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UNDULATORY EXTINCTION IN QUARTZ USED FOR IDENTIFYING POTENTIALLY ALKALI-REACTIVE ROCKS

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SYNOPSIS

The generally accepted method for identifying alkali-reactive quartz is by the determination of the undulatory extinction angle which is a measure of the imperfections in the crystal lattice. This is measured by rotating a quartz grain in a thin section and determining the position at which the first clear evidence of undulatory extinction appears and at which the extinction bands disappear.

The angles obtained using the observations suggested by different authors give a variation of up to 100 per cent. If the UE-angle is to be used for identifying potentially alkali-reactive quartz, it is essential to have a clear definition of both observation positions used. In addition to making recommendations, the paper contains UE-angles determined for several rock samples known to be either alkali reactive or non-reactive.

SAMEVATTING

Die algemeen aanvaarde metode om alkali-reaktiewe kwarts te identifiseer is deur die vasstelling van die golwende uitdowingshoek (GU) wat 'n maatstaf van die vervorming in die kristalrooster is. Dit word gemeet deur 'n kwartskorrel in 'n dun seksie te roteer en die posisie waarby die eerste duidelike teken van golwende uitdowing verskyn en waarby die uitdowingsbande verdwyn, te bepaal.

Die hoeke wat verkry word deur gebruik te maak van waarnemings, soos deur verskillende outeurs voorgestel, toon 'n variasie van tot 100 persent. Indien die GU-hoek gebruik gaan word om potensiële alkali-reaktiewe kwarts te identifiseer, is dit noodsaaklik om 'n duidelike definisie van altwee die waarnemingsposisies te verkry. Benewens aanbevelings bevat die referaat GU-hoeke vir verskeie rotsmonsters wat bekend staan as òf alkalireaktief òf nie-reaktief.

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1. SUMMARY

The most important task of this investigation is to determine the undulatory extinction angle by a method that can be used by other researchers.

(a) The two positions for measuring the undulatory extinction (UE) angle were defined: position 1 at the first appearance of extinction in any part of the quartz grain and position 2 at the disappearance of the extinction except for very slight traces in the area of the last extinction. Repeating the measurements in the opposite direction increases the precision of the UE angle. If necessary, the one-wavelength accessory plate or the universal stage microscope may be used to enhance the precision.

(b) Twenty two thin sections of nine rock types, predominantly arenites, were used for examining the UE angles in 344 quartz grains. The use of the extinction range angle introduced by the author in 1975 was discontinued because the more exact definition of the UE angle makes its use unnecessary. Data in two summarizing tables show a much greater variation in quartz extinction angles than has been indicated by other authors.

(c) The average value of the UE angles in at least ten quartz grains in a thin section should be used for predicting the potential alkali reactivity of rocks containing medium to coarse-grained quartz as an essential constituent. Their use for more than preliminary potential reactivity cannot be substantiated until much more data are accummulated including repeat measurements and the statistical rejection of extreme values. This applies especially to the evaluation of gravel and sand aggregates.

2. INTRODUCTION

One of the tasks of petrographers who specialize in concrete and aggregate is to identify potentially alkali-reactive aggregates in order to prevent (a) their use in concrete, (b) unnecessary testing of aggregates for reactivity, (c) delays in the acceptance or rejection of convenient aggregate sources, and (d) the need for taking more expensive precautions to ensure that harmful expansion of concrete will not occur.

Of the minerals known to react with alkalis in cement, the most difficult ones to identify are alkali-reactive medium to coarse quartz varieties occurring as the only or the essential constituent of some rocks. Vein quartz, quartzite, quartzarenites and the most widespread silicate rocks, the granites, granodiorites and gneisses contain such quartz grains. They are often used as aggregates in large concrete structures.

In 1954 and 1958 Mielenz[1, 2] and in 1955 Brown[3] stated that quartz varieties which had a defective crystal lattice were potentially alkali reactive. The most easily observed indication of crystal lattice irregularity is the UE which can be measured in thin sections between crossed nicols using a polarizing microscope.

Using the UE of quartz, DeHills and Corvalan[4] examined the age of Chilean granitic rocks. They found a direct relationship between the magnitude of the UE angle, the degree of deformation in the quartz crystal lattice, and the intensity of the geological stress to which the granites had been subjected (1964). They reported the maximum UE angle being 35° (p 365). Following DeHills and Corvalan, Gogte[5] found a correlation between the UE angle and other signs of quartz lattice imperfection in a series of rocks, and the expansion of mortar bars (ASTM C 227[6]) containing the same rocks as aggregates. The range of quantitative estimation of the UE angles for five granitic samples was between 10° and 28°, and for one cherty quartzite between 18° and 28° (1973, Table 1). K Mather[7] reported the angular range from 36° to 64° in vein quartz and quartzite gravel (1976, p 6), and the author found a maximum UE angle of 45,5° in an orthoquartzite (1975, p 96).

This paper presents information and data on my continuing examination of alkali-reactive silicate rocks using the UE angle and the extinction range (ER) angle of quartz (introduced in my 1975 paper[8]). About 350 quartz grains from a variety of rocks, mostly from Ontario, were examined (see Table 3, page 4). The objectives of this paper are:

(i) To define the UE angle and the ER angle, and the relationship between these two angles.
(ii) To determine how to obtain, as precisely as possible, the UE angle and to evaluate the results statistically.
(iii) To evaluate the difficulties of using the UE angle for identifying slowly expanding alkali-reactive silica rocks.

TABLE 1: Stage positions related to undulatory extinction in a quartz grain from a mica quartzite

Stage Degree	Birefringence parameters	
356	Orange hue in the entire grain	
316	First greyish shadows observed in a portion of the grain	
313	Clear evidence of extinction	
309	First extinction visible	a
303	Extended areas of extinction	a
301	Last extinction visible	a
299	Distinct dark shadows visible in area of last extinction	
292	Traces of extinction still visible	b
286	Shadows almost disappeared	b
275	All shadows disappeared	b
268	Orange hue in the entire grain	

a - extinction range angle is 8° (309° - 301°).
b - possible second positions for measuring the UE angle.

TABLE 2 : Undulatory extinction angle taken from two sets of different positions

Position A		Position B	
313°	Clear evidence of extinction	309°	First extinction in grain
275°	All shadows disappear	286°	Shadows almost invisible
38°	Undulatory extinction angle	23°	Undulatory extinction angle

3. METHOD OF DETERMINATION OF THE UNDULATORY EXTINCTION ANGLE

Definitions. According to the Glossary of Geology[9] (AGI, 1980) the extinction angle is 'the angle through which a section of a birefringent mineral must be rotated from a known crystallographic plane or direction to the position at which it gives maximum extinction or darkness under a polarizing microscope.' The UE angle is a measure of the amount of dislocation of optical arrangements in the crystal lattice in various portions of a grain.

The UE angle as used by DeHills and Corvalan is not defined but the method of obtaining it is described as follows (italics by the author):

(a) The crystal (of quartz) is set in the position of highest birefringence.

(b) The microscope stage is rotated until the first *clear evidence* of undulatory extinction appears; the reading on the stage is recorded.

(c) The stage is rotated until it passes through the *complete extinction* and further, until the UE *bands disappear* (the extinction *bands should be barely visible);* the reading on the stage is recorded.

(d) The angle measured is recorded.

This description of the method for measuring UE angles leaves some uncertainty about the exact position used for the determination of the angle. The 'first clear evidence' of UE is open to interpretation and may not be the exact position of extinction, and the position at which 'the bands disappear' and that at which the 'bands should be barely visible' are not the same. These instructions leave some uncertainty about exactly how to make the measurements. The following tabulation of the different positions of the microscope stage during the measurement of a UE angle illustrates the difficulties in its determination.

Table 2 shows the UE angle values measured using the different positions on the microscope used by two authors.

The difference in the UE angles in the example taken from positions A and B is 60 per cent. According to Figures 1 to 3 in their paper[4] (1964), DeHills and Corvalan used the positions corresponding to stage numbers 313° and 286° for the UE angles (= 27° in the example).

The UE angle may be defined

A as the angle between the position of clear evidence of extinction and the position of disappearance of all shadows read on the graduated microscope stage when rotating it from the first position to the second position (used by some authors) or

B as the angle between the position of first extinction and the position of almost invisible shadows in quartz read on the graduated microscope stage when rotating it from the first position to the second position (used by author).

Determination of the undulatory extinction angle. Grains cut parallel to the required plane should be selected. Quartz grains with the highest birefringence (whitish, yellowish or orange colour) in a thin section are selected for examination. If a thin section is ground into a wedge shape, the cut plane in quartz may be parallel or nearly parallel to the optical c-axis even when the birefringence colour is greyish. A conoscopic flash figure ensures that the plane is correct.

To obtain values of UE angles that may be compared to the results obtained by different researchers, the following positions for the calculation of the angle are suggested:

Determination of the first position. The first position should be measured when any area in a quartz grain is dark. To identify the position the stage may be rocked between two appearances of slight lightening of the total extinction. The extinction may be gradual or segmented in sheets, bands or irregular stripes. The area of the first extinction may be small, located at the border of a grain, in the centre of an extinction band or stripe or in a portion of quartz overgrowth in a quartzite. The extinction may be easily determined, if the area is small, but is more difficult to determine if the area is large or if the extinction is patchy. To ignore such small areas may significantly diminish the size of the UE angle in the grain.

Determination of the second position. To choose between the positions described by the 'disappearance of extinction' and where the 'extinction bands should be barely visible' is more difficult. The following determination of the second position is suggested: The disappearance of the extinction in a grain is usually determined with sufficient accuracy if attention is paid to the last extinction. The stage is rotated until the main portion of the grain is bright and only a shadow of the extinction is left in the area of the last extinction. In my experience the shadow of the last extinction is more easily determined than the complete disappearance of the shadow because it is a more reproducible position than the brightness of the complete grain which can easily be overshot, especially if the area of the last extinction has not been noted. Magnifications of 25 to 100 times are used depending on the size of grain or extinction patch.

Repeatability of measurements. Experience has shown that the precision of the measurements is improved if they are repeated in the reverse direction. The last extinction becomes the first and the first becomes the last; if the stage is turned further to the position where the shadows almost disappear a second UE angle is determined. The two UE angle values are averaged and the value obtained is taken as the characteristic UE angle for that quartz grain.

Refinement of the method. Because it is intended to use the UE angle for indicating potentially alkali-reactive rocks containing medium to coarse quartz and because the two positions of the UE angle are sometimes difficult to establish, an attempt was made to increase the precision of the method. Although the precision needed in the measurements is not known, the gypsum or quartz one-wave-length accessory plate and the universal stage microscope were used.

The accessory plate may be used to determine the exact positions of the extinctions and the extinction shadows. The plate is most useful when the quartz grain is located close to a crack or to the border of the rock in the thin section. The birefringence colours can then be compared with those of the plate itself.

Universal stage method. Various authors have suggested that the precision of the UE angle determination may be improved by using the universal stage method. However, examination with the universal stage causes some difficulties:

(i) Moving a thin section when selecting at least five quartz grains for examination is very inconvenient because the thin section is attached with glycerin to the segments of the stage.

(ii) High magnifications have a small field of vision and thus the thin section must be moved to inspect the entire grain.

(iii) Changing objectives to adapt the field of vision to the grain size requires recentering the microscope.

(iv) Tilting the stage to angles greater than 20°, when trying to make measurements in the c-axis plane, makes it impossible to bring a large grain, eg 1 mm in size, completely into focus without changing its position. The extinction can only be detected if the dark area is in focus. If the quartz grain is very small, surrounding grains may overlap portions of it.

The universal stage microscope is useful if the thin section is cut in such a way that it does not contain at least ten quartz grains cut in the required crystallographic direction or close to it.

Quantitative numerical considerations involve the grain size, the number of grains examined per thin section and the number of thin sections per aggregate sample.

The grain size of quartz is important when dealing with secondary growth in clastic sediments which may be the centre of irregularities, impurities or both, or when dealing with large quartz grains meandering among constituents of granites. The smallest quartz grain examined was 0,15 mm.

The number of grains examined in a thin section varies in papers by different authors: K Mather[10] - from 5 to 7, and 14 thin sections per sample (1980), DeHills and Corvalan[4] - 10 grains and the author[8] 25 grains (1975).

4. SAMPLES

Nine rock types including several varieties were used to prepare 22 thin sections, 13 of which were arenites (sandstones). In Table 3, page 4 the results on 344 quartz grains showing undulatory extinction are grouped according to rock types. The table contains the number of quartz grains examined in each thin section and the averages and ranges of the ER and UE angles. Each line gives the results from one thin section. If the same rock is represented by two or more thin sections, the rock is numbered. Exceptions are the results obtained on a thin section of a quartz arenite (grading to a quartzose feldspatic greywacke) which are given in three lines (a, b, c). The method of selecting or examining the grains was varied. The results on the ER angles (averages and ranges in the thin section) and both averages of UE angles in the (a) and (b) sets showed a good repeatability. The high average obtained for the UE angle in the quartz arenite (c) shows that the second position of this angle was taken at the disappearance of all shadows. This applies also to the 25 grains in the quartz arenite No 3 examined at the same time. The UE angles of both thin sections should be somewhat lower than shown.

Results and discussion. Table 3 confirms that the average ER angle (varying from 5° to 16°) is much lower than the average UE angle (varying from 15° to 34°) because the ER angle is only part of the UE angle. This is also valid for the ranges of both angles in each thin section.

The correlation coefficient of the UE angle and the ER angle was calculated by A vander Voet using 40 results on the (a) and (b) quartz arenite. His findings are: 'Attempting various functions, the correlation coefficients indicated that there was a correlation (between both angles) but the scatter of points was too great to indicate the most favoured relationship. More numerous data points, repeat measurements and the statistical rejection of extreme values were needed to identify the relationship more clearly.' Thus there was no advantage to retaining the ER angle and further discussion of the results is made for the UE angle only, which is in accordance with other published research.

The most striking results of the present investigation of the undulatory quartz grains is the wide range of the UE angle in almost all thin sections. The number of grains examined varied but in all except 3 thin sections 10 or more grains were examined.

Statistical evaluation of results. Table 4 contains the standard deviations of the averages and the percent relative

TABLE 3 : Extinction range angles and undulatory extinction angles in quartz from various rocks

Rock	No. of grains	Extinction range angle Avg.	Extinction range angle Th.Sec.Range	Undulatory extinction angle Avg.	Undulatory extinction angle Th.Sec.Range
Arkose (1)	6	6	2 - 12	20	10 - 37
Arkose (2)	7	7	4 - 11	25	19 - 32
Arkose+quartzite clusters	10	8	4 - 12	25	20 - 29
Arkosic subarenite	12	9	5 - 16	26	20 - 39
Quartz arenite (1)	17	5	2 - 28	15	3 - 46
Quartz arenite (2)	17	5	3 - 9	15	10 - 25
Quartz arenite (3)	25	6	2 - 14	21	12 - 30
Q. arenite greywacke	10	9	6 - 13	24	15 - 32
Q. arenite (a) quartzose feldspat. greywacke	21	6	2 - 16	20	8 - 38
Q. arenite (b) quartzose feldspat. greywacke	19	7	2 - 13	21	14 - 34
Q. arenite (c) quartzose feldspat. greywacke	25	8	2 - 18	28	14 - 42
Greywacke	10	11	7 - 16	28	20 - 35
Q. arenite quartzite (1)	21	8	4 - 13	25	14 - 37
Q. arenite quartzite (2)	24	7	4 - 31	28	12 - 50
Q. arenite, granulated	12	13	7 - 20	31	20 - 40
Mica quartzite	12	8	4 - 13	26	14 - 35
Garnet biotite gneiss	20	11	3 - 23	27	13 - 43
Schist, biotite	8	7	4 - 10	22	14 - 29
Schist, biotite, cordierite	3	7	6 - 8	22	18 - 24
Vein quartz in cord. schist	8	7	3 - 16	21	12 - 42
Granite, biotite, hornblende	10	10	4 - 21	26	13 - 37
Granite, biotite	10	8	4 - 12	26	20 - 31
Granite, biotite, hornblende	11	14	8 - 25	29	21 - 47
Granite, hornblende, biotite	11	16	9 - 28	34	22 - 47
Dacite, silicified	15	7	2 - 16	22	7 - 32

(a) The 21 grains were selected by the point count method. If the grain co-inciding with the point count was not cut parallel to the c-axis of quartz, the grain with a high interference colour close to the point was examined.
(b) The 19 grains having a high interference colour were selected at random.
(c) The 25 grains were examined in 1975.

standard deviations for the results of the UE angles. The data are shown in order of increasing UE angle averages. This order was selected to show the relationship between the averages of the UE angles of quartz and the alkali reactivity of the rocks containing quartz as the main or essential constituent.

Only two features may be pointed out. The range of the standard deviation of the averages varied from 2,7 to 9,1. The relative standard deviation percentages varied from 11,5 to 58,9. The ranges based on the averages and the deviations show that the observed ranges of the UE angles contain statistically rejected values. The very small values indicate that some grains show almost no undulatory extinction and the very high values indicate the presence of errant grains which are more frequent in clastic sediments than in the igneous and metamorphic rocks.

5. EVALUATION OF THE UNDULATORY EXTINCTION ANGLE FOR IDENTIFYING SLOWLY EXPANSIVE ALKALI-REACTIVE ROCKS

Nine thin sections of the 22 examined were made of rocks which were known to be alkali reactive since they were mostly taken from aggregates in expanding concrete, or parallel samples were examined by tests for identifying alkali-reactive aggregates. Except for the silicified dacite (Dolar-Mantuani, 1976) thin sections of reactive arenites were examined only. The lowest UE angle average is 20,5^{o} and the highest is 31,4^{o}. The latter value was obtained in a quartz arenite with highly granulated grains that show strong undulatory extinction. No data on the behaviour of the rocks in concrete exist for the remaining 13 thin sections.

TABLE 4 : Statistical data on undulatory extinction angles (and reactivity)

Rock	No. of grains	Avg.	Observed range	Std. dev.	Range avg. ± Std.dev.	%Relat. Std.dev.	R*
Quartz arenite (2)	17	15,0	10,5 - 25,0	4,3	10,7 - 19,3	28,8	
Quartz arenite (1)	17	15,2	2,5 - 45,5	8,9	6,3 - 24,1	58,9	
Arkose (1)	6	19,8	10,5 - 37,0	9,1	10,7 - 28,9	46,2	
Q. arenite-greywacke (a)	21	20,5	8,5 - 37,5	6,1	14,4 - 26,6	30,0	R
Q. arenite-greywacke (b)	19	20,8	13,5 - 33,5	5,5	15,3 - 26,3	26,3	R
Q. arenite (3)	25	21,4	11,5 - 30,0	5,3	16,1 - 26,7	24,9	R±
Vein quartz	8	21,4	12,0 - 42,0	8,9	12,5 - 30,3	41,6	
Dacite, silicified	15	21,5	7,0 - 32,0	7,5	14,0 - 29,0	35,0	R
Schist, biotite	8	21,6	14,0 - 29,0	4,1	17,5 - 25,7	18,8	
Schist, cordierite	3	21,7	18,0 - 24,5	2,7	19,1 - 24,5	12,5	
Q. arenite-greywacke	10	23,7	15,0 - 32,5	5,2	18,5 - 28,9	21,8	R
Arkose	7	24,6	19,0 - 32,0	4,8	19,8 - 29,4	19,7	
Q. arenite-quartzite	21	24,8	13,5 - 36,5	6,7	18,1 - 31,5	26,8	
Arkose-quartzite	10	24,9	20,5 - 29,0	2,9	22,0 - 27,8	11,5	R
Granite, biot. hornblende	10	25,7	13,0 - 37,0	7,5	18,2 - 33,2	29,2	
Mica quartzite	12	25,7	14,0 - 35,0	5,8	19,9 - 31,8	22,7	
Arkosic subarenite	12	26,1	20,0 - 39,0	5,7	20,4 - 31,8	21,9	R
Granite, biotite	10	26,2	20,0 - 31,0	3,4	22,8 - 29,6	13,1	
Garnet gneiss	20	27,1	13,0 - 43,0	7,4	19,7 - 34,5	27,3	
Q. arenite-greywacke (c)	25	28,0	13,5 - 42,5	8,2	19,8 - 36,2	29,3	R
Greywacke	10	28,1	20,0 - 35,0	5,1	23,0 - 33,2	18,0	R
Q. Aren.-quartzite (2)	24	28,2	12,5 - 50,0	8,3	19,9 - 36,5	29,6	R
Granite, biot. hornbl.	11	29,3	21,0 - 47,0	6,7	22,6 - 36,0	22,9	
Q. arenite granulated	12	31,4	20,0 - 40,0	6,1	25,3 - 37,5	19,4	R
Granite, hornbl. biot.	11	33,5	21,5 - 47,0	6,8	26,7 - 40,6	20,2	

R* - Thin sections made from alkali-reactive aggregate particles.

S252/36

FURTHER STUDIES ON THE MEASUREMENT OF UNDULATORY EXTINCTION ANGLES IN QUARTZ

The following contribution was received from the author in response to questions put by Prof J McIver of the University of Witwatersrand, South Africa and Dr I Sims, Messrs Sandberg, London to which the author could not reply in the limited time available for discussion.

INTRODUCTION

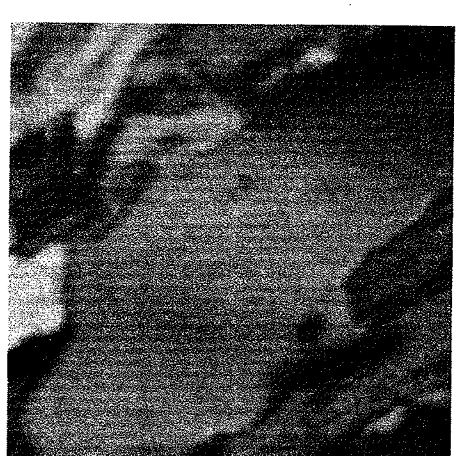
The potential alkali reactivity of medium-to-coarse grained quartz-bearing aggregates can be determined by measuring the undulatory extinction (UE) angles. The magnitude of this angle reflects the degree of strain in the crystal lattice. The angle is measured in thin sections under a polarising microscope with crossed nicols. Although this technique does not measure the angle between the first and the last visible extinction positions, which are fixed for each quartz grain, the angle it does measure is sufficiently reproducible that the results obtained by different petrographers are comparable.

The suggested procedure for measuring the UE angle is:

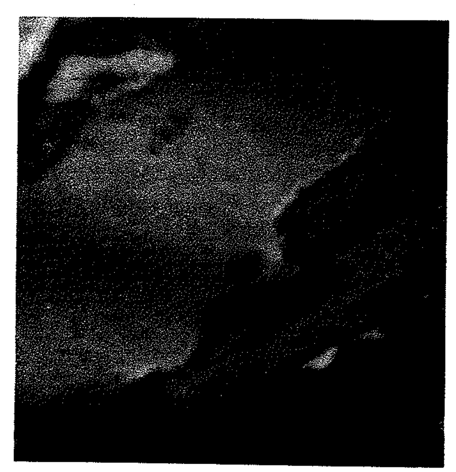
1. Record the position of the graduated microscope stage at which the first extinction of a quartz grain, showing the highest interference colour, is visible.
2. Determine the second position by rotating the grain with the microscope stage through other extinction areas to the last extinction observed in the grain and further until the entire grain is bright coloured again except for some slight grey shadows in the area of the last extinction (Figures 1(a) to 1(d).

(a) First extinction position

(b) Second extinction position



(c) Shadows of last extinction visible



(d) Too-dark shadows of last extinction

Figure 1 : Photomicrographs of extinction positions for determination of undulatory extinction angles
Crossed nicols. Magnification x 120

Considering Gogte's data on reactive granitic rocks using the UE angle criteria, all four granites discussed in this paper are potentially alkali reactive. However, Gogte's conclusions are based also on other signs of lattice defects and stress in quartz and other rock constituents. Using K Mather's range of 36^o to 64^o for the UE angles of definitely alkali-reactive vein quartz and quartzites, even the maximum UE angles measured presently in thin sections of four reactive arenites do not reach these values. Her description of measuring the UE angles (1976) indicates that she used the positions A as shown in Table 2.

The great variation of the UE angle in single thin sections makes the use of the angles as sole definite criterion for identification of reactive rocks elusive although a distinct increase in the average values shown in Table 4 suggests that more strongly reactive rocks have larger UE angles.

There is an indication that UE angles smaller than 15^o characterize non-reactive rocks. But far more data are needed to determine the cutoff UE angle value or at least a small band of angle values characterizing potentially alkali-reactive rocks.

6. RECOMMENDATIONS FOR THE USE OF THE UNDULATORY EXTINCTION ANGLE AS A REACTIVITY INDICATOR FOR AGGREGATES

When using the UE angle method for identifying potentially alkali-reactive rocks, the following parameters should be determined:

(a) The amount of quartz in the rock.
(b) The number of quartz grains with undulatory extinction by estimation or point count.
(c) The intensity of undulatory extinction demonstrated by the size of the undulatory extinction angle.

If more data on these three points for each rock are made available in one or more thin sections, the accuracy of the alkali reactivity indication will improve. Because of the wide range of UE angles in each thin section all three parameters must be considered and the average value of the UE angle should be used. Other signs of lattice disturbance in the quartz should also be recorded, and taken into account in the final assessment.

How many thin sections are needed for any evaluation of alkali reactivity will probably vary depending on the homogeneity of the aggregate. Some information was given at the recent ASTM (Subcommittee C09.02.06) meeting in Chicago at which K Mather's research on alkali reactivity of vein quartz and quartzite was discussed. She used 14 thin sections and examined 5 to 7 grains in each before selecting the gravel samples that were subsequently tested in mortars (1980).

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It helps to avoid errors if a sketch is made of the grain, and the first and the last extinction areas are numbered 1 and 2, and all stage angles are recorded (Figure 2).

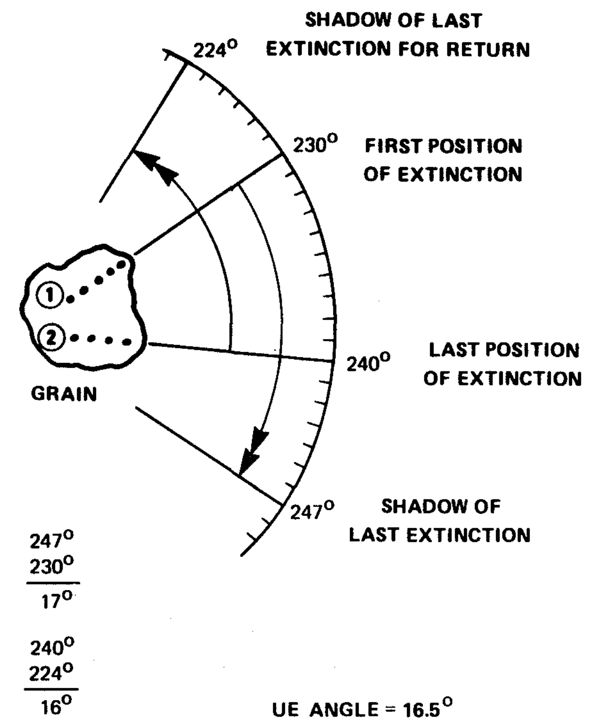

Figure 2: Illustration of the procedure for determining the undulatory extinction (UE) angle

Repeating the measurements in the reverse direction improves the accuracy. The difference between the two values is usually very small. The two values are averaged and the average is taken as the characteristic UE angle for the given grain. The angle for the thin section is obtained by averaging the values of all the quartz grains examined and is usually reported to an accuracy of one decimal place. It takes from 15 to 25 minutes to make the two measurements depending on the grain type and the experience of the petrographer.

The determination of the UE angle is usually simple except in heterogeneous, intensely strained, cracked or granulated grains in which it is very difficult to distinguish the grain outline in the extinction position. This applies, for instance, to the gneissic granite from South Africa shown in Figure 5 in Oberholster's paper[1]. However, the granulation and the intense sutured outline of the quartz grains are sufficient indication of a defective crystal lattice to generate suspicion that the rock is alkali reactive.

SAMPLES

In addition to the UE angle measurements in 22 thin sections of nine rock types which are reported in the main paper, the UE angles of five thin sections of Ontario rocks have been measured. Three are sandstone arenites and two are granite gneiss. This brings the number of quartz grains examined to 410. The average UE angles for quartz in the five thin sections are shown in Table 3a (the numbers after the rock names indicate that more than one thin section was made from the same type of rock, e.g. quartz arenite (4) means that three thin sections of quartz arenites have already been described in Table 3 of the main paper). The arenites are from three sandstone formations.

TABLE 3(a) : Undulatory extinction angles in quartz from five additional thin sections

Rock	No. of grains	Undulatory extinction angle: Average	Thin section range
Calcite arenite (1)	11	24,1	13 - 31
Calcite arenite (2)	15	28,6	18 - 43
Quartz arenite (4)	10	18,9	13 - 27
Granite gneiss (1)	20	22,9	10 - 35
Granite gneiss (2)	20	29,6	17 - 40

If the UE angle values are compared with those in Table 4 in which all data are listed in order of increasing average UE angle (considering also the known reactivity of some rocks) we can assume the quartz arenite (4) is not alkali reactive, the calcite arenite (1) may be moderately reactive and the calcite arenite (2) is probably reactive. Some aggregates prepared from rocks belonging to the same geological formation are known to be reactive.

In Table 3(a) the two thin sections of granite gneiss were prepared from side by side locations in the same coarse aggregate particle occurring in a deteriorated concrete. They are interesting because the average UE angle in thin section 1 is 22,9° indicating that the portion of the particle covered by this thin section is slightly alkali reactive, whereas that of granite gneiss (2) is 29,6° indicating a distinctly reactive rock. The reactivity was confirmed by the presence of a narrow system of gel-filled cracks in the thin section, whereas the thin section of granite gneiss (1) contained narrow apparently empty cracks cutting through quartz and feldspar grains. These results combined with the difference in the UE angles show that the adjacent areas of the same coarse aggregate particle may differ significantly in the degree of alkali reactivity although no difference in texture is recognizable in thin sections.

The difference in composition shown in Table 3(b) page 3 obtained by the point count method in both thin sections of the granite gneiss particle is not significant but is frequently found in multimineral rocks.

Minimum number of quartz grains to be examined in each thin section. The granite gneiss (2) was examined in two sets of ten grains, the difference in the average UE angles between these two sets was 1,1°. In the granite gneiss (1) an additional 10 quartz grains were examined one month after the first set of 10 grains had been measured. The average UE angle was 22,9° which is only 0,1° different from the average of the first ten grains. A third example of

TABLE 3(b) : Modal composition of biotite granite gneiss in two thin sections

Rock constituent	Per cent of constituents in T.S. 1	T.S. 2
Quartz showing undulatory extinction	25,3	26,5
Quartz without undulatory extinction	3,4	6,4
Feldspars (plagioclase, microcline)	65,0	58,1
Micas (biotite, some muscovite)	6,3	9,0

two sets of quartz grains examined in the same thin section is listed in Table 4. Quartz arenite-greywacke (a) and (b) have UE angle averages 20,5° and 20,8° respectively. Such small differences cannot be considered, for the time being, to be the rule; the results from both thin sections of the granite gneiss indicate that it is probably sufficient to examine 10 quartz grains in a thin section.

Statistical evaluation of results. Table 4(a) gives the standard deviation of the averages and the per cent relative standard deviation for the five new results (designated with an asterix). Four examples with the highest UE values taken from Table 4 in the main paper are included for comparison.

In Tables 4 and 4(a) all rocks containing quartz grains with an average UE angle of more than 25° in thin section, and which have been used as aggregates, have an alkali reactivity record.

Information required for a satisfactory UE angle method. To obtain useful results regarding the potential alkali reactivity of an aggregate source based on the UE angles in quartz, the following information is needed:

1. The present examination indicates that the measurement of 10 grains in each thin section is adequate.

2. The number of quartz grains in a thin section and the number showing undulatory extinction should be determined using estimate values or the point count method. The latter method was used for the two thin sections of the granite gneiss discussed above.

TABLE 4(a) : Statistical data on several undulatory extinction angles

Rock	No. of grains	Avg.	Undulatory extinction angle: Observed range	Std. dev.	Range avg. ± Std dev.	% Relat. Std. dev.	R**
Quartz arenite (4)*	10	18,9	13,5 - 27,0	3,8	15,1 - 22,7	20,2	
Granite gneiss (1)*	10	23,0	13,0 - 15,0	7,0	16,0 - 30,0	30,3	R
	10	22,9	10,0 - 34,0	8,5	14,4 - 31,4	37,1	R
Calcite arenite (1)*	11	24,1	18,0 - 31,0	3,9	20,2 - 28,0	16,3	
Q. arenite-quartzite (2)	24	28,2	12,5 - 50,5	8,3	19,9 - 36,5	29,6	R
Calcite arenite (2)*	15	28,6	18,0 - 43,0	6,3	22,3 - 34,9	21,9	R
Granite gneiss (2)*	10	29,4	17,0 - 40,0	6,4	23,0 - 35,8	21,8	R
	10	30,5	17,0 - 38,5	5,7	24,8 - 36,2	18,6	R
Granite, biot. hornbl.	11	29,3	21,0 - 47,0	6,7	22,6 -36,0	22,9	R
Q. arenite granulated	12	31,4	20,0 - 40,0	6,1	25,3 - 37,5	19,4	R
Granite, hornbl. biot.	11	33,5	21,5 - 47,0	6,8	26,7 - 40,3	20,2	

R** Thin section made from alkali-reactive aggregate particles.

3. The minimum number of thin sections needed to give reliable results for an aggregate source should be determined statistically*; it depends on the size and uniformity of the quarry.

4. At this time it appears that average UE angles greater than 25° indicate potential alkali-aggregate reactivity.

However, much more work is needed to confirm this and to be able to assess the degree of reactivity. Other signs of lattice disturbance in the quartz and stress signs in other rock constituents should also be recorded, and taken into account in the final assessment.

* An example of the statistical calculations developed by Dr A Vander Voet is appended to this contribution.

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STATISTICAL EVALUATION OF MINIMUM SAMPLE NUMBER FOR THIN SECTION ANALYSIS

by Dr A Vander Voet

Introduction

The prediction of the potential alkali reactivity of aggregates poses special problems. First of all, this prediction must be based on the microscopic examination of thin sections and the detailed inspection of quartz grains suitably aligned within those thin sections. Secondly, there is no manner, petrographically, in which the degree of reactivity can be quantified; in fact, there is no way in which one can be sure that this potential reactivity will even result in defects in the finished product. The identification of potentially alkali-reactive particles depends entirely on the petrographer's judgement. It is therefore important that this judgement be based on a statistically sound evaluation of potential reactivity. Furthermore, since the preparation and examination of thin sections are costly, it is desirable to obtain the best results (in terms of statistical significance) with the minimum number of thin sections.

Method and discussion

For the choice of an appropriate number of samples for thin section analysis, the following method is proposed:

(1) The sample particles are divided by preliminary microscopic examination into classes and sub-classes based on rock/mineral composition and importance in terms of potential reactivity. It is from each of these sub-classes that samples will be chosen for thin section analysis.

(2) Depending on the number of sub-classes chosen, a minimum number (3 - 5) of particles is chosen from each sub-class for thin sections.

(3) After mounting, each thin section is examined and a number of grains (∿ 10) viewed for potential reactivity. A reactivity factor R, is defined as the percentage of grains viewed which are potentially reactive.

(4) An acceptable error level for the reactivity factor is chosen which adequately expresses the statistical confidence limit with which the judgement is to be made. This in turn defines the standard deviation allowed for the average reactivity factor for the sub-group. One can use the Student-t test for the evaluation of these statistical parameters, where the confidence limits for any particular reading can be expressed as:

$$R \pm ts$$

and the confidence limits of the mean reactivity within a sub-class can be expressed as

$$\bar{R} \pm \frac{ts}{\sqrt{n}}$$

Where S = standard deviation, n = number of determinations and t = student 't' value for the confidence level required.

For example, for a confidence level (risk and probability level) of 90 per cent for n = 3 (the minimum number of thin sections to be examined), t = 2,92.

Thus if one wishes to express the mean potential reactivity within limits of ± Δ R

$$\frac{ts}{\sqrt{n}} = \Delta R \text{ and}$$

$$S = \frac{\Delta R \sqrt{n}}{t}$$

it is possible to estimate standard deviation from the range of observed values, i.e.

$S = k_n$ (range), where k is a function of n as shown in Table 1.

TABLE 1 : Factors for standard deviation approximation

n	k_n
2	0,89
3	0,59
4	0,49
5	0,43
6	0,40
7	0,37
8	0,35
9	0,34
10	0,33

Therefore one can predict the acceptable range of reactivity values over the thin sections examined within a sub-class in order for the predicted reactivity level to have the confidence limits derived.

$$\text{Range} = \frac{S}{k_n}$$

and

$$\text{Range} = R\text{ max.} - R\text{ min.} = \frac{\sqrt{n}\,\Delta R}{tk_n}$$