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A. Burton-Johnson, C.G. Macpherson, J.R. Muraszko, R.J. Harrison, T.A. Jordan

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Tectonic strain recorded by magnetic fabrics (AMS) in plutons, including Mt Kinabalu, Borneo: A tool to explore past tectonic regimes and syn-magmatic deformation

Burton-Johnson, A[a*], Macpherson, C.G.[b], Muraszko, J.R. [c], Harrison, R.J.[c], and Jordan, T.A.[a]

[a]British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK

[b]Department of Earth Sciences, University of Durham, Durham, DH1 3LE, UK

[c]Department of Earth Sciences, University of Cambridge, Cambridge, CB2 3EQ, UK

*Author for correspondence

E-mail: alerto@bas.ac.uk

Tel. +44 (0)1223 221284

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Highlights

(1) The tectonic fabric in the AMS data of Mt Kinabalu, Borneo, reveals Miocene extension in SE Asia between 7.9-7.3 Ma (later than previously recognised). Correcting for paleomagnetic rotation, extension was oriented NW-SE at 319° ±13.1°.

(2) Tectonic strain fabrics are far more ubiquitous in global plutonic fabrics than previously recognised.

(3) AMS determination of tectonic strain in dated plutons is a powerful tool for determining past tectonics within a temporal framework, particularly when combined with evidence for paleomagnetic rotation.

Abstract

Tectonic strain commonly overprints magmatic fabrics in AMS (Anisotropy of Magnetic Susceptibility) data for plutonic rocks produced by both compressional and extensional regimes. Mt Kinabalu, Borneo, is a composite pluton with an exceptional vertical range of exposure and clearly defined internal contacts. We show that tectonic fabrics are recorded pervasively throughout the intrusion, even near contacts, and present a workflow distinguishing compressive and extensional syn-magmatic deformation. At Mt Kinabalu this reveals a pervasive tectonic fabric indicating NW-SE Miocene extension in Borneo at 7.9-7.3 Ma, later than previously recognised, oriented NW-SE at 319° ±13.1°. Comparing data from Mt Kinabalu with data from globally distributed studies shows that tectonic strain is commonly recorded by plutons. Therefore, AMS fabric can be used to identify the syn-magmatic tectonic setting and combined with both geochronology and evidence for paleomagnetic rotation to provide a powerful tool for accurate determination of syn-magmatic tectonic regimes and strain orientations within temporal frameworks.

1. Introduction

Determining syn-magmatic strain is a challenge for research into plutonic intrusions because traditional structural evidence (faults and dykes) can only record the post-magmatic deformation of their host pluton. Instead, evidence is obtained from mineral fabric alignment (Hutton, 1988; Pitcher, 1997; Paterson et al., 1998; Schofield and D'Lemos, 1998). Be this visible alignment of the rock-forming phases, or more subtle alignment of the magnetically susceptible phases, the recorded strain results from combined magmatic, tectonic, and lithostatic stresses during crystallisation.

Identifying the effects of magmatic or tectonic strain provides valuable information. For example, a magma flow fabric would inform how plutons are intruded, whilst a tectonic fabric would record the tectonic strain orientation during emplacement. However, contrasting interpretations of plutonic mineral fabrics as the recorders of magmatic flow or tectonic strain exist, even for similar intrusions and tectonic settings (e.g. Petronis and O'Driscoll, 2013; Tomek et al., 2016).

In this study we use field and magnetic fabric (AMS, Anisotropy of Magnetic Susceptibility) data from the Mt Kinabalu intrusion of Borneo to demonstrate the pervasive overprint of tectonic fabrics upon magmatic fabrics.. We use the Mt Kinabalu intrusion to demonstrate that determining these tectonic fabrics by AMS offers a powerful tool to obtain temporal constraints on past tectonic regimes. In this case, we constrain the syn-magmatic deformation during a period of disputed tectonics in SE Asia. We compare this with data from other globally distributed plutons to show that such records of deformation are commonly present in granitic plutons,

2. Application of AMS to mineral fabric research

Mineral fabrics in granitic plutons have long been mapped and studied but accurate determinations of these fabrics are often difficult and observations risk being biased by the two dimensional nature of an outcrop. Consequently, analysis of the Anisotropy of Magnetic Susceptibility (AMS) has frequently been applied to granitic intrusions (Bouchez, 1997). This method measures variation in the susceptibility of each of the three, principal, magnetic axes of an oriented sample (Jezek and Hrouda, 2004); K1, the axis of maximum magnetic susceptibility; K3, the axis of minimum susceptibility; and K2, the intermediate axis (Fig. 1). This method allows fast, inexpensive, and accurate determination of three-dimensional mineral fabrics even when such fabric cannot be observed in outcrop.

Magnetic fabrics can be hosted by ferro-, ferri-, para-, or diamagnetic phases. These classifications and the grain size of the carrier phase determine the nature of observed magnetic fabrics. The magnetic susceptibility of ferro- and ferrimagnetic phases (e.g. magnetite, and pyrrhotite) is three orders of magnitude greater than paramagnetic phases (Hunt et al., 1995). In ferromagnetic minerals all magnetic moments align, whilst in ferrimagnetic minerals some point in the opposite direction. Below their Curie temperature, ferro- and ferrimagnetic phases magnetise when exposed to a magnetic field and remain magnetic once the field is removed. In contrast, the much less magnetic phases exhibiting paramagnetism (e.g. biotite and hornblende) cease being magnetic once the field is removed. The weakest magnetic effect occurs in diamagnetic minerals (e.g. quartz), which are often classed as 'non-magnetic'.

Magnetic domains in ferro- and ferrimagnetic phases cause their magnetic susceptibility to be grain size dependent, with larger grains displaying greater susceptibilities (Hunt et al., 1995). As grain size increases the magnetic domain state changes from single-domain to multi-domain. This is important for AMS studies, as whilst the axes of magnetic susceptibility in multi-domain grains (and the paramagnetic phases biotite and amphibole; Bouchez, 1997) correspond with the grain shape, in single-domain grains the magnetic susceptibility axes are inverted (Stephenson et al., 1986), producing inverse magnetic fabrics (Hrouda and Ježek, 2017). Multi- and single-domain grains can be differentiated by varying the temperature and magnetic field imposed on a sample, as in this study.

3. Development of plutonic mineral fabrics

Magmatic mineral fabrics form during crystallisation in response to the stress experienced by partially molten magma until it cools to its solidus. This stress can be a result of: (1) the primary magma flow during emplacement, including stress applied by the ascending magma column on the melt (e.g. Horsman et al., 2005, Stevenson et al., 2006, Stevenson et al., 2007a, Clemens and Benn, 2010); (2) regional tectonic stress during emplacement and crystallisation (e.g. Vigneresse, 1995, Benn et al., 1997, Benn, 2009); or (3) a combination of both (e.g. Wennerström and Airo, 1998, Petronis et al., 2012). Whether a plutonic mineral fabric (including AMS) records magmatic or tectonic stresses will be determined by the dominating force during final crystallisation of the pluton at the end of its emplacement.

In response to syn-magmatic stress, crystals align their longest principal axis with the long axis of the resultant strain ellipsoid and their shortest principal axis parallel to the short axis of the strain ellipsoid (Fig. 1, Paterson et al., 1998). This relationship of mineral fabric to the strain ellipsoid has been shown by numerical and analogue experiments for simple, non-coaxial shear, for pure, coaxial shear, and for mixed strain conditions (Jeffery, 1922; N. C. Gay, 1968; No C. Gay, 1968; Arbaret et al., 1997; Schulmann et al., 1997; Schulmann and Ježek, 2012).

The relationship between stress and strain is complex and requires consideration, as observed magmatic fabrics may record a spectrum from coaxial to non-coaxial deformation. The resultant AMS fabrics expected for different deformation settings are shown in Fig. 2. Coaxial, non-rotational shear can be expected away from rheological contrasts (i.e. away from internal and external contacts), resulting from tectonic stress, and stress exerted by the upwelling magma and overburden (Paterson et al., 1998).

Under coaxial, non-rotational shear, the shortest principle axis of the strain ellipsoid is parallel to the direction of maximum compressive stress (σ_1, Fig. 1 and Fig. 2) whilst the longest principle axis of the strain ellipsoid will be parallel to the direction of minimum compressive stress (σ_3, Fig. 1 and Fig. 2). The degree to which rigid particles (i.e. the crystal fabric) rotate in response to the strain ellipsoid will increase at higher degrees of strain (N. C. Gay, 1968), increasing the anisotropy of the fabric. However, assuming a random initial particle distribution, even at low degrees of strain the overall distribution of the respective stress and strain axes (and consequently the AMS fabric) will be parallel; albeit with a lower degree of anisotropy (Arbaret et al., 2000).

Non-coaxial simple, transpressional, and trans-tensional shearing can be expected to affect both magmatic and tectonic fabrics, particularly where there is differential movement near rheological contrasts. This includes both internal and external contacts (Blumenfeld and Bouchez, 1988; Paterson et al., 1998) or where a pluton is emplaced along a shear zone (Archanjo et al., 1999, 2002).

Under non-coaxial shear, with increasing degrees of strain the longest principle axis of the strain ellipsoid (and consequently the crystals) will rotate towards the direction of shearing and consequent stretching (elongation) direction (Fig. 2). The shortest principle axis of the strain ellipsoid and crystals will rotate towards perpendicular to the rheological boundary and orthogonally to the direction of extension (Fig. 2, Arbaret et al., 1997; Benn, 2010). In non-coaxial shear, the relationship between stress and strain orientations is dependent on a number of factors including tectonic setting, the degree of shearing, rheological contrasts and pre-existing structures.

As noted, a crystallising melt will experience a spectrum from coaxial to non-coaxial shearing, complicating derivation of stress and strain vectors. However, coaxial and non-coaxial shear produce distinct and different fabrics (Fig. 2). By predicting these fabrics for the magmatic and tectonic strain regimes of a pluton (Fig. 2) and comparing them with the pluton's observed magmatic fabric, the relative contributions of coaxial and non-coaxial shear can be determined.

4. The Mt Kinabalu Intrusion, Borneo

The Mt Kinabalu intrusion of Sabah, Borneo (Fig. 3), provides an ideal field area to investigate magnetic mineral fabrics in three dimensions across a single composite pluton. This is because it has an extensive, glaciated summit; a 2900m vertical range of granitic exposure; clearly mapped internal and external contacts; and strong temporal constraints on the emplacement historyThe pluton intruded into the shallow crust (3-12 km, Vogt and Flower, 1989; Cottam et al., 2013; Burton-Johnson et al., 2017) as six major granitic units between 7.85 and 7.55 Ma (Cottam et al., 2010) at the contact between the Mesozoic ophiolitic ultramafic basement (Reinhard and Wenk, 1951; Dhonau and Hutchison, 1965; Koopmans, 1967; Kirk, 1968; Leong, 1974) and overlying Eocene to Lower Miocene turbiditic sandstones of the Crocker Formation (Collenette, 1965; van Hattum et al., 2006). Contrasting geodynamic settings have been proposed for NW Borneo at this time, either as a zone of regional compression (Hutchison, 2000; Swauger et al., 2000; King et al., 2010; Pubellier and Morley, 2013) or regional extension (Cottam et al., 2013; Hall, 2013; Burton-Johnson et al., 2017). Contact metamorphism of the adjacent ultramafic rocks generated talc and anthophyllite, indicative of granitoid emplacement at 630-700°C and 2–3 kbar (7-11 km, Bucher and Grapes, 2011).

Recent work (Cottam et al., 2010; Burton-Johnson et al., 2017) has shown that the composite pluton was initially emplaced from the top down in a broadly laccolithic structure (Fig. 3C) through upward deformation of the host rocks. Consequently, the oldest unit (the Alexandra Tonalite/Granodiorite, 7.85 ±0.08 Ma) overlies the subsequent, larger units (the Low's Granite, 7.69 ±0.07 Ma, and the King Granite, 7.46 ±0.08 Ma). The smaller, vertical planar Donkey Granite (7.49 ±0.03 Ma) intruded the King Granite before the latter could fully crystallise, producing contacts that vary from gradational to mingled. The final two porphyritic units (the Paka Porphyritic Granite, 7.32 ±0.09 Ma, and the Mesilau Porphyritic Granite, 7.22 ±0.07 Ma) deviate from the laccolith model having been emplaced laterally and around the periphery of earlier units (Fig. 3c).

Mineralogies of the units are summarised in Table 1. Petrographically the units are largely classified as granites (Burton-Johnson et al., 2017), although their major element composition is largely granodiorite (Burton-Johnson et al., in review). Hornblende is the dominant mafic phase in all units except the Alexandra Tonalite/Granodiorite, in which biotite dominates. Visible mineral macrofabrics are absent in all units except the Alexandra unit, in which a biotite foliation was observed, dipping ~40-60° towards the south-west (Burton-Johnson et al., 2017). To test this observation, image analysis (adapting the methodology of Grove and Jerram, 2011) was conducted on thin sections of each unit (Fig. 4), characterising the colour palettes for biotite and hornblende in each section to determine the 2D orientation of the ferromagnesian crystals (Fig. 4). The standardised resultant vector length, $\bar{R}$, (the data distribution parameter in circular directional statistics, Davis 1986) is higher (i.e. more consistently distributed) for the Alexandra unit than the later units for both hornblende (0.008 compared to 0.002) and biotite (0.004 compared to 0.002). Furthermore, no microstructural evidence for shearing was observed in the thin sections of any unit (Fig. 4).

5. Methodology

Whilst the glaciated summit of Mt Kinabalu provides complete exposure, and the topography provides an exceptional vertical range of outcrop, steep cliffs and rainforest-covered flanks limit the area that can be sampled. However, previous work has shown the remarkable lateral homogeneity of AMS fabrics in plutons at a range of scales, with variations in fabric orientations occurring around a mean vector (Bouchez, 1997; Olivier et al., 1997). What is less constrained is the degree AMS fabric heterogeneity vertically through a pluton. The 2900m vertical range of outcrop at Mt Kinabalu provides a unique opportunity to explore this, and consequently sampling focussed on transects to the North, South, East and West of the pluton. Samples were collected at 50m vertical intervals on the summit and the accessible southern flank, and at 100m vertical intervals elsewhere.

94 oriented block samples were collected (Fig. 5) from which 10 to 24 cylindrical cores of 11cm^3 were drilled per sample at the University of Birmingham, UK (Owens, 1994) The number of cores depended on each sample's weathering and alteration. Oriented cores were analysed on an AGICO KLY-3s Kappabridge at the University of Birmingham to determine the orientation and magnitude (K) of the three principal axes of the AMS fabric (K1, K2 and K3; Fig. 1). Each sub-specimen's results were normalised by the specimen's mean susceptibility (K_{mean}) and averaged for each block sample to determine mean values of the AMS ellipsoid (Jelínek, 1978, Owens, 2000). To determine the magnetic mineralogy,

variability of magnetic susceptibility with temperature was determined on powdered samples at the University of Cambridge, UK. An AGICO MFK1 Kappabridge with a CS4 high temperature attachment and CS-L low temperature attachment was used under an argon atmosphere to reduce secondary oxidation. Samples representing each plutonic unit were selected for detailed magnetic characterisation. Hysteresis loops, DC demagnetisation curves and first-order reversal curve (FORC) diagrams were collected using a Lakeshore Vibrating Sample Magnetometer at the University of Cambridge.

6. Results

6.1. Shape of the AMS fabric

Full results are given in the supplementary material. The shape of the observed AMS fabric is described according to the relative dimensions of the three principal axes of the AMS ellipsoid (Fig. 1). All analysed fabrics lie along a spectrum from purely oblate (a flattened spheroid where K1 = K2 > K3) to purely prolate (an elongated spheroid where K1 > K2 = K3) and are described by the shape parameter, T (Jelinek, 1981) which has a possible range from 1 (purely oblate) to -1 (purely prolate). The degree of measured anisotropy (P', Jelinek, 1981) is used instead of K1/K3 as it refers to deviation of all axes (including K2) from the mean susceptibility. The bulk magnetic susceptibility (K_{Mean}) varies by two orders of magnitude (Fig. 6). The mineral fabric (T) is dominantly oblate (Fig. 6), but for almost all samples the axes are statistically distinct from each other at 95% confidence; allowing statistically valid utilisation of all three axes (including the lineation, K1).

6.2. Magnetic mineralogy

The magnetically susceptible mineralogy can be determined from the variations of magnetic susceptibility with temperature (Fig. 7), hysteresis loops (Fig. 8) and First Order Reversal Curves (FORC diagrams, Fig. 8). All samples except the Alexandra Tonalite/Granodiorite show abrupt reductions in bulk susceptibility on heating between 565-585°C, the Curie temperature of pure magnetite. Although a small Hopkinson peak prior to the 565-585°C reduction in magnetic susceptibility appears to be present in some samples (Fig. 7), the lack of an extreme peak indicates dominance of multi-domain rather than single or pseudo single-domain particles (Orlický, 1990). The susceptibility decrease at 320-420°C results from the conversion of maghemitised magnetite to hematite (Orlický, 1990), an interpretation supported by the absence of this feature in the cooling curves. For all samples the cooling curve has a higher susceptibility than the heating curve, indicating production of secondary magnetite during heating.

The low bulk susceptibility of the Alexandra Tonalite/Granodiorite indicates a paramagnetic carrier phase, most probably biotite and/or amphibole, given the mineralogy of this unit (Burton-Johnson et al., 2017). This is consistent with the parabolic decease in susceptibility at low temperature (Fig. 7) with no increase at -148°C (the Verwey transition; Walz 2002), indicating that magnetite is not the dominant carrier. The hysteresis loops have a high contribution from paramagnetic minerals, which were corrected for in the analysis (Fig. 8). The samples have low coercivity values in the range of 2.7-8.5 mT, consistent for multi-domain grains (see supplementary material for full results). FORC diagrams for the Alexandra Tonalite/Granodiorite and King Granite (Fig. 8) show low coercivity (B_c) and a wide range in the bias field (B_u), with a weakly expressed negative bias region present on the right hand side of the lobe. These features all indicate multi-domain behaviour, as even small proportions of single-domain grains produce the high coercivity and narrow bias range associated with single-domain behaviour (Fig. 8; Harrison et al., 2018). As the magnetic fabric is and hosted by multi-domain magnetite, biotite, and amphibole, the AMS data does not represent an inverse fabric (as would be produced by single-domain magnetite; Stephenson et al., 1986).

6.3. AMS fabric of the different units

Overall the fabrics of most Mt Kinabalu granitic units display lineation with a shallow, NW plunge (K1; Fig. 9), and shallow dipping foliation (to which K3 is the pole; Fig. 8), although there are deviations. In the Alexandra Tonalite/Granodiorite, lineation of the AMS fabric (K1) shows a shallow plunge to the NW whilst the foliation (K3) has a consistent moderate dip to the SW (Fig. 9). Lineation of the Low's Granite also plunges to the NW but the foliation dip is shallower than the Alexandra unit (Fig. 9). The most sampled unit, the King

Granite, has the most homogenous AMS fabric with a lineation consistently plunging sub-horizontally to the NW/SE and a foliation recording a very shallow SW dip (Fig. 9). The Donkey Granite has the lowest areal extent and thus the fewest samples. Its lineation is variable and dominantly contact-parallel (Fig. 9) while the foliation has a shallow west dip (Fig. 9), although it frequently strikes sub-parallel to the contacts (Fig. 5). The AMS fabric of the Paka Porphyritic Granite again has a shallow NW plunge to its lineation and a shallow west dip to its foliation (Fig. 9). However, deviations in both the lineation and foliation are evident at the eastern extent and near internal contacts (Fig. 5). We obtained relatively few measurements of the Mesilau Porphyritic Granite due to the poor accessibility of the lower forested flanks of Mt Kinabalu. AMS measurements of Mesilau are highly variable in both foliation and lineation (Fig. 9). Thin section examinations of this unit reveal accumulations of secondary hydrothermal magnetite within its fractures and along grain boundaries, leading to the poorly defined AMS fabric (Fig. 9) and largest range of bulk susceptibility (Fig. 6).

7. Discussion

7.1. Tectonic or magmatic fabric?

The AMS fabric of Mt Kinabalu shows clear and consistent orientations through most units but to understand the origin of this fabric we must determine if it represents magmatic or tectonic strain. This distinction is achieved by comparing the AMS fabric with field evidence for tectonic strain (Paterson et al., 1998). Burton-Johnson et al. (2017) investigated the orientations and relationship of several, early, post-magmatic strain indicators in and around Mt. Kinabalu, including orientations of faults, aplite dykes and mafic dykes within the pluton. These indicate a post-magmatic sub-vertical principal compressive stress, σ_1 (i.e. lithostatic pressure), whilst the minimum compressive stress, σ_3, was sub-horizontally NNW-SSE oriented (Fig. 10). This extensional regime contrasts with the NW-SE to N-S striking compressive folds and associated thrust faults of the local sedimentary country rocks (Jacobson, 1970; Burton-Johnson et al., 2017), which record the Early Miocene Sabah Orogeny (Hutchison, 1996) that pre-dates the intrusion.

Under coaxial shear, the extensional stress field recorded by the faults and dykes of the pluton (Fig. 10) would be predicted to generate AMS fabrics with shallow NNW-SSE plunging lineations (K1) and sub-vertically dipping poles to the foliations (K3); similar to Fig. 2c. Fig. 10 shows that this is precisely the syn-magmatic AMS fabric demonstrated by all units except the Donkey Granite and the Mesilau Porphyritic Granite (a result of secondary magnetite), indicating similar syn- and post-magmatic stress regimes. The similarity in the predicted directions of extension from both the field and AMS evidence requires agreement between the principal stress and strain vectors, indicating the dominance of coaxial, non-rotational shear rather than non-coaxial simple shear in the development of the AMS fabric (Fig. 2).

As discussed above, the crystallisation of secondary magnetite in the Mesilau Porphyritic Granite has compromised its magnetic record. The foliation of the Donkey Granite shows shallow dips (Fig. 9), however its lineations tend towards contact-parallel orientations rather than the expected fabric. This orientation of contact-parallel lineation and shallow foliation is generated in dykes through post-flow compaction of a contact-parallel magmatic fabric (Park et al., 1988; Ernst and Baragar, 1992), indicating that the deviation of the Donkey Granite fabric from the overall distribution results from the narrow width of this unit (Burton-Johnson et al., 2017).

7.2. Effect of contacts on tectonic AMS fabrics

The mechanical contrast along internal or external contacts will generate contact-parallel fabrics in plutons. Simple shear elongation of the fabric will occur in the stretching direction (Fig. 2d, Paterson and Tobisch, 1988; Paterson et al., 1998). We have noted this effect in the narrow Donkey Granite but how far from a contact does this affect AMS fabric in the larger units?

The contact between the King Granite and the later Paka Porphyritic Granite can be traced for over 2km on the south flank of Mt Kinabalu (Fig. 5). Samples from either side of the contact show that the lineation in both units reflects the tectonic overprint even from samples <5m from the contact (Fig. 5c). The foliation is more sensitive to contact-parallel fabrics, with the strike of samples close to the boundary rotated towards the contact but only for samples up to 100m from the contact (Fig. 5d). Th presence of a contact-parallel foliation but a tectonic fabric in the lineation indicates rotation about a lineation-parallel zone axis or the development of a variably contact-parallel fabric, subsequently overprinted by invariable extension in the lineation direction.

As observed in studies of other intrusions (Bouchez, 1997; Olivier et al., 1997), the AMS fabric of Mt Kinabalu shows remarkable lateral homogeneity across the pluton. The vertical range of exposure at Mt Kinabalu also reveals comparable vertical homogeneity. Overprinting of magmatic fabrics by tectonic strain from coaxial, non-rotational shear is pervasive, even <5m from the contacts and across the entire 2900m vertical range of the intrusion. This implies that plutonic AMS fabrics can be used to determine syn-magmatic tectonic strain even when the geometry of the pluton is unknown.

7.3. Application of the AMS fabric to tectonic interpretation

Excluding the two units for which the tectonic fabric is not recorded (The Donkey Granite and Mesilau Porphyritic Granite), the orientations of the maximum (σ_1) and minimum (σ_3) syn-magmatic tectonic compression directions interpreted from AMS are in close agreement with the field evidence (Fig. 10). However, unlike the syn-magmatic strain recorded by the AMS fabric, because faults and dykes must postdate their host they can only date post-magmatic deformation. The AMS data is also less dispersed, and less ambiguous as its vectors correspond with specific vectors of the strain ellipsoid. As the AMS fabric is hosted by the rock itself, it can be dated directly (unlike most faults and other evidence for paleostrain) allowing determination of the strain ellipsoid at a specific time. This provides a powerful tool for structural and tectonic research.

The paleomagnetic rotation of the Mt Kinabalu intrusions since emplacement was determined from granitic samples as 11° anticlockwise (±2.4° at 95% confidence, (Fuller et al., 1991). By correcting the azimuth of the lineation (eigenvector of 308° ±10.7° at 95% confidence, the proxy for the syn-magmatic extension direction) by the paleomagnetic rotation we can determine that at 7.9-7.3 Ma Sabah was undergoing NW-SE crustal extension at 319° ±13.1°. This supports the presence of a NW-SE oriented extensional regime in Sabah during the Miocene, which may be the result of SE-directed slab rollback during subduction of the Celebes Sea to the SE (Cottam et al., 2013; Hall, 2013). Our findings are not compatible with models invoking contemporaneous tectonic compression in the region (Hutchison, 2000; Swauger et al., 2000; King et al., 2010; Pubellier and Morley, 2013). Emplacement during regional extension is more consistent with a setting affected by slab rollback, which has been proposed between 11-10 Ma (Hall, 2013), although our observations suggest that extension persistent until, at least, 7.5Ma..

7.4. Tectonic overprinting of magmatic AMS fabrics: A widespread phenomenon?

We have shown that extensional tectonics pervasively overprinted the AMS fabric of the Mt Kinabalu intrusion. Where observed elsewhere, similar observations have been utilised to infer local strain partitioning (Archanjo et al., 1992, 2002; Benn, 2010), but can AMS be applied to determine tectonic deformation on a global scale? To investigate whether similar overprinting occurs elsewhere we compiled data from intrusions of varying age and dimensions, and from globally distributed compressional and extensional tectonic regimes (Fig. 11). Whilst not a complete global dataset, this provides a global distribution of plutons from known tectonic settings for which there is comprehensive sample coverage, and includes numerous well-recognised studies (e.g. Mt Stuart, Monte Capanne, Dinkey Creek, and Mono Creek – respectively (Bouillin et al., 1993; de Saint Blanquat and Tikoff, 1997; Cruden, 1999; Benn et al., 2001).. The tectonic settings and orientations of compression or extension are from the literature, with the specific orientation shown in Fig. 11 determined by ourselves as in Fig. 1.

Some of the AMS datasets included in our compilation have already been interpreted as recording a tectonic overprint (e.g. the Shellenbarger and Mt Stuart plutons, USA) whilst others have not (e.g. the Pinto Peak intrusion, USA, and the Monte Capanne intrusion, Italy). However, in all cases a clear and consistent fabric is shown by each intrusion. For each example included in our study the orientation of tectonic strain required to generate each fabric through coaxial shear (as illustrated in Fig. 2) is always in agreement with the contemporaneous tectonic regime of the region (Fig. 11).

As with Mt Kinabalu, the close agreement of the AMS fabric vectors and regional tectonic stress directions in both compressional and extensional settings indicates the dominance of coaxial, non-rotational shear rather than simple, non-coaxial shear in pluton-scale AMS fabrics. This allows simple interpretation of the stress and strain vectors. Even in plutons associated with major shear zones, field studies have shown that simple shear is only pervasive close to the shear zone (Gleizes et al., 2001; Tikoff et al., 2005; Benn, 2010), returning to more homogenous, coaxial, non-rotational shear fabrics at greater distances from the shear zone; as observed near the contacts of Mt Kinabalu. The pervasiveness of the simple shear regime is dependent on the rheology of the lithology, timing and degree of shearing, and the scale-dependant cooling history of the pluton (Archanjo et al., 2002; Tikoff et al., 2005; Benn, 2010). Where intrusions were metamorphosed and recrystallised in the deeper crust after emplacement, this coaxial tectonic fabric can be imparted millions of years after magmatism (Hrouda et al., 1988; Hrouda and Faryad, 2017).

In extensional plutons the lineation direction (K1) is consistently parallel to the azimuth of extension, whilst the foliation dip varies, similar to our observations in the Alexandra Tonalite/Granodiorite of Mt Kinabalu. Similarly, in compressional plutons the pole to foliation (K3) is consistently in the direction of compression whilst the plunge of the lineation varies. In a compressive regime this lineation variation reflects whether σ_2 (Fig. 1) represents lithostatic (vertical) or lateral (tectonic) compression. If σ_2 represents lithostatic compression the lineation will be sub-horizontal but if the degree of tectonic compression is increased and σ_2 becomes horizontal then the lineation will be sub-vertical (Fig. 2a and 2b). Similarly, in an extensional regime the foliation variation reflects the orientation of σ_1 (Fig. 1). If σ_1 represents lithostatic compression the foliation will be sub-horizontal but if the degree of lateral compression increases, and σ_1 becomes horizontal then the foliation dip will be sub-vertical.

Because of these variations in extensional foliation and compressional lineation, comparing the confidence limits of the mean K1 and K3 vectors (Fig. 12) distinguishes whether a pluton was emplaced in a compressive or extensional setting even in the absence of other data (e.g. field evidence for deformation). Using symmetrical 95% confidence angles for the mean spherical vectors of K1 and K3, compressional plutons can be identified at 90% confidence where "K1 confidence angle / K3 confidence angle" <1.2, and extensional plutons can be identified at 90% confidence where "K1 confidence angle / K3 confidence angle" >1.5 (Fig. 12).

We conclude that coaxial tectonic strain is commonly preserved in the AMS fabric of plutonic intrusions. This explains the remarkable homogeneity of AMS fabrics within many individual plutons (Bouchez, 1997; Olivier et al., 1997) and opens up the possibility of using AMS fabrics to determine syn-magmatic deformation. As intrusive magmatism is a common feature of many tectonic settings throughout Earth's history, the nature of a tectonic regime can be investigated from its accompanying plutons. Just like traditional structural evidence, granitic magmatism has long been seen as a product of tectonic deformation (Vigneresse, 1999). By applying this technique, plutons can be used as a potent structural tool for investigating those tectonic processes and identifying tectonic regimes.

8. Conclusions

- The AMS fabric of the Mt Kinabalu intrusion, Borneo, was largely derived by syn-magmatic crustal extension.

- Tectonic strain is highly pervasive throughout the Mt Kinabalu pluton, dominating the AMS foliation to within 100m of contact surfaces, and the AMS lineation to <5m from contact surfaces.

- After paleomagnetic correction for rotation, the AMS data indicates that crustal extension in Sabah at 7.9-7.3 Ma was oriented NW-SE at 319° ±13.1°. This is consistent with other evidence for Late Miocene extension in NW Borneo (Hall, 2013).

- In compressive settings, AMS foliations are consistent but lineations vary. Likewise, in extensional settings, AMS lineations are consistent but foliations vary. Consequently, compressional plutons can be distinguished by the relative scales of the K1 and K3 confidence angles.

- A compilation of global AMS data for intrusions in extensional and compressional regimes reveals the common occurrence of magnetic fabrics preserving tectonic strain. This indicates that the AMS fabrics of plutonic rocks have the potential to be employed globally to determine syn-magmatic tectonic settings.

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Figure Captions

Fig. 1. Relationship of mineral fabrics (foliation and lineation) and the principal vectors of magnetic susceptibility describing the AMS fabric (K1 – Maximum susceptibility; K2 – Intermediate susceptibility; K3 – Minimum susceptibility) to the strain ellipsoid and the principal stress directions during crystallisation (σ_1 – Maximum compression direction; σ_2. – Intermediate compression direction; σ_3 – Minimum compression direction).

Fig. 2. Example stereonets (lower hemisphere projection) of the resultant AMS fabrics developed in response to coaxial and non-coaxial strain. Shown are the principal stress directions, simple shear direction, and principal vectors of magnetic susceptibility: K1 – Maximum susceptibility; K2 – Intermediate susceptibility; K3 – Minimum susceptibility.

Fig. 3. A) Regional geography of Mt Kinabalu and Sabah within SE Asia. B) Aerial photograph of Mt Kinabalu from the south highlighting its extreme vertical relief; courtesy of Tony Barber. C) Internal structure and emplacement ages (Cottam et al., 2010) of the Mt Kinabalu intrusion, as determined from field evidence (Burton-Johnson et al., 2017).

Fig. 4. Representative thin section images of (a) the Alexandra Tonalite/Granodiorite, and (b) the King Granite (itself representative of the post-Alexandra units). Rose diagrams show the orientations hornblende and biotite crystals in each section. Sections are arbitrarily orientated. Abbreviations as in Fig. 1, plus Hb – Hornblende; Bt – Biotite.

Fig. 5. Geological map of Mt Kinabalu highlighting the (A) foliation and (B) lineation of the summit plateaux and eastern ridge. Variations in these orientations close to the contact between the King Granite and Paka Porphyritic Granite (box shown in B) are shown in (C) and (D). Abbreviations as in Fig. 5.

Fig. 6. Relationship of the degree of magnetic anisotropy, P', to the mean bulk susceptibility, K_{Mean} (A), and shape parameter of the AMS fabric, T (B). Abbreviations: Tn – Tonalite, Gd – Granodiorite, Gt – Granite, Pph – Porphyritic Granite.

Fig. 7. Variation in bulk magnetic susceptibility of each granitic unit with temperature. Abbreviations as in Fig. 5.

Fig. 8. Hysteresis loops and First Order Reversal curves for: a) the Alexandra Tonalite/Granodiorite; b) the King Granite. The King Granite is representative of the plutons' other composite units. Two synthetic binary mixtures of c) purely multi-domain (MD), and d) a mixture of multi- and single-domain (SD) magnetite are shown for comparison (Harrison et al., 2018).

Fig. 9. Lower hemisphere projections of the lineation (K1) and pole to the foliation (K3) for the AMS fabric of each of Mt Kinabalu's composite units. Abbreviations as in Fig. 5.

Fig. 10. Poles to planes for faults, aplite dykes and mafic dykes cross-cutting Mt Kinabalu (Burton-Johnson et al., 2017) compared to lineation (K1) and poles to foliation (K3) of the AMS fabric (excluding the Donkey Granite and Mesilau Porphyritic Granite). Open arrows illustrate the interpreted associated principal stress directions for structural data. Diamonds indicate maximum eigenvectors.

Fig. 11. Global compilation of lineation (K1) and pole to foliation (K3) directions of AMS data from intrusions emplaced in both extensional and compressive tectonic settings showing the orientation of the principal extensional or compressional direction generating the tectonic fabric.

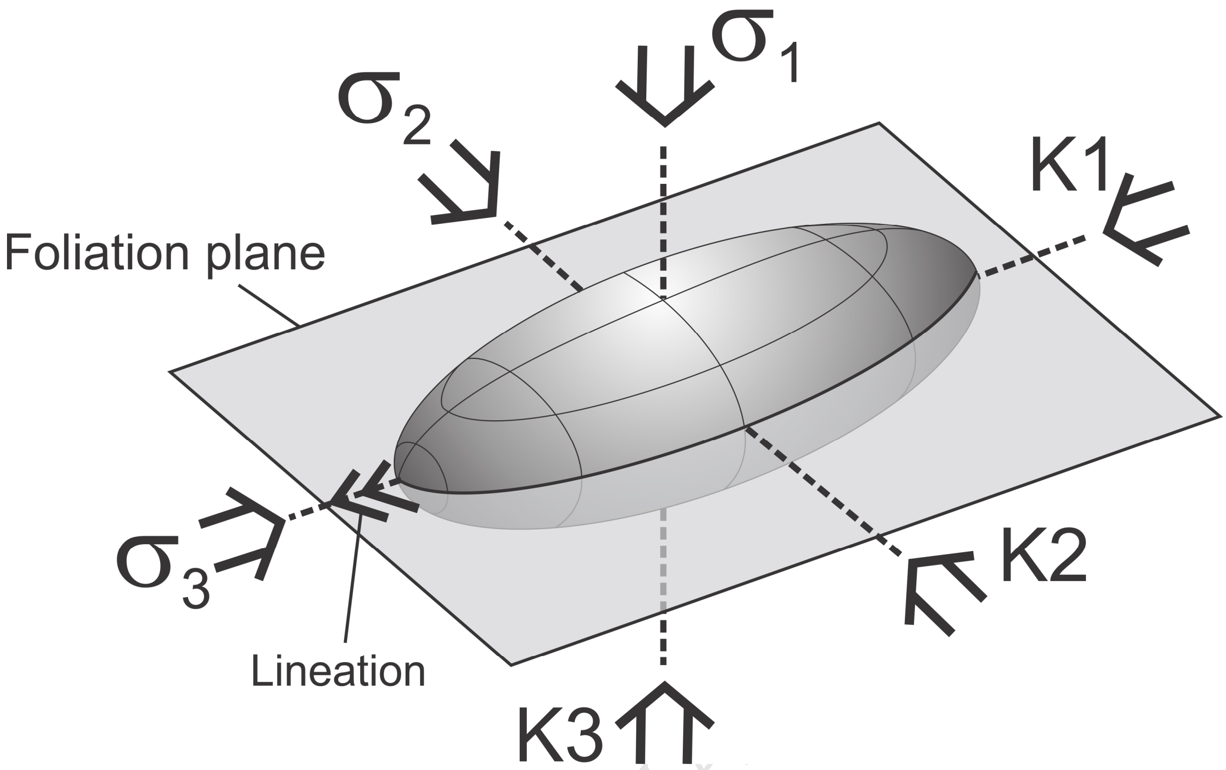
Mt Kinabalu, Borneo – This study; Yiwulüshan massif - Lin et al. (2013); Zahedian - Sadeghian et al. (2005); Monte Capanne - Bouillin et al. (1993); Aigoual–Saint Guiral–Liron - Talbot et al. (2005); La Tojiza - Aranguren et al. (2003); Shigujian - Deng et al. (2013); Ross of Mull - Petronis et al. (2012); Pinto Peak - Petronis and O'Driscoll (2013); Namwon - Otoh et al. (1999); Lavadores - Martins et al. (2011); Las Tazes - Wilson (1998); Wyangala - Lennox et al. (2016); La Gloria - Gutiérrez et al. (2013); Mt Stuart - Benn et al. (2001); Dinky Creek - Cruden (1999); Shellenbarger - Tomek et al. (2017); Mono Creek - de Saint Blanquat and Tikoff (1997).

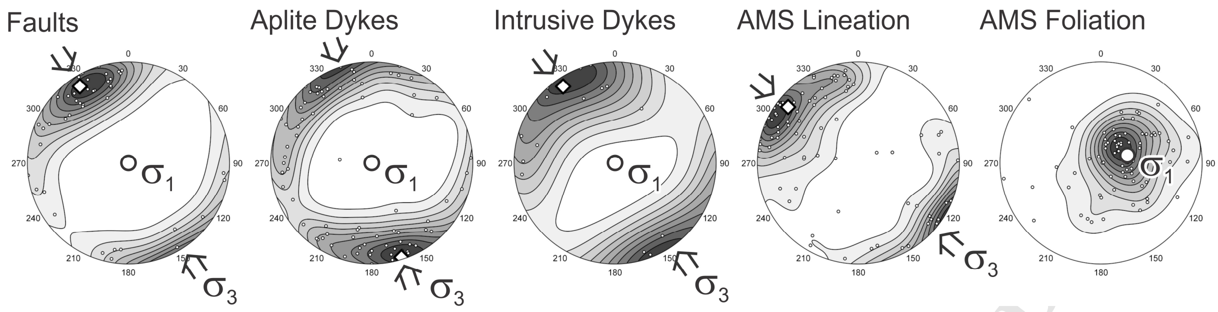
Fig. 12. 95% symmetrical confidence limits of the mean spherical K1 and K3 vector for the compressional and extensional plutons in Fig. 11. Compressional plutons can be identified at 90% confidence where "K1 95% Confidence Angle / K3 95% Confidence Angle" <1.2, and extensional plutons can be identified at 90% confidence where "K1 95% Confidence Angle / K3 95% Confidence Angle" >1.5.

Table 1. Summary of U-Pb zircon ages (Cottam et al., 2010), SiO_2 and Mg# (Burton-Johnson et al., in review), estimated volumes and modal mineralogies (Burton-Johnson et al., 2017) of the major granitoid units. Abbreviations used: Tn – Tonalite; Gd – Granodiorite; Gt – Granite; Pph – Porphyritic Granite; Qz – Quartz; Pl – Plagioclase; Kfs – Potassium Feldspar; Hb – Hornblende; Bt – Biotite; Cpx. – Clinopyroxene; Ap – Apatite; Ep – Epidote; Zrn – Zircon; Spn – Sphene (Whitney and Evans, 2010).

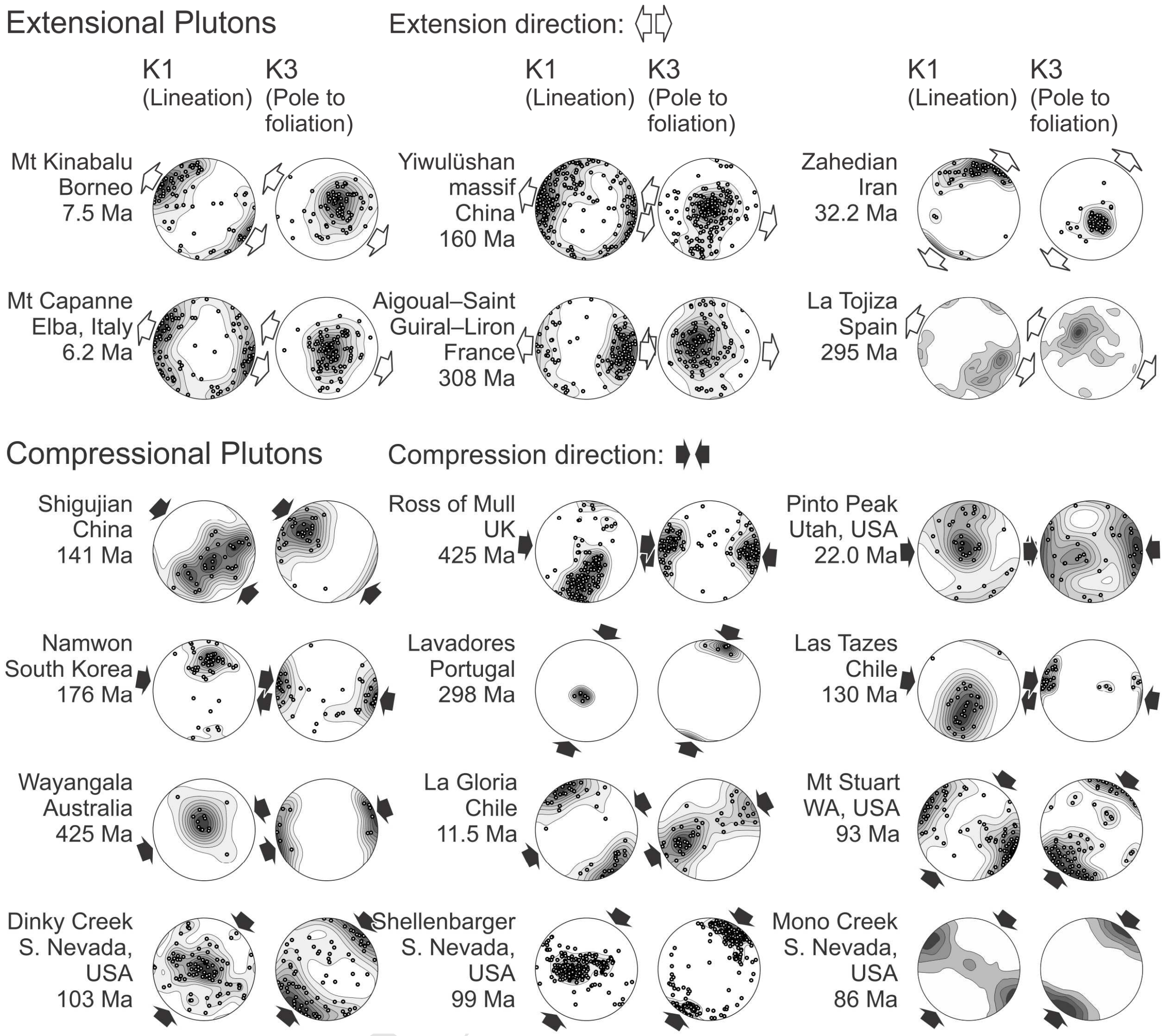
Unit	Alexandra Tn/Gd	Low's Gt	King Gt	Donkey Gt	Paka Pph	Mesilau Pph
U-Pb Age (Ma)	7.85 ±0.08	7.69 ±0.07 – 7.64 ±0.11	7.46 ±0.08 – 7.44 ±0.09	7.46 > t > 7.32	7.32 ±0.09 – 7.22 ±0.07	–
Approx. Vol. (Km3)	0.2	2 (W) 4 (N)	90	0.4	40	40
SiO2 (wt. %)	61-65	59-64	62-66	63-65	63-67	60-65
Mg#	47-52	50-53	44-53	43-50	44-47	44-47
Phases (Modal %)						
Qz	23-28	16-28	14-27	23	15-21	7-21
Pl	40-45	25-33	21-38	26	23-33	24-28
Kfs	4-7	18-29	26-36	25	23-35	38-48
Hb	4-13	21-28	9-21	11	11-24	8-23
Bt	9-19	4-7	0-5	13	1-2	0-5
Cpx	–	–	–	–	–	0-2
Accessory	Ap, Ep	Ap, Ep, Zrn	Ap, Ep, Zrn	Ap	Ap	Ap, Spn

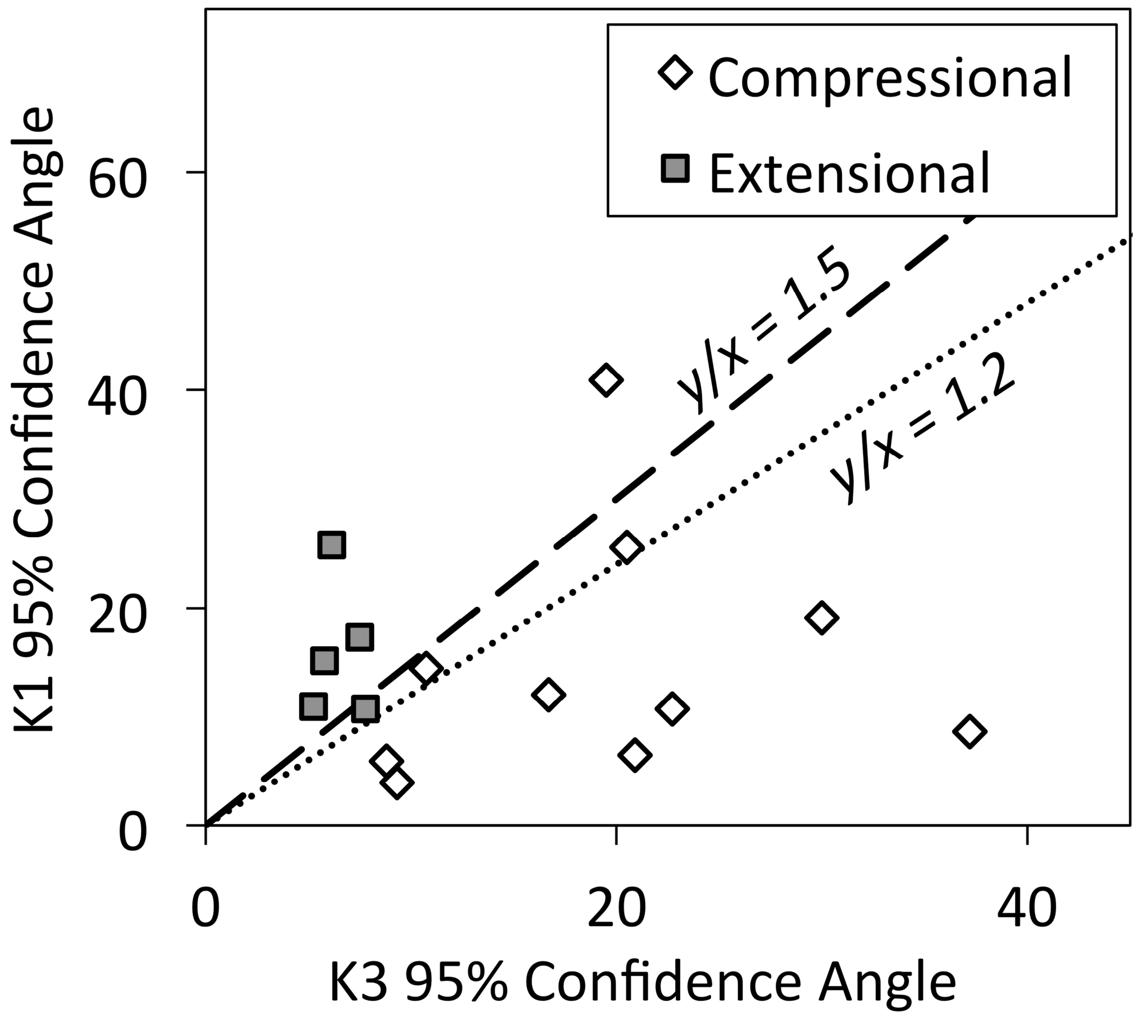
Table 1. Summary of U-Pb zircon ages (Cottam et al., 2010), SiO2 and Mg# (Burton-Johnson et al., In Review), estimated volumes and modal mineralogies (Burton-Johnson et al., 2017) of the major granitoid units. Abbreviations used: Tn – Tonalite; Gd – Granodiorite; Gt – Granite; Pph – Porphyritic Granite; Qz – Quartz; Pl – Plagioclase; Kfs – Potassium Feldspar; Hb – Hornblende; Bt – Biotite; Cpx. – Clinopyroxene; Ap – Apatite; Ep – Epidote; Zrn – Zircon; Spn – Sphene (Whitney and Evans, 2010).

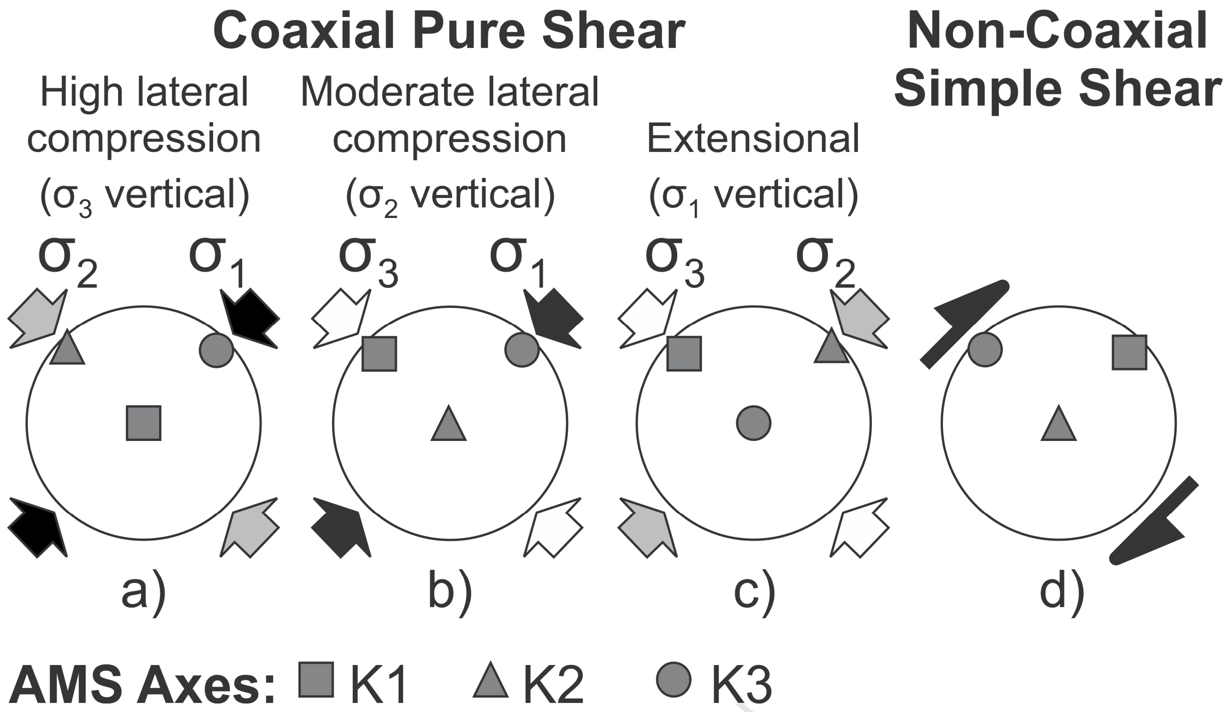

σ1
σ2
K1
Foliation plane
σ3
K2
Lineation
K3



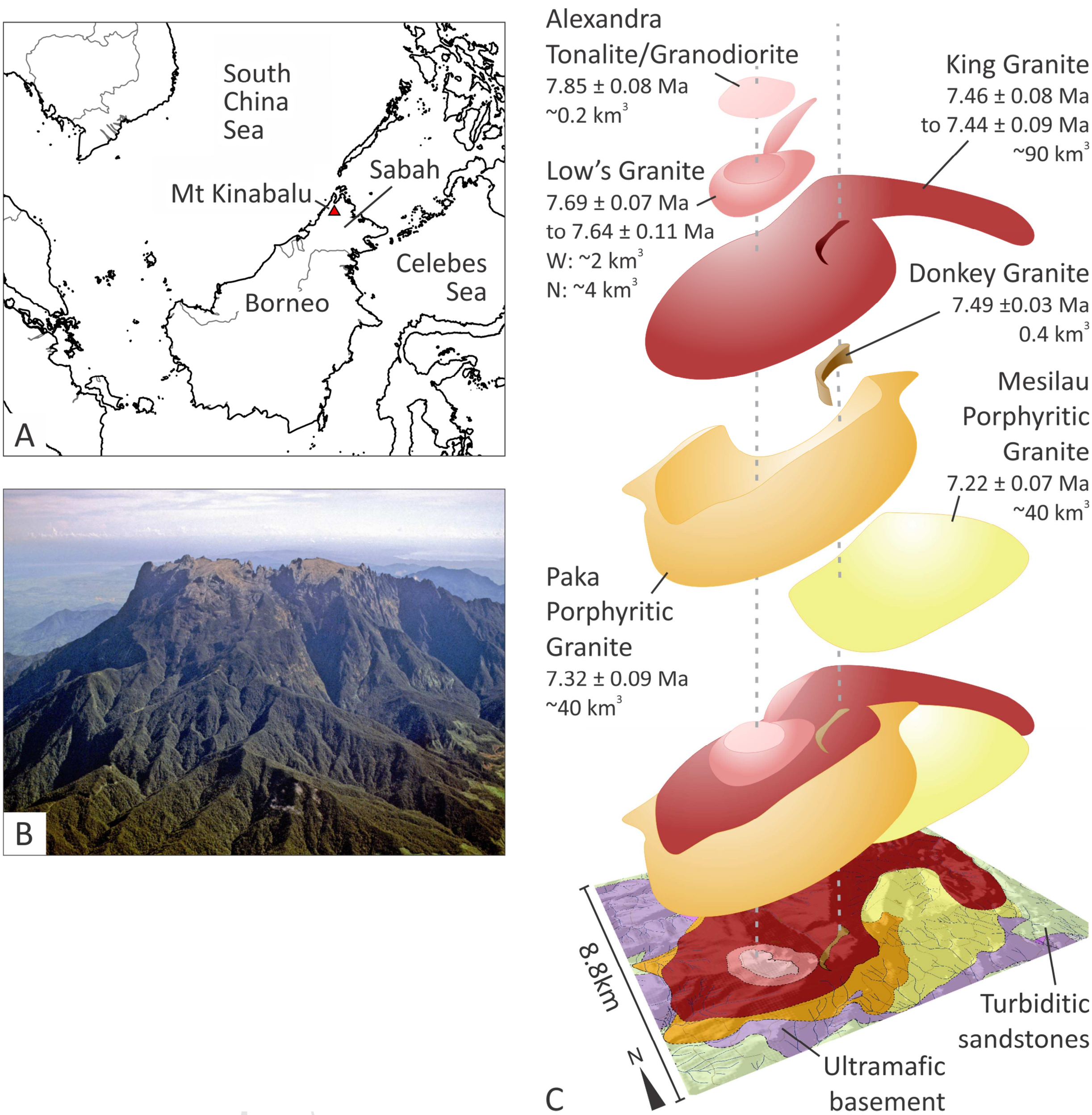
Faults
Aplite Dykes
Intrusive Dykes
AMS Lineation
AMS Foliation
σ1
σ3


Extensional Plutons
Extension direction:
K1
(Lineation)
K3
(Pole to foliation)
Mt Kinabalu
Borneo
7.5 Ma
Yiwulüshan
massif
China
160 Ma
Zahedian
Iran
32.2 Ma
Mt Capanne
Elba, Italy
6.2 Ma
Aigoual–Saint
Guiral–Liron
France
308 Ma
La Tojiza
Spain
295 Ma
Compressional Plutons
Compression direction:
Shigujian
China
141 Ma
Ross of Mull
UK
425 Ma
Pinto Peak
Utah, USA
22.0 Ma
Namwon
South Korea
176 Ma
Lavadores
Portugal
298 Ma
Las Tazes
Chile
130 Ma
Wayangala
Australia
425 Ma
La Gloria
Chile
11.5 Ma
Mt Stuart
WA, USA
93 Ma
Dinky Creek
S. Nevada,
USA
103 Ma
Shellenbarger
S. Nevada,
USA
99 Ma
Mono Creek
S. Nevada,
USA
86 Ma

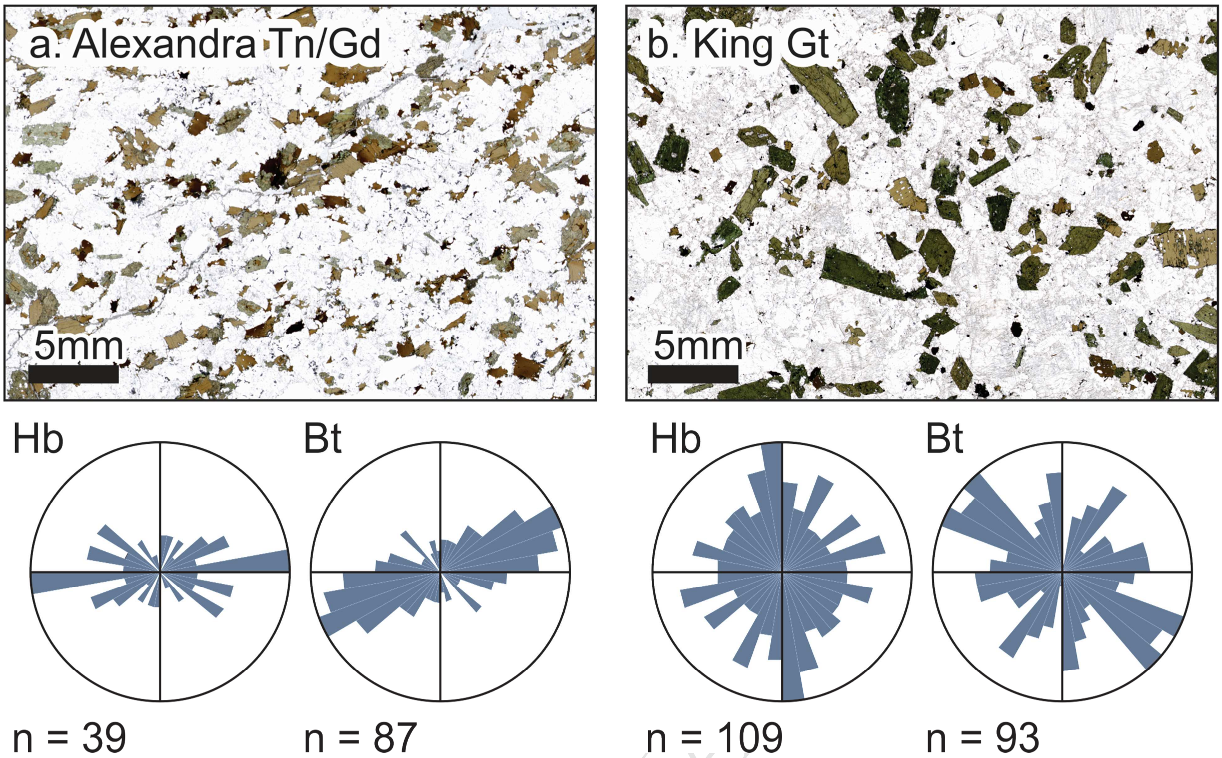

Compressional
Extensional
y/x = 1.5
y/x = 1.2
K1 95% Confidence Angle
K3 95% Confidence Angle
0
20
40
60
0
20
40

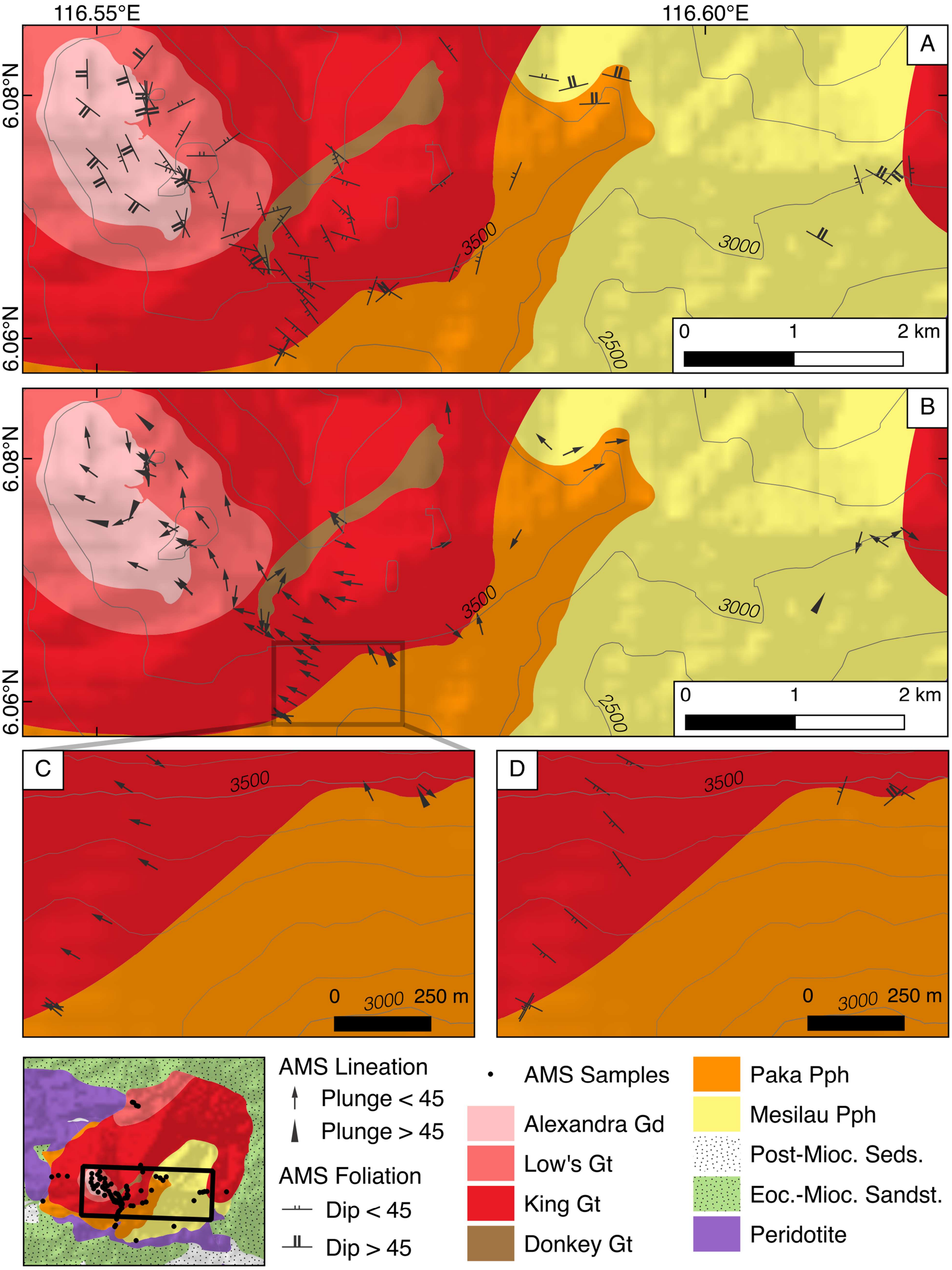


Coaxial Pure Shear
Non-Coaxial Simple Shear
High lateral compression (σ3 vertical)
Moderate lateral compression (σ2 vertical)
Extensional (σ1 vertical)
σ2 σ1
σ3 σ1
σ3 σ2
a)
b)
c)
d)
AMS Axes: K1 K2 K3

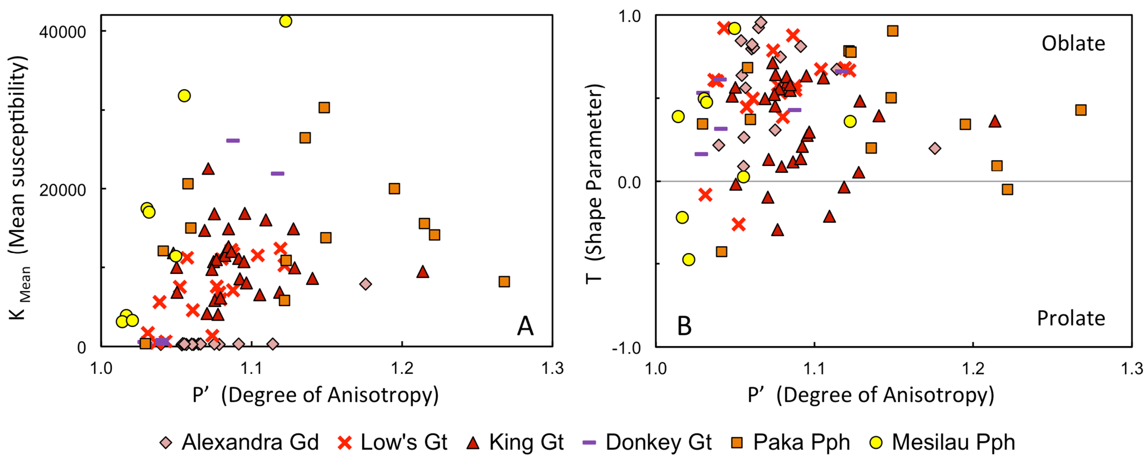


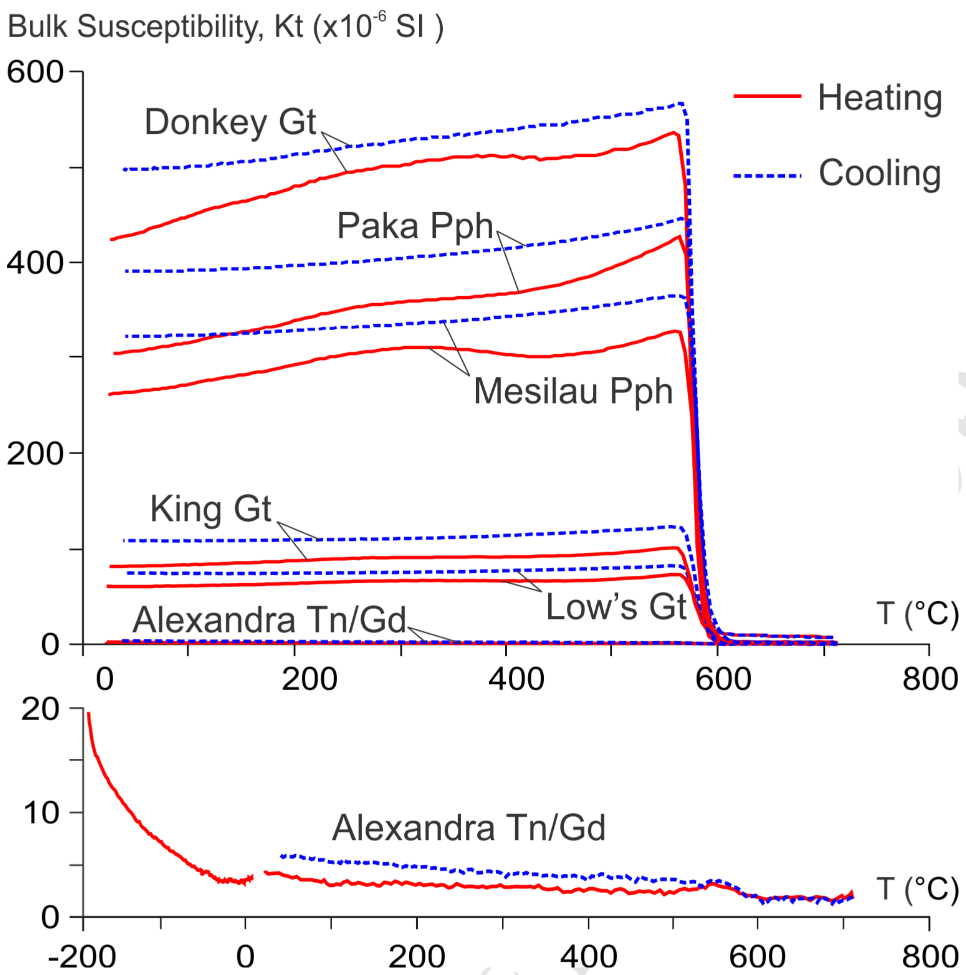
South
China
Sea
Sabah
Mt Kinabalu
Celebes
Sea
Borneo
A
B
Alexandra
Tonalite/Granodiorite
7.85 ± 0.08 Ma
~0.2 km3
Low's Granite
7.69 ± 0.07 Ma
to 7.64 ± 0.11 Ma
W: ~2 km3
N: ~4 km3
King Granite
7.46 ± 0.08 Ma
to 7.44 ± 0.09 Ma
~90 km3
Donkey Granite
7.49 ±0.03 Ma
0.4 km3
Mesilau
Porphyritic
Granite
7.22 ± 0.07 Ma
~40 km3
Paka
Porphyritic
Granite
7.32 ± 0.09 Ma
~40 km3
8.8km
N
Turbiditic
sandstones
Ultramafic
basement
C

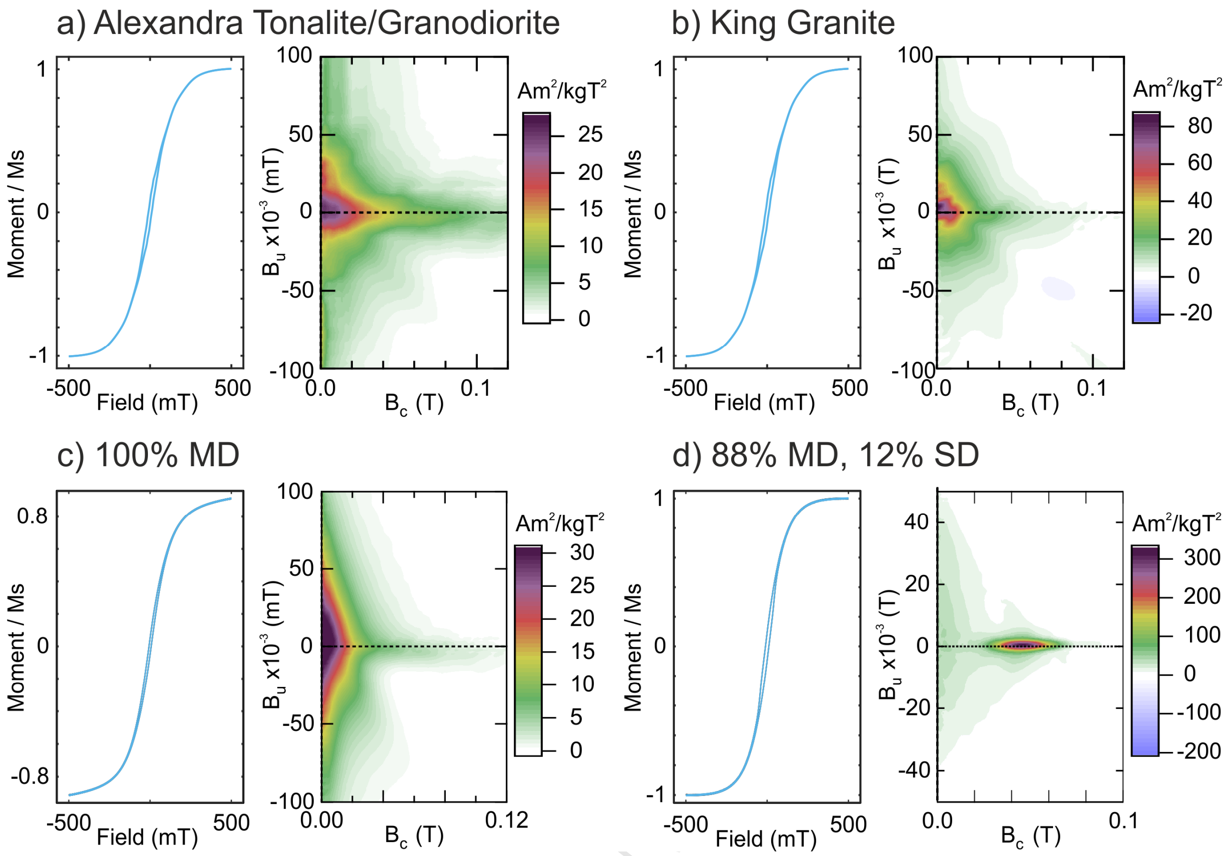

a. Alexandra Tn/Gd
5mm
b. King Gt
5mm
Hb
Bt
Hb
Bt
n = 39
n = 87
n = 109
n = 93



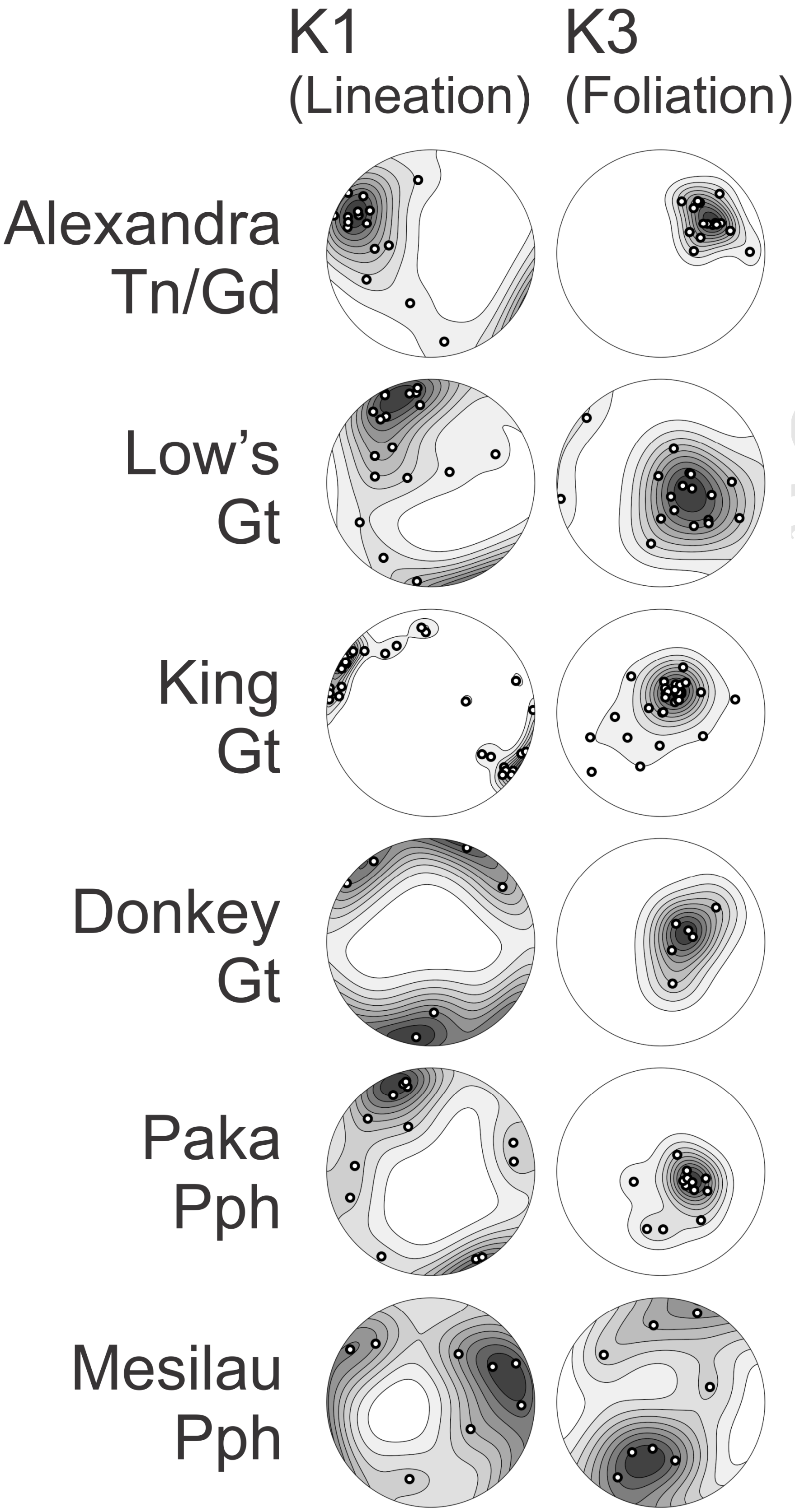
116.55°E
116.60°E
6.08°N
6.06°N
A
B
C
D
3500
3000
2500
0
1
2 km
250 m
AMS Lineation
Plunge < 45
Plunge > 45
AMS Foliation
Dip < 45
Dip > 45
AMS Samples
Alexandra Gd
Low's Gt
King Gt
Donkey Gt
Paka Pph
Mesilau Pph
Post-Mioc. Seds.
Eoc.-Mioc. Sandst.
Peridotite


40000
20000
0
K Mean (Mean susceptibility)
1.0
1.1
1.2
1.3
P' (Degree of Anisotropy)
A
1.0
0.0
-1.0
T (Shape Parameter)
Oblate
Prolate
B
Alexandra Gd
Low's Gt
King Gt
Donkey Gt
Paka Pph
Mesilau Pph


Bulk Susceptibility, Kt (x10-6 SI)
Heating
Cooling
Donkey Gt
Paka Pph
Mesilau Pph
King Gt
Low's Gt
Alexandra Tn/Gd
T (°C)
600
400
200
0
0
200
400
600
800
20
10
0
Alexandra Tn/Gd
T (°C)
-200
0
200
400
600
800



a) Alexandra Tonalite/Granodiorite
b) King Granite
c) 100% MD
d) 88% MD, 12% SD
Moment / Ms
Field (mT)
-500
500
B_u x10^{-3} (mT)
B_c (T)
B_u x10^{-3} (T)
Am^2/kgT^2


K1
(Lineation)
K3
(Foliation)
Alexandra
Tn/Gd
Low's
Gt
King
Gt
Donkey
Gt
Paka
Pph
Mesilau
Pph