8 Discussion and General Conclusions

The use of silicate mineral fertilisers has been criticised by some agricultural scientists. Critics claim that the required application rates are too high and the mineral dissolution too slow for them to be of any value in crop and pasture production. The results of this research show that milled silicate fertilisers do provide nutrients to plants and the research provides a clear indication of some factors that influence the effectiveness of silicate mineral fertilisers. Attrition milling greatly improved the effectiveness of silicate minerals and may provide a procedure for developing cost effective silicate fertilisers.

The major findings of this research include:

- The attrition milling of silicate minerals was accompanied by a reduction in particle size (many particles <100nm) and an increase in surface area (up to 170 m^2 g^{-1}). The greatest changes in these parameters occurred during the first six hours of milling.
- Changes in biotite and hornblende were greater than for microcline as indicated by values of particle size and surface area. The strong natural cleavage of biotite and hornblende resulted in extensive fragmentation of particles, while the framework nature of microcline resulted in initial fragmentation followed by amorphization rather than by further fragmentation.
- In a laboratory dissolution experiment, fine-grained, high surface area milled minerals dissolved to a greater extent than unmilled minerals. Dissolution was characterised by an initial rapid, incongruent release of base cations with respect to Si, with dissolution becoming more congruent as dissolution proceeded. Dissolution rates and incongruent dissolution increased with increased milling.
- Dissolution was greatest in acid solution with dissolution in deionised water being limited by increases in pH associated with mineral dissolution.
- Dissolution rates of Si, K and Ca in both deionised water and acid solution and Na in acid solution were linearly related to specific surface area, while Mg in both solutions and Na in deionised water were not directly related to specific surface area.
- The increase in cation dissolution due to milling during dissolution experiments was reflected in the results of plant growth experiments with nutrient uptake increasing with milling time. In several instances where nutrients were supplied as

ground minerals, ryegrass growth was sustained through nine harvests over a 10 month period. Over a six week period, plant growth and nutrient uptake was much less than where equivalent amounts of soluble fertilisers had been used.

- Exchangeable cations increased in soils fertilised with ground silicate minerals with larger increases occurring with increased milling. Plant growth and cation uptake and cation uptake persisted where the exchangeable cation pool was not exhausted.
- The application of milled mineral increased soil pH, although the lime equivalence of silicates was less than 10%.
- The uptake of nutrients by plants increased with surface area up to 100 m^2 kg^{-1} for K, 60 m^2 kg^{-1} for Mg, 40 m^2 kg^{-1} for Ca and 300 m^2 kg^{-1} for Si, and surface area may be used as a predictor of agronomic effectiveness of ground rocks and thus for determining optimal milling procedures and application rates for silicate minerals.
- The cost of grinding silicate minerals is considerable which combined with their low agronomic effectiveness means that they are not viable substitutes for chemical fertilisers for conventional agriculture.

This research has several limitations including the use of pure minerals rather than whole rocks and the use of sand in the glasshouse experiment rather than soil. The complex reactions and relationships between milled silicate rocks and soil properties were not evaluated during this work. Bakken et al. (1997) indicate that the amount of plant available K derived from crushed rocks and minerals might differ between different soil types and environments so that these factors require consideration.

Much further work is required to identify the most appropriate milling conditions and to determine appropriate application rates and procedures for the ground materials. The practical considerations relating to the use of a very fine-grained siliceous product in field applications are also important and possible health hazards must be identified.

This thesis focused on the plant nutrition benefits of ground silicate minerals. The importance of milled silicate minerals in relation to other aspects of plant growth and soil management were not considered. Fine-grained minerals can affect the physical and chemical properties of the soil such as water retention, water repellency and surface charge characteristics, but these issues were not considered. Torn et al. (1997) has proposed the importance of high-surface area, non-crystalline minerals in soils in controlling soil organic carbon storage and turnover in humid environments. Milled silicate minerals may also affect organic carbon dynamics in soils through chemical and microbiological processes. Milled silicates may also have potential in controlling soil environmental quality such as by the retention of toxic organic compounds and heavy metals in a similar manner to engineered clay nanocomposite products (Prost and Yaron, 2001).

This work only addresses dissolution in purely chemical systems. Mineral dissolution in a biologically active soil will reflect rhizosphere and microbial processes and may be enhanced (Barker et al., 1997). Microbial dissolution of minerals is mostly a surface mediated process (Banfield and Hamers, 1997; Robert and Berthelin, 1986) so that the presence of a large highly reactive mineral surface in soils containing milled silicates may increase microbial activity and mineral dissolution. Attrition milled minerals may thus have a role in enhancing soil health and quality, particularly where chemical additives (e.g. fertilisers) are considered undesirable.

A central concept emerging from this research has been that the increased surface area of milled silicate minerals relates directly to dissolution and plant nutrient uptake. Further consideration of the use of silicate mineral fertilisers must strongly address surface area and surface processes rather than considering only solute chemistry. This approach can be used to assess local sources of silicates and developing appropriate engineering to minimise production costs, application rates and transport costs.