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A preliminary Scanning Electron Microscope (SEM) study of magnetite surface micro-textures from the Wahianoa moraines, Mt Ruapehu, New Zealand

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Abstract

Scanning electron microscope (SEM) of quartz micro-textures has routinely been used to identify the depositional environment of sediments in areas of former ice-sheet glaciation. On volcanic mountains, where the geomorphic origin of ridge deposits is often poorly understood, quartz is much less abundant, so SEM analysis has not been used as a depositional discriminator. Preliminary research on surface micro-textures of abundant magnetite grains from the Wahianoa moraines, south-eastern Mt Ruapehu, suggests that SEM of magnetite may be useful in determining the process-origin of deposits. We describe micro-textures and surface characteristics of samples of magnetite, and our study shows that many of the micro-textures visible on quartz, thought to be diagnostic of glacial transport, are present on magnetite too. However, evaluating whether SEM analysis of magnetite is an applicable technique will require a better understanding of the micro-textures occurring on known glacial, fluvioglacial and aeolian deposits on volcanic mountains.

Key words: SEM; magnetite; moraines; volcanoes; process-origin

Introduction

Landform-scale analysis of sedimentary features normally identifies characteristics that will enable an interpretation of the process and environment of sediment deposition (e.g., Mills & Grab 2005). Increasingly, however, it is becoming apparent within glacial geology that macro-scale analysis does not always yield sufficient information to reliably demonstrate the depositional history of many lithofacies (Carr 2004). While there has been a significant volume of research on the application of micro-morphological techniques over the last decade (Mahaney & Kalm 2000; Mahaney *et al*. 2004), the application of scanning electron microscopy (SEM) to sedimentology extends back forty years (Krinsley & Donahue 1968; Krinsley & Doornkamp 1973; Whalley 1978; Hart 2006). The main objective of this work has been to identify process-origins from the range of imprinted micro-textures, with various micro-textures used to develop diagnostic criteria of different depositional environments (e.g., Whalley 1978). For example, Mahaney and Kalm (2000) compared a large number of quartz grains from Quaternary tills in eastern Europe and compared the results with non-cemented Devonian sandstones, the study showing distinctive differences. The glacially-transported grains showed a large number of sub-parallel linear fractures with high relief, whereas the Devonian sand showed low relief and edge rounding (Mahaney & Kalm 2000).

Mahaney and Kalm (2000) and Van Hoesen *et al*. (2004) have highlighted a number of features indicative of glacial transport visible via SEM. Quartz grains entrained subglacially develop micro-features in response to vibrational energy released during stick-slip processes and basal sliding and abrasion (Atkins *et al*. 2002; Cuffey *et al*. 1999; Hart 2006). In particular, micro-features thought to develop due to grain-on-grain interactions in the subglacial environment include: (1) directional curved troughs or grooves, (2) crescentic gouges, (3) conchoidal and linear crushing features, (4) arc-shaped steps, and (5) conchoidal fractures (Mahaney 1995; Mahaney *et al*. 2001).

Given the substantial history of research using SEM (Mahaney 1995), only limited accounts exist of SEM analysis of micro-textures of mineral grains other than quartz (e.g., Stieglitz 1969; Folk 1975). On garnet grains in till, Folk (1975) identified chattermark trails, and Gravenor (1980) found that the chattermarks increased in abundance with increasing glacial transport distance. Nevertheless, the routine use of abundant quartz grains in the northern hemisphere as a target for SEM analysis has meant the SEM technique has not been extended to sedimentary deposits on volcanic mountains (either terrestrial or planetary), because the presence of quartz is often negligible or totally absent. On such mountains, the exact process-origins of debris ridges are often unknown (e.g., Porter 2005; Neukum *et al*. 2004), with ridges of unconsolidated debris possibly forming from a range of process mechanisms, such as debris flows, lahars, pronival ramparts, rock glaciers and glacial activity (Mills & Grab 2005). Though heavy mineral grains, such as magnetite, are often present in such volcanic terrains (Wood 1994), the potential for their use as an environmental discriminator via SEM analysis has not been explored.

Here, we present a preliminary investigation of the potential of magnetite as an environmental discriminator, the aim being to investigate whether diagnostic 'glacial' micro-textures visible on quartz are visible on magnetite grains. Magnetite is often present in volcanic terrains, including Mt Ruapehu, the focus of this study, and if successful, SEM analysis of magnetite could prove a useful tool in mapping the extent of former glaciers in the area. Magnetite can be separated very easily, and like quartz, it has no cleavage, and a hardness of 6 on Moh's scale compares favourably with quartz (Moh's hardness of 7; Dietrich & Skinner 1979). It should be clear that not all micro-textures described on grain surfaces in this study necessarily indicate a glacial origin, nor do we attempt to evaluate the precise origin of individual grains.

Study Site

Mt Ruapehu is an active andesitic strato-volcano with a multiple vent system, the volcano being formed over the last 250 ka in at least four cone-building episodes (Donoghue & Neall 2001). The Ruapehu massif is comprised of products of both effusive and explosive volcanic eruptions, forming a ring-plain consisting of re-worked debris, coarse laharic volcaniclastic deposits, airfall tephra units and glacigenic sediments (McArthur & Shepherd 1990; Proctor 2003). The current glaciers on Mt Ruapehu are above 2100 m and have been receding over the last c. 150 years since early observations, and are limited to small cirque glaciers (McArthur & Shepherd 1990). Evidence in the form of unconsolidated debris ridges, ice-moulded surfaces, striated and faceted boulders indicates more extensive glacier activity in the past, though the range of possible process-origins of ridge deposits has apparently precluded any detailed glacial-geologic mapping on the mountain (McArthur & Shepherd 1990). McArthur and Shepherd (1990) identified a series of lateral moraines radiating out from the summit area down to an altitude of c. 1200 m, suggesting the former presence of a small ice cap. McArthur and Shepherd (1990) tentatively ascribed a Late Otiran age of 23 ka (MIS 2) for the moraines, which is consistent with the local last glacial maximum (LGM) within New Zealand (Alloway *et al*. 2007). Our sample sites for magnetite sediments were from four 1.5m deep pits, excavated into the matrix-supported diamict that forms the Wahianoa lateral moraines on the south-eastern flank of Mt Ruapehu (Fig. 1, 2). These c. 5 km long moraines were formed by an extended Wahianoa Glacier during the LGM, and form some of the most impressive glacial features on Mt Ruapehu, rising to 30-50 m above the surrounding ring plain (McArthur & Shepherd 1990).

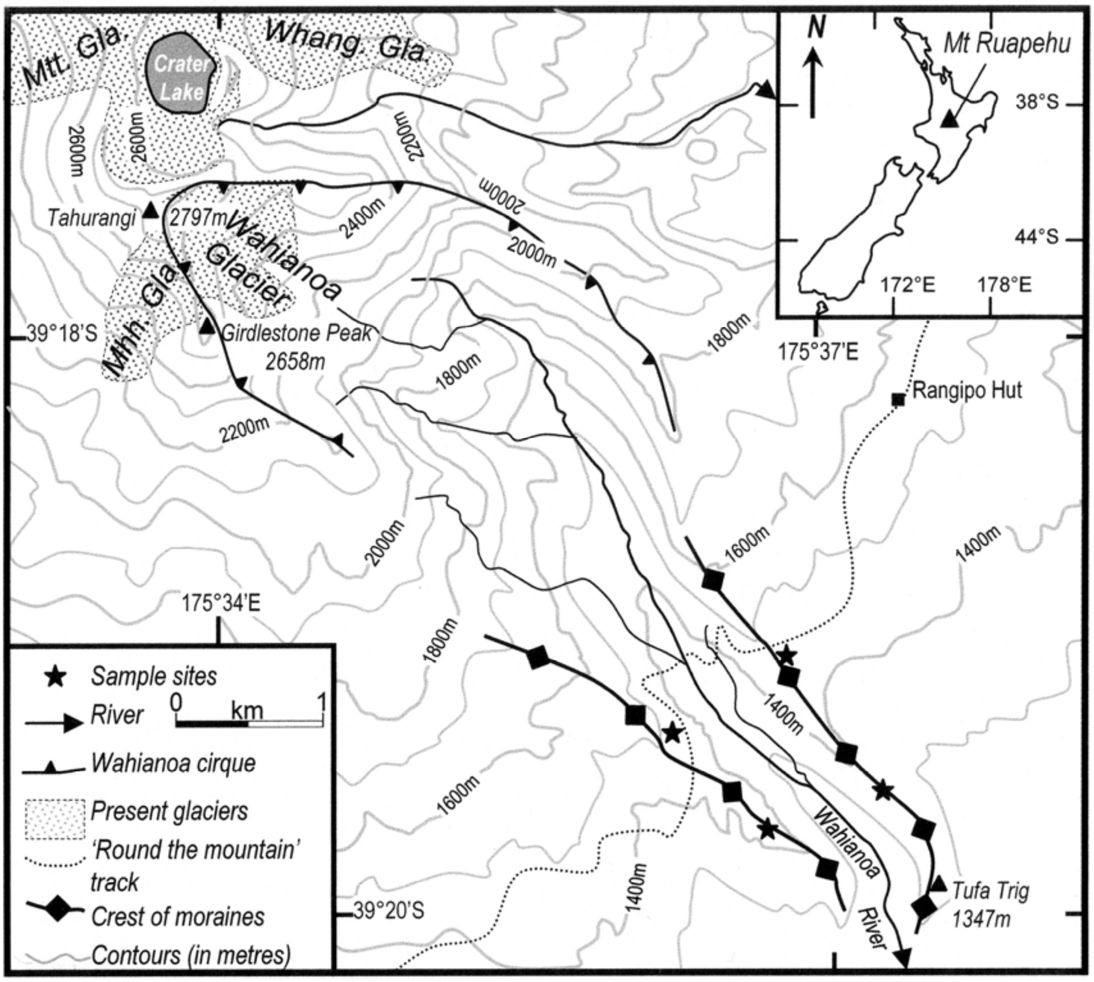

Figure 1. Location of the Wahianoa moraines, south-eastern Mt Ruapehu.

Methods

Four sediment samples were removed from each pit for SEM analysis. Following Krinsley and Doornkamp (1973), grains from the coarse sand fraction (0.5-1 mm) were sub-sampled, and cleaned using the method described by Blakemore *et al*. (1987). Grains were then placed in a solution of oxalic acid (H2C2O4), ammonium oxalate (C2H8N2O4) and distilled water for 12 hours before being placed into an ultrasonic bath to remove contaminants, and then oven-dried. Seventy-six grains were then separated with a hand-held magnet under a binocular microscope and then mounted on a metal stub. Grains were then coated in a thin layer of gold by a Baltec SCD 050 sputter-coater for 200 s at 60mA sputtering current. Stubs were then placed in a Cambridge 250 Mark 3 SEM for analysis.

Figure 2. Looking north-west up the Wahianoa valley toward the summits of Girdlestone (2658 m) and Tahurangi (2797 m). The lateral moraines (arrowed) rise 30-50 m above the surrounding ring-plain and the valley is c. 150 m deep in the foreground.

Results and Discussion

Following Mahaney and Kalm (2000) and Hart (2006), surface texture analysis was used to visually identify surface micro-textures present on each of the magnetite grains. A suite of representative photomicrographs from the Wahianoa samples is shown in Fig. 3. To aid comparison with previous studies that analysed quartz as an environmental discriminator, the series of twenty-four micro-textures outlined by Mahaney and Kalm (2000) was used (Fig. 4). The bar chart compares their study of quartz micro-textures from Estonian tills with results from the present study. The ultimate aim is to determine whether such textures diagnostic of glacial transport on quartz, are visible on magnetite. Following Hart (2006), visual inspection of the seventy-six grains revealed that several 'styles' of magnetite grain could be identified, such as grains of low relief and subangular edges (Fig. 3A), well-rounded particles showing original uneroded surfaces (Fig. 3B), and grains with conchoidal fracture pattern and subparallel linear fractures (Fig. 3C). In addition, fracture faces and faceting (Fig. 3D) were present, as were grains exhibiting sharp edges and linear steps (Fig. 3E). Also evident were sub-rounded particles (Fig. 3F), with some grains showing generally well-rounded surfaces, truncated by fresh fracture faces (Fig. 3G).

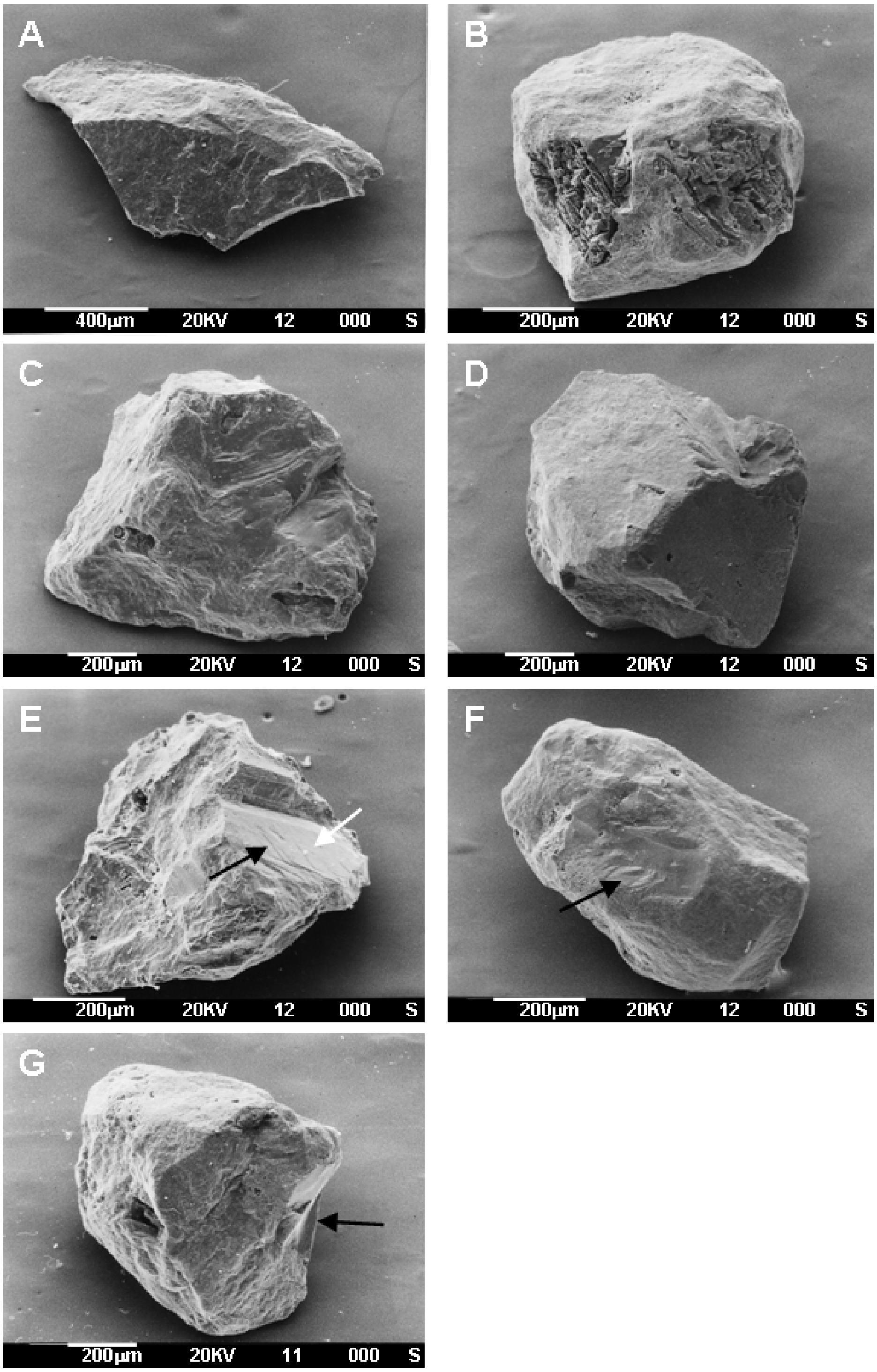

Figure 3. SEM photomicrographs of typical micro-textures evident on magnetite: (A) subangular edges; (B) subrounded particles showing original uneroded surfaces; (C) conchoidal fracture pattern and subparallel linear fractures (in square); (D) fracture faces and faceting; (E) sharp edges and linear steps (black arrow) and adhering particles (white arrow); (F) subrounded particles with linear steps (arrow); (G) generally well-rounded surfaces, truncated by fresh fracture face (arrow). Scale bar is shown on each image.

A moderate proportion of grains (44%) showed evidence of adhering particles (Fig. 3C & E), which are thought to result from subglacial transport (cf. Smalley 1966; Krinsley & Doornkamp 1973). V-shaped percussion cracks, which on quartz grains have usually been interpreted as reflecting transport by water (e.g., Passchier *et al*. 1997), were not present on any of the magnetite samples (Fig. 4). This is consistent with the SEM study of subglacial sediments at Briksdalsbreen, Norway, by Hart (2006), where only a small proportion of quartz grains (12%) had V-shaped percussion cracks evident on their surfaces. At Briksdalsbreen, the minor appearance of this micro-texture was thought to reflect transport in the proglacial lake or a subglacial R-channel channel prior to deposition.

Surface texture analysis shows several major similarities with Mahaney and Kalm's (2000) examination of Estonian till-quartz which are worth discussing. First, there is a marked consistency in the proportion of sharp angular features in the Estonian quartz (45%) and Ruapehu magnetite (56%) samples (Fig. 4). Second, a similarly large proportion of grains in the quartz (60%) and magnetite (52%) show high relief features (Fig. 4), thought to be due to grain-on-grain contact in the subglacial basal traction zone under extreme shear stress (Mahaney *et al*., 2001, p. 168). In direct contrast to 'glacial' grains, both of these micro-textures are nearly or completely absent in Mahaney and Kalm's (2000) comparative SEM analysis of Devonian sandstones of fluvial origin. Third, a similar proportion of grains in Mahaney and Kalm's (2000) study (56%) showed the presence of adhering particles. These are considered by Smalley (1966) to represent the degree of glacial grinding, and were totally absent from Mahaney and Kalm's (2000) comparative analysis of Devonian fluvial deposits.

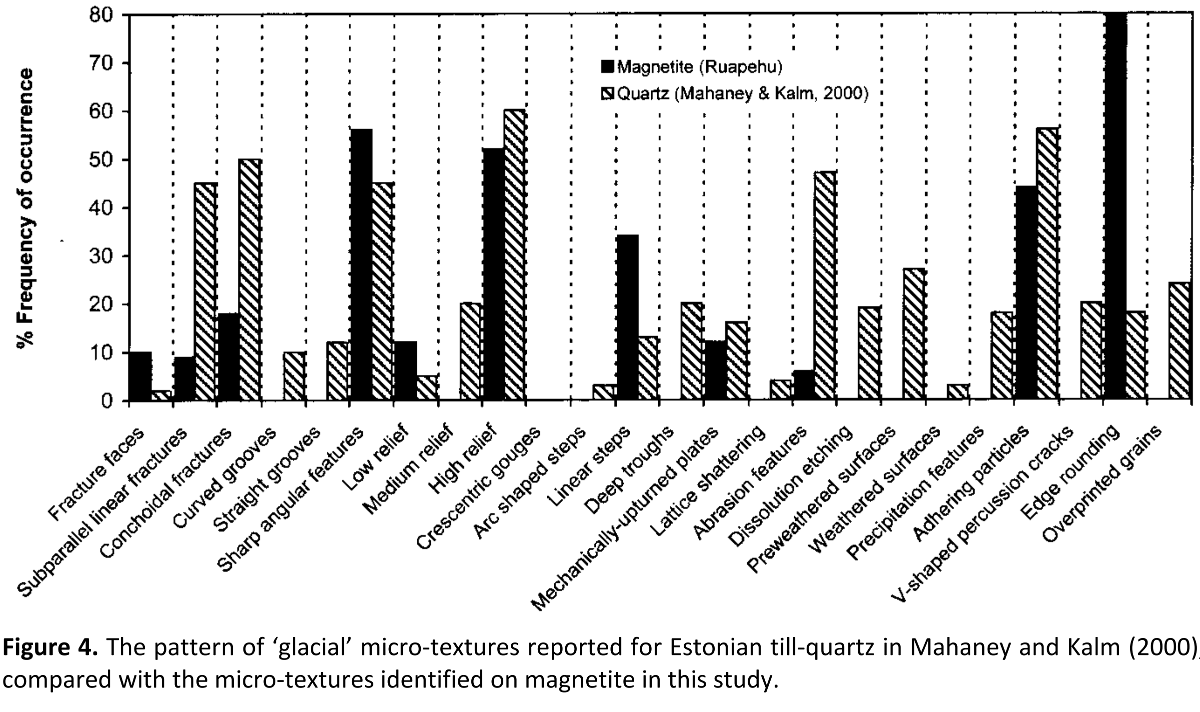

Figure 4. The pattern of 'glacial' micro-textures reported for Estonian till-quartz in Mahaney and Kalm (2000), compared with the micro-textures identified on magnetite in this study.

Despite these similarities, there are several major inconsistencies with Mahaney and Kalm's (2000) results (Fig. 4). These include features that Mahaney and Kalm (2000, p. 47) have specified as being "the major glacial crushing features". In particular, though they were present on some grains, only modest proportions of the magnetite samples showed subparallel linear fractures (9%) or conchoidal fractures (18%), compared with the Estonian tills (45% and 50% for each of these micro-textures, respectively). Abrasion features, though abundant in the Estonian tills (47%) are uncommon in the Ruapehu magnetite samples (6%). Finally, the feature most abundant on the magnetite grains was edge rounding (80%), a complete contrast to the Estonian tills, where only 18% of quartz grains displayed this feature, although intriguingly, 56% of the Estonian sandstones (of fluvial origin) did display edge rounding. In summary, the magnetite grains show some encouraging similarities with the Estonian till-quartz, but also reveal some contrasting micro-textures too.

Conclusion

This study suggests that similar micro-textures to those specified as being of glacial origin on quartz, have been identified on magnetite from the Wahianoa moraines, Mt Ruapehu. We conclude that the presence of micro-features such as high relief, sharp angular features, linear steps, adhering particles and, to a lesser extent, conchoidal and subparallel linear fractures indicate a glacial origin. However, we caution that further study on additional glacial deposits and a range of other depositional environments is needed to evaluate the consistency of micro-textures on magnetite. Indeed, just as Mahaney and Kalm (2000) and Van Hoesen *et al*. (2004) set out to establish the characteristics of glacial grains using quartz in areas of the northern hemisphere subject to ice sheet glaciation, the ultimate aim with magnetite would be to establish the precise geometry and representative micro-textures for a range of depositional environments. However, though the present study has identified some similarities between 'glacial' micro-features on quartz and magnetite, inconsistencies exist too. Moreover, other processes, unrelated to glacial transport on volcanic mountains, may give rise to intergranular attrition, such as lahars (Lecointre *et al*. 2004). This begs the question of whether or not the magnetite grains are modified by active glacial transport, glaciofluvial transport, or are simply modified by water action? One way forward could be a detailed statistical analysis of the co-variance of different microtextural features. Indeed, Hart (2006) alludes to this, stating "numerous researchers have shown that subglacial erosion produces a distinct set of surface textures" (Hart 2006, p. 143). Careful sampling of magnetite from a range of known depositional environments around the Ruapehu ring-plain would provide a basis for this in the future.

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