

Silicate rock powder: effect on selected chemical properties of a range of soils from Western Australia and on plant growth as assessed in a glasshouse experiment

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Abstract

Soil samples were collected from 20 locations from the south western part of Western Australia and incubated at 25 °C for 60 days without or with finely ground granite powder at a rate of 20 g kg⁻¹ soil, equivalent to about 20 t ha⁻¹. Electrical conductivity and exchangeable Na, Ca and Mg were not significantly affected by granite application for most soils. Conversely, among the 20 soils studied, nine exhibited a significant increase in exchangeable K (at $p < 0.01$) due to granite application. Six of them showed a consistent increase in soil pH as measured in a CaCl₂ extract, corresponding to less than 0.26 pH units. The concomitant increase in exchangeable K due to granite application ranged between 10 and 390%. However, in absolute value it amounted to less than 0.07 cmol K kg⁻¹ soil, suggesting that a maximum of 59 g kg⁻¹ of the applied granite dissolved during the course of this incubation experiment. One of the most granite responsive soils was used for a pot experiment conducted with wheat grown for 88 days in a glasshouse. In this experiment, the soil was either untreated (control) or mixed with either granite or diorite powders at six different rates of application. The wheat biomass and cation contents in plant tissue were not significantly affected by the application of diorite at any rate of application. Conversely, for the granite-treated soil a significant increase in wheat biomass was encountered for rates larger than 2.5 g kg⁻¹ soil. Since a significant increase in K content was obtained at the same rates of application it was concluded that the positive response of wheat growth to granite application was due to potassium supplied by granite dissolution. The use of granite powder as a potential K fertilizer thus needs further attention even though its efficiency as compared to a soluble fertilizer would almost certainly be poor.

Introduction

The use of ground rock to improve soil properties and plant growth is an ancient agricultural practice: carbonate (limestone, dolomite) or sulphate (gypsum) rocks are currently used worldwide for liming whereas phosphate (mostly apatitic) rocks are widely used as P fertilizers, especially in the tropics. However, very little is known about the possible use of silicate rocks. Quarries produce large quantities of silicate rock powders as a by-product which are often stock-piled. Being composed of fine, dusty material, they represent locally a

potential health hazard which reinforce the interest in finding ways to use them. Some are used as fertilizers or soil amendments, on their own or as components in mixtures. Commercial products containing silicate rocks are increasingly used as they are recommended for alternative agriculture practices which ban the use of conventional, manufactured fertilizers (Bockman et al., 1990). The scientific literature on this topic is however extremely scarce and shows conflicting results, as reviewed by Weerasuriya et al. (1993). It is noteworthy that most of the published material deals with massive, unrealistic doses of application. For instance, Gillman

(1980) reported a highly significant improvement in the chemical properties of an acid soil (increases in pH, CEC and exchangeable Ca and Mg) due to application of basalt scoria at rates ranging between 100 and 300 t ha⁻¹. Additions of various silicate rock powders at a minimum rate of 50 to 100 g kg⁻¹ were required to obtain a substantial increase in plant biomass in pot experiments (Kahnt et al., 1986; Baerug, 1991). Only a few workers have mentioned results obtained with more realistic rates of application. Blum et al. (1989a, b) concluded that no significant improvement of soil properties such as pH and CEC could be gained from yearly rates of about 1 t ha⁻¹ of silicate rocks such as granite, diabase and basalt, even in the long term. Von Fragstein et al. (1988) calculated that the cost of application of a range of silicate rocks according to their ability to release mineral nutrients such as K, Ca and Mg, as assessed by water or HCl extractions, would be highly dissuasive for any agricultural use. Von Mersi et al. (1992) however reported a highly significant increase in pH and consequent stimulation of microbiological activity of soils from various forested experimental sites in Austria, at a rate of less than 5 t ha⁻¹. This astonishing result was obtained with commercial products made of mixtures of basalt, diabase and bentonite in various proportions. However, the chemical composition of the various mixtures used in this study shows anomalously high Ca, P and S contents and the presence of carbonates suggesting that the observed effect could not be univocally attributed to these silicate rocks and bentonite. A more convincing field experiment designed for investigating the potential use of a ground silicate (sanidine feldspar) as a K fertilizer for low input pastures in Columbia showed no significant plant response in the year of application at a rate of 1.1 t ha⁻¹ (Sanz Scovino and Rowell, 1987). On the other hand, some pot experiments revealed a substantial yield increase at rates of application equivalent to 2 to 6 t ha⁻¹ of ground basalt, micaschist and migmatite (Leonardos et al., 1987). The present paper presents the results of two complementary experiments: (i) an incubation experiment which was aimed at evaluating the short term effect of a granite powder on selected chemical properties of a range of acid, highly weathered soils from Western Australia and (ii) a pot experiment designed for evaluating the short term effect of two ground silicate rocks (granite and diorite) on plant growth for several rates of application.

Materials and methods

Characteristics of the ground rocks

The ground rocks used in the present experiments were kindly supplied by Pioneer Quarries at Herne Hill, near Perth (Western Australia). A biotite-containing granite was used in both experiments whereas a diorite was used only in the pot experiment. In the pot experiment, the <1180 µm fraction of ground rock was used after sieving the coarsely crushed material as sampled on the quarry stock-pile. The particle size of these crushed rocks are indicated in Table 1. For the incubation experiment, the crushed granite was finely ground by hand with an agate mortar and pestle, then wet-sieved with deionised water so as to obtain particles of a uniform 45–90 µm size. Chemical compositions of the rock powders are summarized in Table 2.

Incubation experiment

For this experiment 20 Western Australian soils were investigated. Selected properties of these soils are listed in Table 3. Two treatments were applied to these soils: a control treatment for which no granite was added to the soil and a granite treatment for which 45–90 µm size granite was added at a rate of 20 mg g⁻¹ soil, i.e. equivalent to about 20 t ha⁻¹ assuming that it would be incorporated into the top 10 cm of the topsoil. To obtain a uniform rate of application the granite powder was thoroughly mixed with the dry soil in a bag. The granite-treated soil was thereafter subsampled from this bag. For each treatment and each soil, sixteen 10-ml centrifuge tubes were prepared which contained one gram of soil. Half of these were wetted by adding 1 ml deionized water and immediately analysed to check the chemical changes induced by granite application at t = 0 days. After adding 1 ml deionized water to the other 8 tubes, these were incubated for 60 days at a constant temperature of 25 ± 1 °C, in dark conditions so as to prevent algal growth. The tubes were sealed with a cap in order to prevent any water loss. The absence of water loss was regularly checked by weighing the tubes. At t = 60 days, the incubated samples were treated according to the following procedures which had been similarly applied to the t = 0 days samples. Four replicates were used for measuring electrical conductivity and pH while the other four replicates were used for measuring exchangeable Ca, Mg, K and Na. For electrical conductivity and pH measurements, 4 ml deionized water were added

Table 1. Particle size of the coarsely ground rocks used in the pot experiment as sampled at the Pioneer quarry, Herne Hill; all values are in g kg^{-1}

	ground granite	ground diorite
< 2 μm	24	21
2-20 μm	66	61
20-75 μm	74	52
75-106 μm	28	23
106-150 μm	31	25
150-180 μm	21	18
180-300 μm	74	64
300-600 μm	140	138
600-1000 μm	127	135
> 1000 μm	416	463

Table 2. Chemical composition of the ground rocks used in the two experiments; all values are in g kg^{-1}

	finely ground granite	ground granite	ground diorite
SiO_2	738	673	495
Al_2O_3	124	135	134
TiO_2	3.7	6.0	11.4
Fe_2O_3	28.6	53.5	129
MnO	0.4	0.7	1.8
CaO	23.4	35.6	112
MgO	9.7	13.8	51.5
K_2O	28.1	22.9	3.4
Na_2O	35.9	39.2	19.3
P_2O_5	0.3	0.8	1.0
SO_3	0.4	0.3	1.2
LOI ^a	8.7	9.1	11.8

^aLOI stands for loss on ignition at 1200°C

per tube so as to get a final soil to solution ratio of 1:5 (weight:volume). The soil suspensions were then shaken for 60 minutes before the electrical conductivity was measured. The pH in water (pH- H_2O) was then measured prior to the addition of 0.2 ml 0.25 M CaCl_2 per tube, yielding a final concentration of about 0.01 M CaCl_2 in the soil suspension. The tubes were then shaken for another 60 minutes before measuring the pH of the soil suspension (pH- CaCl_2). For the other four replicates, exchangeable cations were extracted as follows: 10 ml SrCl_2 0.01 M was added to each tube which was shaken for 60 minutes before being centrifuged at 2000 rpm for 5 minutes. The supernatant was then filtered with Whatman ashless filter paper (Whatman 42) and another 10 ml SrCl_2 0.01 M was added to each tube. The same procedure was repeated twice and the three filtered supernatants collected in the same tube which was then adjusted to a final

volume of 30 ml. The K and Na concentrations were measured using flame photometry with standards prepared in 0.01 M SrCl_2 . The concentrations of Ca and Mg were measured using atomic absorption spectrometry in a LaNO_3/HCl matrix (1 g La l^{-1} and 0.2 M HCl). Standards were prepared with various amounts of SrCl_2 according to the various dilutions of the SrCl_2 -extracts. Analysis of variance was performed on data for the four replicates. Granite application was considered to have a significant effect when average values for the control and granite treatments were significantly different at $p < 0.01$.

Pot experiment

Soil number 0 in Table 3 was used for the glasshouse experiment. The soil was collected from 'Amery Acres', Dowerin, in the Western Wheatbelt of Aus-

Table 3. Selected properties of the 20 Western Australian soils

No	Ref. ^a	Classification ^b	Location	Sand	Clay	C org.	Electr. pH	pH	Titrr. ^c	Titrr. ^c	Ca	Mg	Na	K	Al	
							Cond. H ₂ O	CaCl ₂	Ac.	slope	exchangeable cations					
				g kg ⁻¹			μS cm ⁻¹				cmol _{cat} kg ⁻¹					
0		Dy 3.43	Dowerin	930	40	4.2	28	5.51	4.69	6.4	0.1300	0.70	0.11	0.03	0.02	0.05
1	BSN4.1	Um 5.21	Busselton	705	87	51	109	5.42	4.59	49.1	0.0273	0.58	0.52	0.78	0.12	0.13
2	BTN2.1	Dy 5.61	Bridgetown	868	90	69	70	5.94	5.31	33.1	0.0145	8.02	2.06	0.15	0.14	0.13
3	GTN5.1	Uc 5.11	Geraldton	909	63	4.6	12	5.93	5.02	2.7	0.1500	0.82	0.23	0.04	0.03	0.04
4	JER5.1	Dy 5.86	Jerramungup	979	11	4.8	16	5.85	4.85	3.3	0.2100	0.45	0.11	0.06	0.06	0.01
5	PTN3.1	Gn 2.61	Pemberton	752	161	65.8	109	5.48	4.84	44.1	0.0177	6.46	2.16	0.28	0.22	0.28
6	PTN5.1	Uc 3.32	Pemberton	878	46	132.3	85	4.85	3.99	158.0	0.0117	9.86	4.33	0.44	0.20	0.29
7	SCP 3.1	Dr 2.41	Pinjarra	842	79	34.7	73	5.57	4.70	30.8	0.0318	2.89	1.38	0.35	0.20	0.16
8		Gn 2.14	Boyanup	783	141	41.1	119	4.33	3.88	53.0	0.0349	1.17	0.23	0.06	0.06	1.42
9		Um 4.25	S. Harvey	590	21	49	59	5.52	4.64	27.4	0.0570	2.67	1.69	0.46	0.16	0.87
10		Um 2.21	Harvey	825	76	47.8	152	5.50	4.67	57.3	0.0199	6.52	4.33	1.22	0.02	0.21
11		Dy 5.81		799	146	12.6	20	5.03	4.35	21.2	0.0760	0.16	0.12	0.05	0.03	0.76
12	KS-Uc 5.11		Tuttanang	842	132	7.7	18	5.44	4.50	13.0	0.0884	0.21	0.44	0.06	0.03	0.34
13		Gn 3.11	Pingelly	714	155	15.6	38	5.85	4.80	27.3	0.0565	0.03	2.25	0.48	0.03	0.73
14		Gn 2.24	Boyanup	710	240	13	45	4.86	4.03	27.7	0.0697	1.39	0.64	0.11	0.06	0.90
15		Uc 5.22	Pinjarra	986	8	11.8	24	5.88	5.01	3.6	0.0699	2.45	0.35	0.04	0.02	0.01
16		Uc 5.21	Bassendean	990	0	13.8	22	5.33	3.96	13.9	0.1200	2.09	0.45	0.09	0.05	0.04
17		Gn 2.14	Pemberton	695	196	12.9	30	6.10	5.13	18.1	0.0481	1.62	1.93	0.22	0.19	0.15
18		Gn 2.1	Pemberton	427	501	4.2	54	6.07	5.63	6.5	0.0533	1.34	1.78	0.28	0.31	0.01
19		Dr 2.61	Wungong	540	290	27.5	19	6.15	5.03	25.9	0.0332	9.34	3.75	0.23	0.19	0.04

^a Soils sampled close to reference sites according to McArthur (1991)^b According to Northcote (1979)^c Titratable acidity (Titrr. Ac.) is expressed as $\mu\text{mol OH}^+ \text{g}^{-1}$ and titration slope (Titrr. slope) as pH unit ($\mu\text{mol OH}^+ \text{g}^{-1}$)⁻¹

tralia. Non draining pots were prepared with 3 kg soil per pot and various amounts of either coarsely ground granite or diorite (<1180 μm fraction) were added. These were thoroughly mixed with the dry soil in a bag which was thereafter used for lining the pots. The various treatments were: (i) a control treatment of soil without rock application, (ii) six treatments with granite applied at 0.625, 1.25, 2.5, 7.5, 15 and 30 g per pot and (iii) six treatments with diorite applied at 0.3125, 0.625, 1.25, 2.5, 7.5 and 15 g per pot. A rate of 30 g per pot, or 10 g ground rock kg^{-1} soil is equivalent to a field application of about 10 t ha^{-1} , assuming that it would be incorporated into the top 10 cm of the topsoil. For each treatment, three replicates were prepared. The pots were then watered to field capacity with deionized water. After a 7 day equilibration period, the pots were sown with wheat (*Triticum aestivum*, cv Gutha). Of the 9 plants sown per pot 8 were kept and grown for 88 days in a glasshouse, during the southern autumn 1993. During this period the pots were regularly re-randomized and watered by weight in order to maintain the soil water content close to field capacity. The whole top parts of plants were then harvested, oven-dried and weighed so as to measure the dry biomass (DW). Plant material was then analysed for K, Na, Ca and Mg. The ground tops were digested in sulphuric acid and hydrogen peroxide (Yuen and Pollard, 1954). The K and Na concentrations in the digest

were measured by flame photometry whereas Ca and Mg concentrations were measured by atomic absorption spectrometry. Analysis of variance was performed to determine any significant differences in plant yield and K content between the various treatments.

Results

Incubation experiment

Among the 20 soils which were investigated, electrical conductivity did not change significantly due to granite application, either at $t = 0$ or $t = 60$ days. The pH-H₂O of six soils and pH-CaCl₂ of eight soils increased significantly after granite application and incubation for 60 days (Figs. 1 and 2). In some instances (three soils for pH-H₂O and four soils for pH-CaCl₂), pH even increased significantly immediately after granite application (at $t = 0$). These pH changes at $t = 0$ remained small however (0.02–0.06 pH units). Only one soil (number 3) showed a consistent increase at $t = 0$ and after incubation for 60 days for both pH-H₂O and pH-CaCl₂. In this case, the pH increase amounted to only 0.03 at $t = 0$ and to 0.13–0.14 at $t = 60$ days. After 60 day incubation, a significant pH increase was measured in both H₂O and CaCl₂ for five soils including

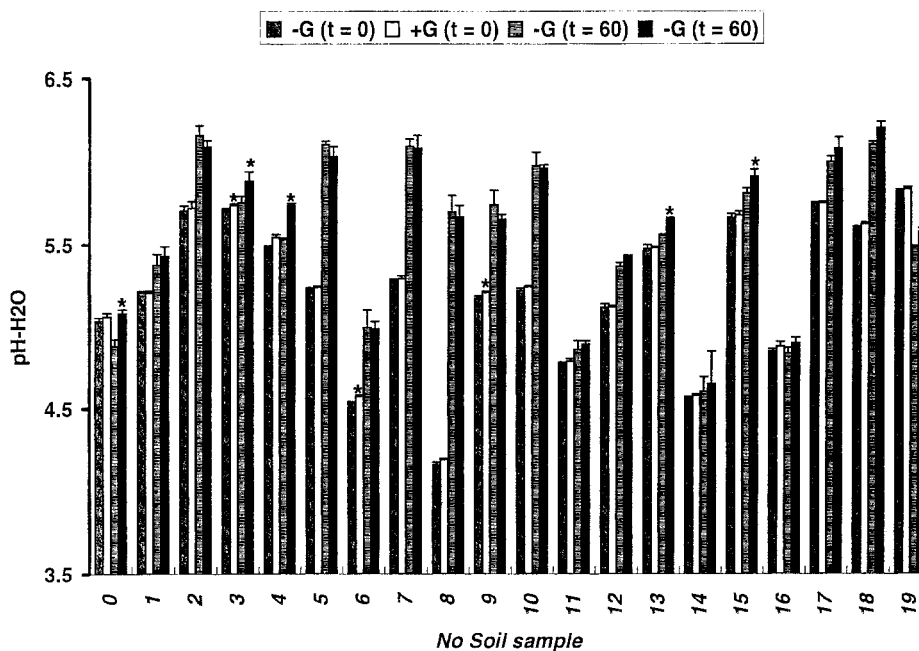


Figure 1. Changes of pH-H₂O after granite application at t=0 and t=60 days incubation. The bars indicate the standard deviation as calculated for the four replicates per treatment. For each duration and soil, a significant difference (at p < 0.01) between the granite (+G) and the control (-G) is indicated by an asterisk (*).

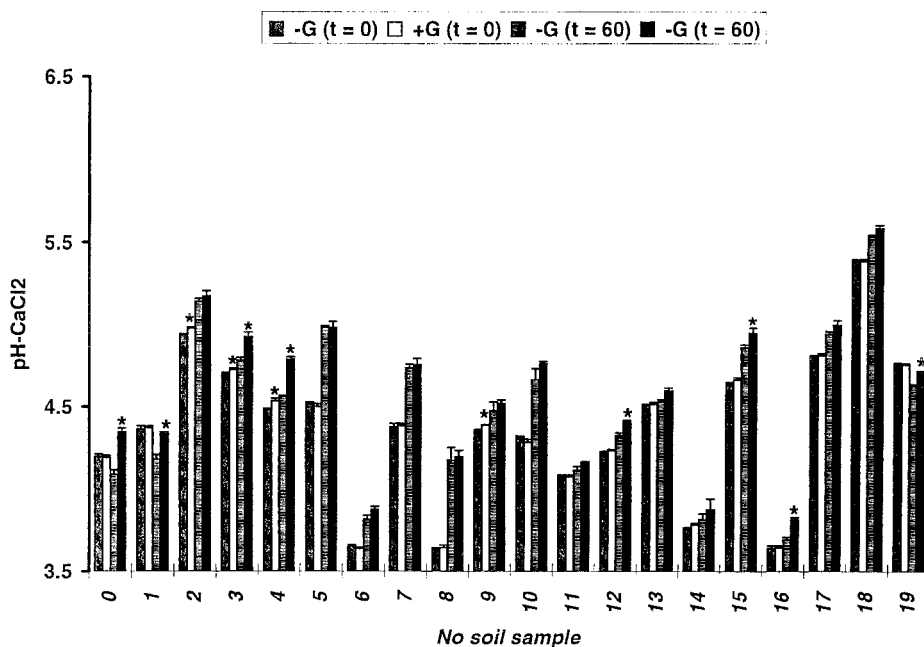


Figure 2. Changes of pH-CaCl₂ after granite application at t=0 and t=60 days incubation. The bars indicate the standard deviation as calculated for the four replicates per treatment. For each duration and soil, a significant difference (at p < 0.01) between the granite (+G) and the control (-G) is indicated by an asterisk (*).

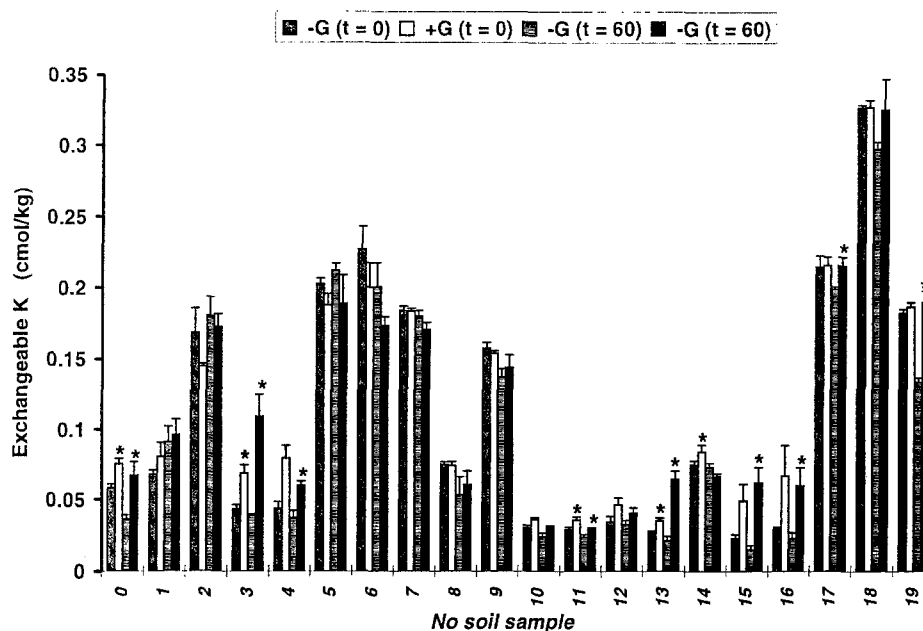


Figure 3. Changes of exchangeable K after granite application at $t = 0$ and $t = 60$ days incubation. The bars indicate the standard deviation as calculated for the four replicates per treatment. For each duration and soil, a significant difference (at $p < 0.01$) between the granite (+G) and the control (-G) is indicated by an asterisk (*).

Table 4. Potassium content and cation concentration in the plant top tissue as a function of the rate of application of granite or diorite (average value of three replicates)

Treatment	control	granite						diorite						Fisher
Rate of application (g pot ⁻¹)	0	0.625	1.25	2.5	7.5	15	30	0.312	0.625	1.25	2.5	7.5	15	lsd*
K content (mg pot ⁻¹)	35.1	38.3	35.3	35.1	42.8**	47.7**	57.0**	35.8	35.4	33.3	32.6	35.4	35.9	5.3
K concentration (mg g ⁻¹)	4.0	4.2	4.1	3.9	4.4	4.7**	5.4**	4.1	3.9	3.8	3.9	4.0	4.1	0.6
Na concentration (mg g ⁻¹)	0.4	0.4	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.4	0.5	0.4	0.4	0.2
Ca concentration (mg g ⁻¹)	4.0	3.6	4.6	3.7	4.0	3.7	3.1	4.3	4.4	4.3	4.6	3.8	4.2	0.9
Mg concentration (mg g ⁻¹)	1.9	1.7	2.1	1.8	2.0	1.9	1.6	2.1	2.1	2.0	2.0	1.8	2.0	0.4

* least significant difference according to a Fisher test (at $p < 0.01$)

** significantly different from the value for the control treatment according to a Fisher test (at $p < 0.01$)

the soils numbers 0 and 4 which yielded the largest pH change: 0.20 for pH-H₂O and 0.22–0.26 for pH-CaCl₂.

In most instances exchangeable Ca, Mg and Na were not significantly affected by the application of granite, either at $t = 0$ days or after incubation for 60 days. For soil samples numbers 9 and 10, exchangeable Na and Ca slightly decreased in the granite treated soil as compared to the untreated soil. This decrease was significant only for $t = 0$ days. Soil sample number 0 exhibited a significant decrease in exchangeable Mg at $t = 0$ days and of exchangeable Ca at $t = 60$ days. In most cases, these changes remained small as compared to the amounts of native exchangeable Ca, Mg or Na.

Conversely, for exchangeable K, five and nine soils showed a significant increase as a consequence of granite application at $t = 0$ and $t = 60$ days, respectively (Fig. 3). Four soils exhibited a consistent increase at $t = 0$ and 60 days. After 60 day incubation, the increase ranged between 0.005 and 0.070 cmol_{c(+)} kg⁻¹. As the initial levels of exchangeable K were fairly low for many soils (Table 3), the increase in exchangeable K ranged between about 10% of the initial level for soil number 17 up to 390% for soil number 15. For four soils, the exchangeable K was more than doubled due to granite application. Six soils exhibited both a significant increase in exchangeable K and pH-CaCl₂.

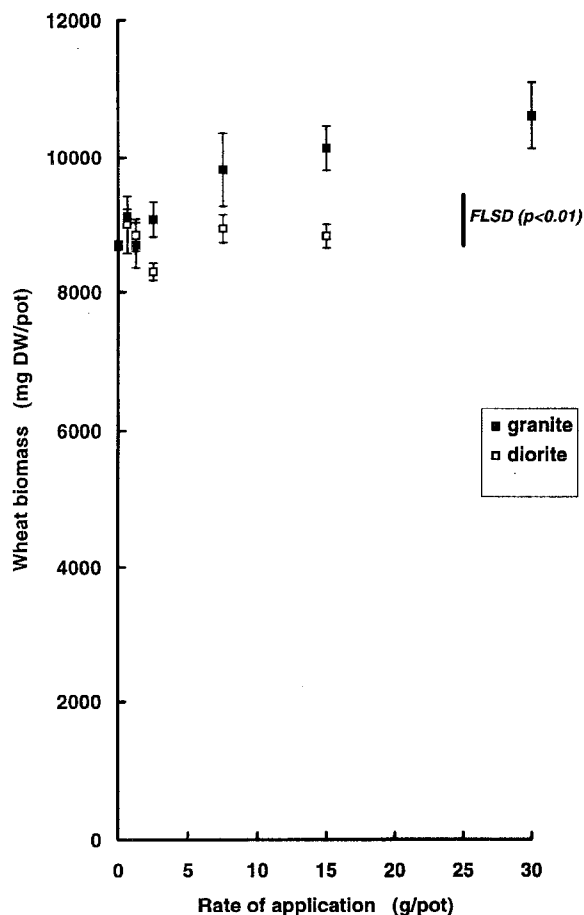


Figure 4. Wheat biomass (shoot dry weight) as a function of the rate of application of granite or diorite powders. The thin bars indicate the standard deviation as calculated for the three replicates per treatment. The thick bar indicates the least significant difference according to a Fisher test (FLSD at $p < 0.01$).

Pot experiment

The changes in biomass of plants indicate that whereas wheat did not respond to diorite application, it responded to granite application (Fig. 4). Indeed, according to the Fisher test for least significant difference at $p < 0.01$, biomass measured for the granite treatment was significantly higher than for the control (without rock) for rates of application of 7.5 g per pot and higher.

The results of plant analyses indicate that the K concentration in plant tissue increased with rate of application of granite while it remained constant when diorite was applied (Table 4). The K concentration of plants supplied with granite at rates larger than 15 g per pot was significantly higher than in control plants (Table 4). As a consequence of a simultaneous increase

in biomass and K concentration of wheat plants, the amount of K in the tops increased significantly with application of granite for rates of 7.5 g per pot and higher (Table 4). Meanwhile, the amount of K in plants for the diorite treatment remained constant. The concentrations of Na, Ca and Mg did not change significantly as compared with the control treatment, for the various rates of application of granite or diorite (Table 4). These results suggest that the observed response to granite application might be due to K supplied by this rock.

Discussion

Dissolution of rock powder: quantitative aspects

About half of the soil-rock mixtures investigated in the present experiment did not show any evidence of granite dissolution as indicated by an absence of significant changes of electrical conductivity, pH and exchangeable cations due to granite application. For the other half, dissolution remained restricted to between 4 and 59 mg g^{-1} , as estimated by the increase in exchangeable K after 60 days. For a majority of these granite-responsive soils, pH and exchangeable K consistently increased while for most soils, the other chemical properties remained unchanged.

In order to understand why some soils showed changes in chemical properties in response to granite application while others did not, linear correlation coefficients between the dissolution estimates and various physical and chemical properties of soils were calculated among the 20 soils investigated. The correlation matrix in Table 5 lists these coefficients for dissolution as estimated through the change of either $\text{pH-H}_2\text{O}$ ($\Delta\text{pH-H}_2\text{O}$), pH-CaCl_2 ($\Delta\text{pH-CaCl}_2$) or exchangeable K ($\Delta\text{exch.K}$). Firstly, this matrix confirms the fairly good agreement between the various estimates of granite dissolution, notably between $\Delta\text{pH-H}_2\text{O}$ and $\Delta\text{exch.K}$ or between $\Delta\text{pH-H}_2\text{O}$ and $\Delta\text{pH-CaCl}_2$. Conversely the correlation coefficients between any of these three estimates of granite dissolution and the various soil properties mostly indicated only loose linear relationships. The strongest association concerns $\Delta\text{pH-H}_2\text{O}$ and titration slope (reciprocal of buffering capacity). Surprisingly though, dissolution is positively related to the soil pH and negatively to titratable acidity. The hypothesis that dissolution of granite powder in soil is due to soil acidity is thus unproven since such a process would be expected to be enhanced by

Table 5. Correlation matrix between various physical and chemical soil properties and the granite dissolution as assessed through the change of either pH-H₂O (Δ pH-H₂O) or pH-CaCl₂ (Δ pH-CaCl₂) or exchangeable K (Δ exch.K) for the 20 soils under study.

	Clay %	Sand %	C org. %	pH -H ₂ O	pH -CaCl ₂	Tit. Ac.	Tit. slope	Exch. K	Exch. Na	Exch. Ca	Exch. Mg	Δ pH -H ₂ O	Δ pH -CaCl ₂	Δ exch.K
Clay %	1													
Sand %	-0.929	1												
C org %	-0.167	0.006	1											
pH-H ₂ O	0.164	-0.171	-0.297	1										
pH-CaCl ₂	0.465	-0.421	-0.262	0.895	1									
Tit. Ac.	-0.141	0.007	0.914	-0.477	-0.446	1								
Tit. slope	-0.321	0.436	-0.538	0.014	-0.023	-0.483	1							
Exch. K	0.304	-0.250	0.153	0.271	0.391	0.078	0.002	1						
Exch. Na	-0.012	-0.186	0.396	0.025	0.017	0.429	-0.402	-0.106	1					
Exch. Ca	0.035	-0.115	0.724	0.087	0.038	0.628	-0.457	0.217	0.391	1				
Exch. Mg	0.235	-0.351	0.567	0.145	0.125	0.603	-0.506	0.175	0.690	0.825	1			
Δ pH-H ₂ O	-0.086	0.206	-0.665	0.305	0.185	-0.487	0.742	0.111	-0.332	-0.436	-0.322	1		
Δ pH-CaCl ₂	-0.433	0.431	-0.363	0.125	0.048	-0.293	0.842	0.024	-0.079	-0.289	-0.298	0.778	1	
Δ exch.K	-0.209	0.234	-0.443	0.473	0.203	-0.408	0.410	-0.213	-0.300	-0.071	-0.097	0.618	0.424	1

the ability of the soil to supply protons, i.e. low pH and high titratable acidity. Nineteen of the twenty soils used in the present experiment had been used in an earlier work by Hughes and Gilkes (1994) for evaluating their ability to dissolve phosphate rock as assessed by a short-term incubation in conditions very similar to the present incubation study. They showed on a larger population of soils that the dissolution of phosphate rock was primarily affected by the ability of the soil to supply protons. This is confirmed on the subpopulation of 19 soils used in the present study for which phosphate rock dissolution was related notably to titration slope (buffer capacity, $r = -0.722$) and titratable acidity ($r = 0.648$). Contrary to what was obtained for granite dissolution, the dissolution of phosphate rock was positively related to titratable acidity and negatively to pH-H₂O ($r = -0.387$). This results in a fairly strong negative relationship between the dissolution of phosphate rock and the dissolution of granite as assessed by Δ pH-H₂O ($r = -0.776$), Δ pH-CaCl₂ ($r = -0.642$) or Δ exch.K ($r = -0.663$). These results suggest that the mechanisms involved in the dissolution of phosphate rock and granite in these soils are not the same and more specifically that acid hydrolysis is not responsible for granite dissolution (see below).

Dissolution of rock powder: positive effects on soil properties and plant growth

For about half of the twenty soils investigated in the incubation experiment, soil pH (Fig. 1 and Fig. 2) and exchangeable K (Fig. 3) increased significantly for granite-treated soils relative to control soils. The increase in soil pH remained however very low (less

than 0.3 pH units) in spite of the substantial rate of application of rock powder. This suggests that the liming effect of granite powder is obviously much lower than the effect that would have been obtained with similar rates of application of conventional, liming material such as crushed limestone. Conversely, for five of the nine granite responsive soils, exchangeable K increased from about two-fold in soil number 0 to nearly four-fold in soil number 15 after 60 day incubation with granite powder. Considering the improvement of K status obtained in these soils which all had initial low levels of exchangeable K, granite powder can thus be regarded as a potential K fertilizer.

Indeed the results of the pot experiment which applied to one of these responsive soils (soil number 0) indicate that plant growth was significantly enhanced by granite application suggesting that wheat responded to potassium supplied by granite powder. This growth response was obtained for rates ≥ 7.5 g granite per pot, equivalent to 2.5 t granite ha⁻¹ assuming that the granite was incorporated into the top 10 cm of the topsoil (Fig. 4). The results of plant analyses further support that the positive response to granite application is a response to K as supplied by granite dissolution since a significant increase in K concentration in plant tissue occurred for the granite treatments whilst the concentration of other cations remained unchanged (Table 4). A fairly good linear relationship between wheat biomass (DW in mg) and K concentration in plant tissue (K in mg g⁻¹) was obtained for the various granite treatments: $DW = 1338 + 3605 K$ ($r^2 = 0.92$), further suggesting that the growth response to granite application was due to K. In addition no significant response to diorite was encountered under iden-

tical conditions (Fig. 4 and Table 4). Such a difference between the two rocks is due to their differences in chemical and, more critically so in mineralogical composition (types and relative abundance of K-bearing silicates) according to Blum et al. (1989a). Indeed the K content of the diorite powder was about sevenfold smaller than that of granite (Table 2).

For soil number 0 the dissolution rate of granite powder in the incubation experiment amounted about 26 mg g^{-1} as estimated by the increase in exchangeable K. When comparing the amounts of K in wheat tops from granite treated pots with control pots containing soil number 0, it can be calculated that the application of granite at rates of 7.5, 15 and 30 g pot^{-1} yielded an additional offtake of 7.7, 12.6 and $21.9 \text{ mg K pot}^{-1}$, respectively (Table 4). Considering the K content of granite powder (Table 1) these amounts of K represent, respectively 54, 44 and 38 mg K of each gram of K applied as granite. Since the standard deviation of K content measurements ranged between 0.8 and 5.4 mg pot^{-1} , the above calculations are not reliable at the lowest rate of granite application. At the rate of 30 g pot^{-1} for which the relative error is minimal, the additional amount of K due to granite application (38 mg K per gram of applied K) gives an estimate of granite dissolution which is in good agreement with the figure obtained from the incubation experiment (26 mg g^{-1}), in spite of the differences between the conditions of the two experiments.

Dissolution of rock powder: hypothetical processes

For most of the granite-responsive soils investigated in the incubation experiment exchangeable K significantly increased while the contents of the other exchangeable cations remained unchanged. This suggests that the dissolution of granite powder in these soils was not congruent. Thus K-bearing silicates obviously dissolved first or at a faster rate than the other minerals contained in the granite. Biotite being the most weatherable K-bearing component of granite (Goldich, 1938), it is most likely that the K in this mica dissolved preferentially. In moderately acid conditions phyllosilicates such as biotite are known to evolve into vermiculitic clay minerals through a simple exchange process during which interlayer K is released and replaced by hydrated cations such as Na, Mg or Ca (Robert, 1971; Gilkes et al., 1973; Fanning et al., 1989). Such a process may account for the increase in exchangeable K and concomitant decrease in exchangeable Mg and Ca which occurred in some instances and was signifi-

cant only for soil number 0 at $t = 60$ days. However, the amount of exchangeable Ca involved in this case was larger than required for a simple exchange with the released K. It is thus not possible to state if such a process occurred to any significant extent in the present experiment. It is likely that it would be restricted in the closed conditions of this incubation experiment where the released K would rapidly hinder the process since the exchange of interlayer K is known to occur only when K concentration is below a fairly low critical level (Fanning et al., 1989). For this reason, it is likely that such a process would be enhanced in field conditions due to removal of dissolved K by leaching or uptake by plants (Hinsinger and Jaillard, 1993). Considering that in most cases a pH increase occurred concomitantly, it is almost certain that this simple ion exchange process did not occur alone, if it occurred at all. On the other hand, the acid dissolution (hydrolysis) of a maximum of about 50 mg g^{-1} of granite which might account for such a pH increase would have yielded an increase of $0.083 \text{ cmol}_{c(+)} \text{ Ca kg}^{-1} \text{ soil}$, $0.012 \text{ cmol}_{c(+)} \text{ Mg kg}^{-1} \text{ soil}$ and $0.116 \text{ cmol}_{c(+)} \text{ Na kg}^{-1} \text{ soil}$, with the hypothesis of a congruent dissolution. For a majority of soils in the present experiment, these amounts of Ca or Mg were lower than the standard deviation of the mean of four replicated measurements of exchangeable Ca or Mg. One may thus conclude that no significant dissolution of granite occurred according to the measurements of exchangeable Ca and Mg. As a direct consequence, it is not possible to conclude if any congruent dissolution occurred on the basis of changes in amounts of these elements. For Na however, the variability of the exchangeable Na measurements was lower, the standard deviation being much less than $0.116 \text{ cmol}_{c(+)} \text{ Na kg}^{-1} \text{ soil}$ in all cases. Nevertheless, the increase in exchangeable Na due to granite application remained very low and was not significantly different from zero, reaching a maximum value of $0.005 \text{ cmol}_{c(+)} \text{ Na kg}^{-1} \text{ soil}$ for soil number 13, that is much less than would have been yielded by congruent dissolution of granite. Indeed for this soil, dissolution of about 36 mg g^{-1} of granite occurred according to the increase in exchangeable K which should have been accompanied by an increase of about $0.096 \text{ cmol}_{c(+)} \text{ Na kg}^{-1} \text{ soil}$. These results clearly indicate that the dissolution of granite powder which occurred in the present incubation experiment was not congruent. All these interpretations are based on the hypothesis that in this closed system the dissolved cations originating from granite would be fully recovered into the exchangeable pool of cations. This almost certainly holds true

for Ca, Mg and Na. The released cations may however be recombined as constituents of new minerals such as secondary phyllosilicates or be incorporated into pre-existing soil minerals: in particular, K may be fixed by expandable 2:1 phyllosilicates. In this case, the change of exchangeable K would underestimate the actual amount of K released by granite dissolution. However the released K that exchanged with the inter-layer cations of expanded 2:1 phyllosilicates should have yielded a corresponding increase in exchangeable Ca, Mg or Na, which did not significantly occur in most instances. The changes in exchangeable cations may however be considered as to provide an approximate but valuable estimate of the dissolution of granite.

Conclusion

The present results suggest that only minor dissolution of granite powder might be expected when applying granite to the acid soils of Western Australia. Nevertheless a significant improvement of some soil chemical properties such as soil pH and exchangeable K was obtained for about half of the soils which were investigated in an incubation experiment in laboratory conditions. Although significant the increase in soil pH due to granite application remained small suggesting that the liming effect of granite powder would be of a limited practical interest compared with what would have been obtained with much lower rates of application of conventional, liming materials such as crushed limestone. However, the substantial increase in exchangeable K which was measured for a few soils and the growth response of wheat which was obtained for rates of application equivalent to a few tons of rock per hectare in a glasshouse experiment suggest that granite powder deserves to be further assessed as a potential K fertilizer. Since these first results have been obtained in controlled conditions, they do not allow us to state if granite could be successfully used as a K fertilizer in broadacre conditions. Some further research is thus needed to assess the agronomic effectiveness of granite powder as compared to conventional, soluble K fertilizers such as KCl under field conditions. As granite is expected to dissolve slowly as confirmed by the present incubation experiment, its effect on plant growth needs to be assessed for the long term, i.e. not only in the year of application. Its residual effect for many years beyond the year of application needs to be measured as well.

Nevertheless, an estimate of the cost of granite as a K fertilizer can be derived in the light of these preliminary results. If only a few percent of granite (about 5% at most) dissolves rapidly whilst 100% KCl dissolve rapidly and considering that the K concentration of granite powder is about 0.05 that of KCl, granite powder would need to be about 400 times cheaper than KCl to be an economically viable substitute to soluble K fertilizers. As in 1994, the price of a ton of granite powder is about A\$ 13 in Western Australia whilst a ton of KCl costs about A\$ 282, it is obvious that granite would hardly compete with KCl in terms of economics. Taking into account the additional cost of transportation and application which would be much larger for granite due to its low K concentration, granite powder would need to dissolve completely to compete economically with high grade, soluble fertilizers such as KCl. This estimate of economic value of granite as a fertilizer confirms that pointed out earlier by Von Fragstein et al. (1988): silicate rock powders such as the granite employed in the present study are definitely not viable substitutes for soluble fertilizers from a purely economical point of view.

From an environmental point of view, this work however suggests that some benefit could be gained from using by-products of the quarrying industry such as granite powder for some land use situations such as agriculture and forestry rather than stock-piling them. The use of granite powder as a slow-release K fertilizer requires further attention especially for highly leaching, acid sandy soils such as on the coastal plain of south-western Australia where substantial losses of K are expected due to leaching when soluble fertilizers are applied. In addition, granite powder may be used as a source of K in some alternative farming systems which ban the use of manufactured fertilizers and recommend the use of substitutes such as silicate rocks. These first results suggest that granite powder may be used as a potential source of K albeit at considerable cost.

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