, that have been explained (Wojtal 1996) as resulting from fault linkage (abruptly increasing length without increasing displacement) followed by the fault adjusting to increase its displacement with little or no increase in strike length. An analogous pattern in pluton length–width data (Fig. 2) can be interpreted at 3–10 km length on the Rockland Brook fault (grey arrow in Fig. 2c), with a cluster of pluton bodies of similar width for a considerable range of lengths, followed by an increase in width for little change in length. This latter trend is also seen for 1–3 km long plutons of the stepover zone (Fig. 2b).

Most component bodies cluster in the size range 1.5–4 km length and 0.1–2 km width (Fig. 2), whether in the stepover zone or in the large plutons along the major fault strands. The control of the upper limit of kilometer length is probably related to dynamics of the fault system. A small fault will experience frequent self-sealing. A longer fault has a greater chance of tapping magma in the brittle–ductile transition zone of the crust and thus maintaining an active pathway for magma for a longer time, allowing larger plutonic bodies to develop. In contrast, small faults experienced occasional permeability during continuing deformation and slip in the shear zone and only if a period of high permeability corresponded to middle crustal supply of magma would a plutonic body be emplaced.

The relationship of component bodies to composite plutons

The rank distribution of body length (Fig. 4) shows a pronounced inflection at about 9 km length for the largest component bodies. Those that are plotted form parts of three plutons (Cape Chignecto, Pleasant Hills and Wentworth) and developed along linked fault segments totaling > 50 km in length. The inflection at 9 km length and 3 km width can be accounted for if component bodies larger than this value have coalesced and interacted. The locations at which component bodies are initiated may be widely spaced, at > 9 km along strike and > 3 km across strike. Field data supporting this comes from the Pleasant Hills pluton, where primitive gabbros are widely distributed within the area that later hosted the main granitoid

pluton (Fig. 1d). The size of composite plutons shows a different distribution from the size of the component bodies (Fig. 4) and resembles plots of rank size of faults (Wojtal 1996). Being localized by faults and made up of bodies with a restricted range of width to length ratios, the composite plutons themselves show a relatively narrow range of width to length ratio (1:2.5 to 1:5). All these observations suggest that the mechanical behavior of faults appear to be an important mechanism in defining the size of composite plutons. This study has shown that if information on processes is to be extracted from the geometry of composite shear zone plutons, it is necessary to map and understand the component bodies.

Conclusions

1. Individual bodies defining the dyke to pluton construction have typical length to width ratios of 1:4, with more extreme elongation only where flattened in highly deformed zones. In most plutons, the total width of the pluton varies systematically with width of the highly deformed zone along the master fault. These relationships imply that the creation of space for pluton emplacement appears to be related in a rather systematic manner to fault processes in the shear zone.
2. Component bodies of plutons show length to width relationships analogous to length to displacement relationships in fault systems and quite different from length to width relationships in dykes and veins. This implies that “dyke to pluton” construction is controlled by the mechanical behavior of faults.
3. Small faults allow the emplacement of plutons 1.5–4 km long and 0.1–2 km wide. They are limited by the self-sealing properties of faults and the inability of small faults to drain large amounts of percolating magma from the brittle–ductile transition zone of the crust. Such small plutons show low enrichment in incompatible elements in the older component bodies, but increasing amounts in younger component bodies as a result of progressive magma expulsion from crystal mush in the fault zone. Wider plutons have > 0.1 km wide highly deformed zones, with evidence of multiple intrusion of igneous bodies along the high strain zone. They generally have longer fault strands and are inferred to result from the organization of shorter fault strands into major faults accommodating more strain and penetrating deeper in the crust. Component bodies of all ages show enrichment in incompatible elements, pointing to important magma segregation in building these upper crustal plutons.
4. The geometry of large composite plutons does not show identical distribution patterns to the component bodies that make up those plutons: similarities in geometry are rather a consequence of the development of component bodies along a master fault zone. It is the component bodies that provide information on processes on faults.

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