SOIL CLAY MINERALOGY AND POTASSIUM BUFFER CAPACITY AS POTENTIAL WINE QUALITY DETERMINING FACTORS IN WESTERN CAPE VINEYARDS

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Abstract

The potassium (K) supply characteristics and clay mineralogies of a population of Western Cape soils were investigated to determine their potential effects on vine K uptake and wine quality. The total K contents of granite-, shale- and sandstone-derived soils varied, averaging 33.7, 26.1 and 4.5 cmol(+)/kg, respectively. Corresponding M NH_4Cl exchangeable soil K levels were: 0.172, 0.042 and 0.035 cmol/kg. Ability to fix applied K also varied, decreasing from 0.350 in the shale-, to 0.188 in the sandstone- to -0.177 cmol/kg in the granite-derived soils. Potential buffering capacity for K was pH / liming dependent, particularly in the shale soils. Potassium uptake by Italian rye grass correlated negatively with K fixation. The K contents of Italian rye grass grown on the sandstone, shale and granite soils were, respectively, 2.32, 2.12 and 5.56 dry mass %. These results were explicable in terms of soil mineralogy. The presence of kaolinite in the clay fraction, with mica and K-rich feldspar cores in the silt fraction enabled the granite soils to release primary K, but conferred little power to fix, or to buffer K against luxury uptake or loss through leaching. In contrast, the shale soil clay fractions consistently contained vermiculite and interstratified 2:1 minerals. These conferred marked pH / liming dependent K buffer capabilities. The shale soils also contained K in micas in the non-clay fractions. The sandstone soils varied in terms of both mineralogy and clay content. Sandstone soils, in which the sand fractions were quartzitic were unable to deliver primary K. Similarly, sandstone soils having low clay contents had severely limited K buffering capabilities. The observed differences in the abilities of sandstone-, shale- and granite-derived soils to supply and buffer K may be sufficient to affect grape vine performance and wine quality in Western Cape vineyards.

INTRODUCTION

Potassium (K) is a non-structural macronutrient required for enzyme activation, cross-membrane transport, anion neutralisation and the regulation of osmotic potential (Iland, 1988). In wine grape vines, K is essential for both vine growth and yield (Mpelasoka *et al.*, 2003). However, grape berries are powerful sinks for K, notably during ripening. High grape K concentrations are linked with decreased tartaric acid levels, and with precipitation of tartaric acid as potassium bitartrate. Both processes lead to increased pH levels in the juice, must and wine. High juice pH levels are detrimental to wine quality (Iland, 1988; Mpelasoka *et al.,* 2003), and are not easily rectified during vinification. High pH wines tend to be unbalanced, to mature poorly and, in the case of red wines, to lack good colouration (Saayman, 1992).

Potassium, together with other cations, is taken up by grape vine roots from the soil. Roots have limited abilities to select between cation species during uptake. In consequence, plant tissues often contain ratios of cation species that are not physiologically ideal. Where K is readily available excessively high tissue K concentrations may accumulate (luxury consumption), potentially leading to high grape K concentrations, raised must pH levels and reduced wine quality.

In the interests of quality wine production it is desirable that those soil factors which affect the availability of K to grape vines should be well understood. This is particularly important in the Western Cape winelands where the geological structures and materials from which the soils derived are diverse, ranging from late Precambrian shales and granites in the exposed basement of the coastal lowlands and valley bottoms to the Palaeozoic sandstones and shales of the mountain belts (Theron *et al*., 1992). These materials underwent deep chemical weathering (etching) from late Cretaceous to

mid Miocene times, creating the African Surface. Most modern Western Cape landscapes, their terroirs and soils are products of the further (late Miocene to Recent) weathering and dissection of the residues of this ancient weathering cycle (Partridge & Maud, 1987). The overall effect is that, in the Western Cape, soil materials differ and landscapes differ considerably over short distances.

Little is currently known about about the effects of soils and their diverse mineralogies on K uptake by grape vines. Much can be nevertheless be inferred from a series of chemical, mineralogical and plant extraction studies which were carried out on a population of Western Cape soils in the 1980's (Wooldridge, 1988, 1990). The purpose of the present article is to review those aspects of soil K which this earlier work indicates as being potentially able to affect grape vine K uptake and wine quality.

MATERIALS AND METHODS

The materials and methods discussed in this article have already been described (Wooldridge, 1988, 1990). Only a brief outline will therefore be presented here.

Selection and preparation of soils

A typical red- (Hutton, Hu); yellow- (Clovelly, Cv); well drained, moderately structured footslope- (Oakleaf, Oa) and a bottomland, hydromorphic (hydro) soil were bulk sampled on catena (slope) sequences developed in apparently virgin soils derived from sandstone, shale and granite. After passing through a two mm sieve, each bulk sample was split. Soils from one set of sub samples were moist incubated in plastic jars with sufficient agricultural lime to neutralise all titratable acidity. Soils in the second set of subsamples were stored moist, without lime, for a similar period. After the pH had stabilised the soils in both sets of subsamples were sieved again, air-dried and stored.

Analysis

Each bulk soil sample was analysed to determine particle size range and clay fraction mineralogy (by X-ray diffraction). Non-clay fraction mineralogies were identified by microscopy (data not presented). Acid dissolution was used to determine total soil K content. Each unlimed and limed soil was analysed to determine unbuffered M NH_4Cl exchangeable K, calcium (Ca) and magnesium (Mg), and cation exchange capacity (CEC). Ability to fix applied K was determined by carrying out NH_4Cl exchange determinations on soils which had been subjected to three wet / dry cycles following the addition of K in dilute aqueous solution at a rate equivalent to one cmol(+)/kg. The Quantity / Intensity relationship (Q/I) and K buffer capacity (PBC_K) of each unlimed and limed soil was determined in accordance with the method of by Beckett (1964, 1965).

Plant K extraction

Plant extractable K was determined by the Italian Rye grass test (Quemener, 1979). This entails cropping the soil under controlled conditions until too little K remains to sustain further growth. Frequent harvesting of the grass leaf blade above the intercalary meristem prevents K recycling within the plant. Samples (250 g) of each limed and unlimed soil were placed in plastic pots distributed on benches in a temperature controlled (15°C min., 25°C max.) greenhouse in a randomised factorial block design with 10 replications per soil x lime treatment. Each pot was densely sown with Italian Rye grass seeds. Thereafter, sufficient dilute (50%), K-deficient Hoaglands nutrient solution was supplied to maintain the soils in a moist state. Leachates were collected and returned to their pots of origin. Whenever the grass blades reached a height of 12 cm they were harvested by cutting off the topgrowth about 20 mm above the intercalary meristem. The harvested grass samples were separately washed, dried, weighed, milled and analysed for K. After growth had ceased the soils were dry sieved to remove the remaining plant material for analysis. Results were subjected to an analysis of variance. Tukey's LSD values were calculated at the 5% probability level to facilitate comparison between treatment means. Regression analyses were carried out where appropriate.

RESULTS AND DISCUSSION

Catena position had no consistent effects on the soil and plant parameters listed in Tables 1, 2 and 3, or as shown in Fig. 1. This article therefore mainly concerns the effects of parent material.

/ insert table 1 /

Total and exchangeable K, and CEC

Total soil K concentrations ranged widely, from < 1 to > 50 cmol(+)/kg (Table 1). However, in no case did the NH_4Cl exchangeable K concentrations exceed 0.30 cmol(+)/kg, or 1.9% of the total K present. Exchangeable and total K were not significantly correlated. Exchangeable K is therefore not a reliable indicator of total soil K.

In South African vineyards, exchangeable soil K is normally maintained at approximately 4% of the CEC (Conradie, 1994). Relative to this norm, exchangeable K in the sandstone- and shale-derived soils were low, ranging from 0.48% 1.98% of the CEC. In contrast, in the unlimed, granite-derived Hu, Cv and Oa, and the limed Oa soil, exchangeable K percentages varied from 4.24% to 14.29% of the CEC. Exchangeable K concentrations tended to be higher in the unlimed than the limed soils, probably because liming induced increases in CEC.

Plant extractable K, dry mass yield and tissue K content

The Italian rye grass and the NH_4Cl removed similar percentages of the total soil K (Table 2). Dry mass yields were nevertheless greater from the limed than from the unlimed soils, by averages of 32%, 38% and 21% in the sandstone, shale and granite soils, respectively (Table 3). Yields from the sandstone and shale soils were similar. In contrast, the average yield from the granite soil population was almost 37% higher than from the sandstone and shale soils. The average topgrowth (tissue) K concentration in the granite treatment was 141% higher than in the sandstone-, and 185% higher than in the shale treatments. The disproportionately high (relative to yield) average tissue K concentrations in the granite treatments are indicative of luxury consumption which, in wine grapes, could lead to diminished quality (Conradie, 1994; Mpelasoka *et al.*, 2003).

/ insert table 2 /

Plant K uptake and K fixation

Ability to retain applied K against exchange by NH_4Cl (fixation) was negative in the granite soils, signifying release of K (probably from primary sources), but positive in the shale- and sandstone-derived soils. In the experimental soil population, plant K uptake diminished with increasing fixation according to the significantly (**) correlated negative curvilinear relationship:

plant K uptake = 0.123 + (-0.401 K fix.) + 0.410 K fix.^{2},

where plant K uptake and K fixation were expressed in cmol(+)/kg.

/ insert table 3 /

Quantity / Intensity relationships

The essence of the Q / I concept is that if soils which contain K are equilibrated with solutions which contain low concentrations of K, then K will be released from the soil until a balance is reached between soil and solution, and *vice versa*. Movement of K between soil and solution may be monitored by determining the level of K in the solution before and after equilibration. The steeper the slope of the curve relating adsorption or release of K (ΔK) to the activity of K in solution (AR^K) the greater the buffer capacity of the soil for K (PBC^K).

/ insert figure 1 /

The curves shown in Fig. 1 indicate that parent material and liming have varied effects on Q/I characteristics. The granite soils (Fig. 1a) release K even at high values of AR^K, although K release is moderated by liming. Curves for individual granite soils appear to be composite, probably reflecting the differing site specificities of a range of soil minerals. Only one soil (the limed Hu, designated PM1) had an appreciable ability to buffer K. In contrast, curves for the shale-derived soils (Fig. 1b) are remarkably similar in character regardless of catena position. Shale soils release native K only at very low AR^K values, and steepen considerable (increased PBC^K) following liming. Certain of the sandstone-derived soils (Fig. 1c), notably the Oa (BD1) and Cv (Fr1) also show marked PBC^K increases following liming. Other curves tended to parallel the zero ΔK axis. In the case of the hydromorphic sandstone soil LM1, for example, this indicates that very little K is available for release at low ARK values, and that too little exchanger (clay) is present to adsorb K from high AR^K equilibrating solutions. That LM1 contained only 2.4% clay and was dominated by quartz sand tends

to support this supposition, as do the facts that LM1 delivered little K to Italian Rye grass, and supported little dry mass production.

Liming increased dry mass yields in the sandstone, shale and granite derived soils, by 16%, 32% and 8%, respectively, relative to the unlimed soils (Tables 3 and 4). In comparison to these increases the lime-induced increases in CEC were of large (43.6%, 65.0% and 28.0%). The lime-induced increases in PBC^K (108%, 553% and 69%) were even larger, especially in the shale soils. The disproportionately large lime-induced increase in PBC^K shown by the shale soils meant that although PBC^K and CEC correlated (**) for the unlimed soil population, no significant correlation was found for the limed soils. Since the main difference between PBC^K and CEC lies in the specificity for K of the former, as opposed to the general non-specificity of the latter, these findings indicate that, for the limed shale soils at least, K may be better buffered than might be expected from the CEC values.

Clay mineralogy, CEC and K buffer capacity
Soil colloids, including clay minerals, differ considerably in terms of their CEC values. Approximate CEC values for humus, vermiculite, montmorillonite (not present), hydrous mica, chlorites, kaolinite and hydrous oxides are, respectively, 200, 150, 100, 30, 8 and 4 cmol(+)/kg (Brady, 1974). Thus, although the granite soils contained 28.8% clay on average, their ability to exchange of buffer K was limited because the clay mineral assemblage was dominated by the low-CED mineral kaolinite. Kaolinite is a product of severe chemical weathering, notably of the K-rich mineral orthoclase which is a major constituent of granite. Granite derived soils are nevertheless able to release primary K from weathered orthoclase cores and from mica flakes, mainly in the silt fraction. This combination of restricted K buffering and primary K release is clearly reflected by Fig. 1a.

The shale derived soils contain less clay (average 21.7%) than the granite soils. However, in addition to kaolinite, they also contain clay-fraction mica, vermiculite and other 2:1 minerals. These latter three minerals are characterized by a sandwich structure in which adjacent aluminosilicate layers, or sheets, are held together by interlayer cations, notably K. Removal of interlayer K during weathering allows the sheets to spread open at the margins, exposing interlayer exchange sites. The deepest of these sites have high specificities for K (Beckett & Nafady, 1967). This specificity explains why high PBC^K values may be exhibited by the shale soils. If K is supplied as fertiliser the wedges may close. Though protected (buffered) against rapid uptake or leaching, much of this K remains accessible to vine roots. Conversely, in acid soils, the wedge zones may become blocked by aluminium, a process called chloritisation. Chloritisation blocks access to wedge and interlayer sites by other cations, including K, which can no longer be buffered affectively. If, however, the aluminium is displaced by liming, then the high CEC of the mineral will be restored, as will its specific ability to buffer K. Potassium buffering in shale soils is therefore a function of both mineral structure, and of pH / lime status, as is implied by Fig. 1b. Shale soils also contain reserves of K, mainly in micas in the non-clay fractions.

The sandstone soils differed from the shale soils in two respects: they contained less clay, and did not consistently contain mica, vermiculite or chloritised 2:1 clay minerals. Variability between sandstone soils in terms of the Q.I characteristics was therefore expected. That this occurs in practice is shown in Fig. 1c

CONCLUSIONS
Investigation of a population of virgin Western Cape soils showed that the geological provenance of the soil parent materials (sandstone, shale, granite) affects soil clay mineral assemblage and total soil K content. Clay mineral assemblage, in turn, affects the readiness with which K is released and taken up by plants (K buffering). Depending on the clay minerals present, K buffering may increase if an acid soil is limed. Buffering affects the efficiency with which K is utilized, poorly buffered soils tending to contribute to high tissue K concentrations and low dry mass yields (luxury consumption).

In this trial, granite-derived soils contained high total K concentrations and were able to release some of this K for plant uptake and exchange by NH_4Cl. The clay fractions of granite-derived soils are dominated by kaolinite, which is unable to buffer K against rapid root uptake or loss through leaching. Grasses grown on granite soils are characterized by high tissue K concentrations. By implication, the potential for luxury K consumption by grapevines growing on granite soils is also high. Shale-derived soil clay fractions, in contrast, are characterized by the presence of 2:1 minerals

which have pronounced, but pH / liming dependent, K buffer capabilities. Thus, although shale-derived soils contain appreciable amounts of total K, mostly in mica in the silt fraction, luxury K consumption is unlikely to occur in vineyards on shale soils, particularly if aluminium has been eliminated from the exchange sites by liming. Sandstone-derived soils generally contain diverse clay mineral assemblages, but may lack 2:1 minerals. Absence of 2:1 minerals, and low soil clay contents limit K buffer capacity. Since the sandstone-derived soils of the Western Cape winelands contain a predominance of quartz grains in the non-clay fractions very little structural K is available for release. Vines grown on quartzitic sandstone soils are therefore dependent for their K requirements on the application of K as fertilizer. Poor K fertilization practices could result in deficiencies or luxury consumption of K in vineyards on these soils.

Collectively the results obtained from this work imply that geological provenance of the soil parent materials, through conferred mineralogy, affects K supplying power, which in turn appears to possess the potential to affect vine growth and wine quality. Vineyard trials must be carried out to test the validity of these observations in the contexts of demarcation and terroir.

LITERATURE CITED

Beckett, P.H.D., 1964. Studies on soil potassium II. The 'immediate' Q/I relations of labile potassium in the soil. Soil Sci. 15, 9-23.

Beckett, P.H.D., 1965. Activity coefficients for studies on soil potassium. Agrochimica 9, 150-153.

Beckett, P.H.T. & Nafady, M.H.M., 1967. Potassium-calcium exchange equilibria in soils: The location of non-specific (Gapon) and specific exchange sites. Soil Sci. 18, 263-281.

Brady, N.C., 1974. The nature and properties of soils. 8th edn. MacMillan, New York.

Conradie, W.J., 1994. Vineyard fertilisation. Proc. Work session on vineyard fertilisation, Nietvoorbij, 30 September 1994. ARC Fruit Vine and Wine Research Institute, Nietvoorbij, Stellenbosch.

Theron, J.N., Gresse, P.G., Siegfried, H.P. & Rogers, J., 1992. The geology of the Cape Town area. Explanation to Sheet 3318. Geological Survey. Government Printer, Pretoria, South Africa.

Iland., P.G., 1988. Grape berry ripening: The potassium story. Aust. Grapegrower & Winemaker 289, 22-24.

Mpelasoka, B.S., Schachtman, D.P., Treeby, M.T. & Thomas, M.R., 2003. A review of potassium nutrition in grapevines with special emphasis on berry accumulation. Aust. J. Grape Wine Res. 9, 154-168.

PartridgeT.C. & Maud, R.R., 1987. Geomorphic evolution of southern Africa since the Mesozoic. S. Afr. J. Geol. 91(2), 179-208.

Quemener, J., 1979. The measurement of soil potassium. International Potash Institute Research Topics, no. 4. International potash Institute, Berne, Switzerland.

Saayman, D., 1992. Natural influences and wine quality. Part 2: The role of soil. WineLand, August 1992, 49-51.

Wooldridge, J., 1988. The potassium supplying power of certain virgin upland soils of the Western Cape. Thesis, University of Stellenbosch, Private Bag X1, Matieland 7602, South Africa.

Wooldridge, J., 1990. Effect of liming and parent material on the potassium quantity/intensity relationships of some upland soils of the western Cape. S. Afr. J. Plant Soil 7(1), 62-67.

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TABLE 1
Effect of soil parent material, catena position and liming on soil and plant parameters.

Parameter		Sandstone				Shale				Granite			
		Hu	Cv	Oa	Hydro	Hu	Cv	Oa	Hydro	Hu	Cv	Oa	Hydro
Soil chemical characteristics													
Total soil K (cmol(+)/kg)		2.410	3.430	11.730	0.530	22.340	20.480	41.120	20.340	41.310	19.910	22.180	51.240
Exch. K (cmol(+)/kg)	Unlimed	0.030	0.020	0.060	0.010	0.030	0.010	0.050	0.020	0.120	0.160	0.270	0.100
	Limed	0.040	0.030	0.070	0.010	0.050	0.040	0.060	0.030	0.140	0.160	0.300	0.090
CEC (cmol(+)/kg)	Unlimed	1.560	0.920	3.660	1.100	2.840	1.470	3.820	2.360	2.830	1.660	1.890	2.840
	Limed	2.020	2.850	9.190	1.200	5.010	5.150	7.640	6.260	5.800	4.690	5.980	3.960
Exch K (% of CEC)	Unlimed	1.920	2.170	1.640	0.910	1.060	0.680	1.310	0.850	4.240	9.640	14.290	3.520
	Limed	1.980	1.050	0.760	0.830	1.000	0.780	0.790	0.480	2.410	3.410	5.020	2.270
Plant parameters													
Plant extr. K (cmol(+)/kg)	Unlimed	0.014	0.015	0.066	<0.001	0.027	0.007	0.045	0.013	0.108	0.133	0.225	0.107
	Limed	0.024	0.013	0.097	<0.001	0.046	0.031	0.060	0.024	0.147	0.123	0.233	0.115
Dry massYield (g/100 g soil)	Unlimed	0.180	0.158	0.318	0.145	0.207	0.154	0.228	0.199	0.248	0.264	0.395	0.248
	Limed	0.235	0.182	0.494	0.145	0.280	0.311	0.256	0.236	0.375	0.324	0.415	0.280
Particle size analysis													
Clay (%)		5.8	13.4	18.4	2.4	25.0	17.8	25.8	18.2	40.4	26.2	38.6	10.8
Silt (%)		0.6	9.2	19.0	0.8	22.2	15.6	34.4	17.2	7.0	12.8	12.8	11.0
Fine sand (%)		36.4	32.0	30..2	19.3	46.0	49.8	36.0	54.4	29.8	19.0	24.6	35.6
Med. sand (%)		46.0	34.4	25.0	46.4	4.4	10.0	2.2	4.6	7.4	24.0	9.6	21.2
Coarse sand (%)		11.2	11.0	7.4	31.1	2.4	6.8	1.6	5.6	15.4	18.0	14.4	21.4
Clay mineralogy													
Montmorillonite		-	-	-	-	-	-	-	-	-	-	-	-
Pyrophyllite [1]		W	-	-	-	-	-	-	-	-	-	-	-
Talc [2]		W	-	-	T	-	-	-	-	-	-	-	-
Mica		-	-	T	W	T	T	W	T	T	-	-	W
Vermiculite		T	-	T	-	W	T	W	W	-	-	-	-
Chlotised or interstratified 2:1		T	W	W	-	W	W	W	W	-	-	-	-
Chlorite		T	-	-	-	-	-	-	T	-	T	T	-
Kaolinite		W	M	M	M	W	W	M	M	S	S	S	D
Quartz		-	T	T	-	-	-	-	-	-	T	-	M
Gibbsite [2]		W	-	-	-	-	-	T	-	-	-	-	-

X-ray diffraction peak intensities: D = dominant; S = subdominant; M = medium; W = weak; T = trace.
[1] confirmed by infra red spectroscopy, [2] confirmed by differential thermal analysis.

TABLE 27
Effect of parent material and liming on total soil K, exchange and buffer parameters, and plant K uptake.

Parameter	Unit	Sandstone		Shale		Granite	
		Unlimed	Limed	Unlimed	Limed	Unlimed	Limed
Total soil K	cmol(+)/kg	4.52b		26.07a		33.66a	
Exchangeable K	cmol(+)/kg	0.032d	0.038c	0.037c	0.047b	0.170a	0.173a
	% of total K	0.71	0.84	0.14	0.18	0.51	0.51
Plant K uptake	cmol(+)/kg	0.032d	0.045c	0.027e	0.046c	0.155b	0.168a
	% of total K	0.71	1.00	0.10	0.18	0.46	0.50
CEC	cmol(+)/kg	2.250d	3.230c	3.340c	5.510a	3.290c	4.210b
PBC^K	cmol(+)/kg) / (mol/dm^{-3})$^{1/2}$	6.23b	12.98b	12.99b	84.83a	12.72b	21.47b
K fixation	cmol(+)/kg	0.210c	0.220c	0.280b	0.320a	-0.310e	-0.290d

Values in the same row, followed by the same letter, do not differ at $P \leq 0.05$.

TABLE 3
Effect of parent material and liming on dry mass yield by Italian Rye grass, and on topgrowth K concentration.

Parent material	Unlimed	Limed	Mean
Dry mass yield (g dry mass/250 g soil)			
Sandstone	0.200	0.264	0.232b
Shale	0.197	0.271	0.234b
Granite	0.289	0.349	0.319a
Mean	0.229b	0.294a	-
Topgrowth K concentration (% of dry mass, first harvest)			
Sandstone	2.35	2.28	2.31a
Shale	1.77	2.12	1.95a
Granite	5.47	5.65	5.56b
Mean	3.20a	3.35a	-

Means followed by the same letter do not differ at $P \leq 0.05$.
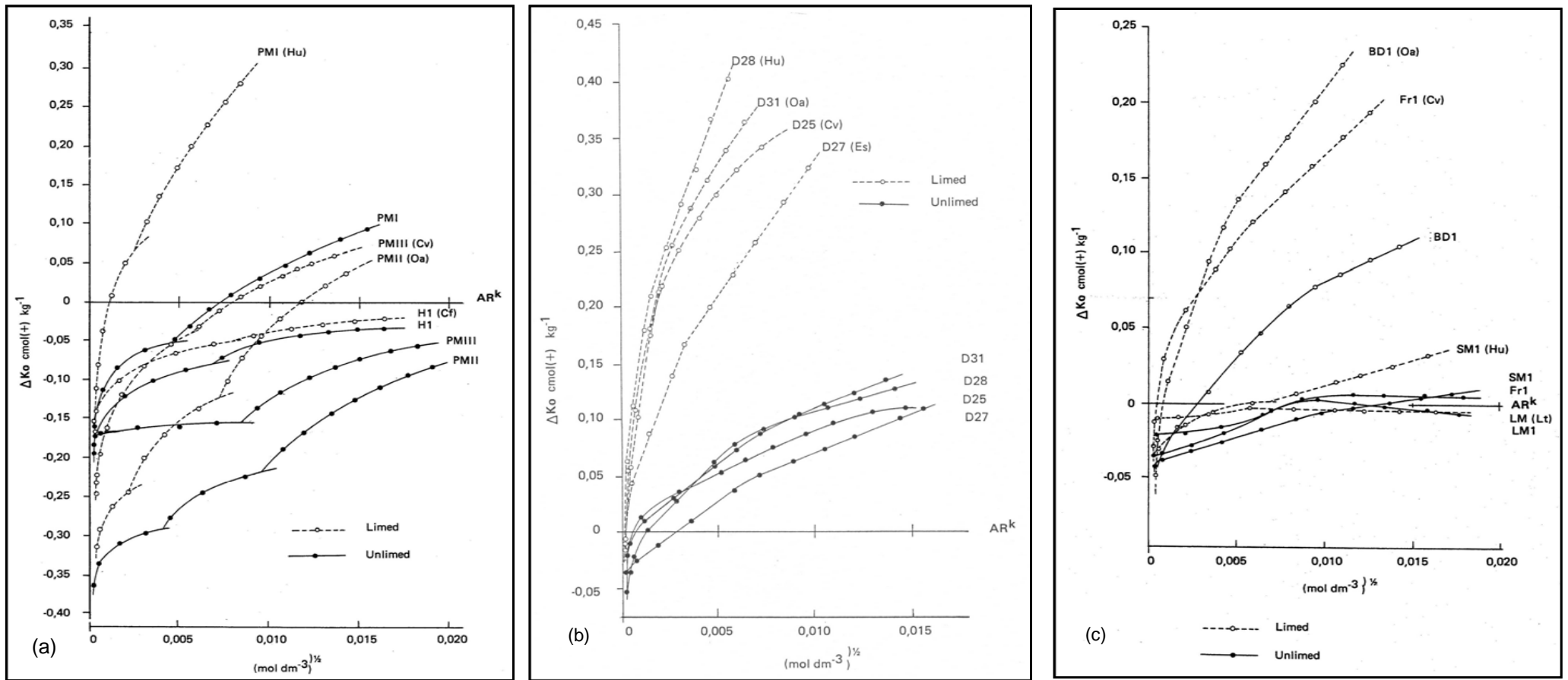
FIGURE 1
Quantity / Intensity relationships for (a) granite-, (b) shale- and (c) sandstone-derived soils representative of the Western Cape winelands.