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Geochemical constraints on the composition of sandstone matrix and the interpretation of Detrital modes

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Abstract

Using petrographic detrital modes and major-element concentrations in matrix-rich sandstones, it is possible to calculate upper limits of the amounts of various detrital components that may have recrystallized in sandstone matrices. With exception of samples in which the matrix includes large contributions of recrystallized detrital feldspar, detrital modes of graywackes can provide accurate provenance and tectonic setting information.

Introduction

Detrital modes of sandstones are useful in interpreting provenance and tectonic setting (Dickinson, 1970; Dickinson & Suczek, 1979; Maynard et al. 1982). One of the limitations of the method, however, is that original detrital components may have recrystallized and become part of the sandstone matrix. To avoid this problem, most investigators eliminate from consideration sandstones with more than 20–25% matrix (Dickinson, 1970; Dickinson & Suczek, 1979). This is a serious limitation in that some of the most difficult sandstones to reconstruct provenance and tectonic setting are those with more than 25% matrix, such as most graywackes and subgraywackes (and their metamorphic equivalents).

We herein propose a geochemical approach to constrain sandstone matrix composition in terms of specific compositions of detrital rock and mineral fragments. The method involves recalculation of the proportions of detrital components as constrained by major-element contents of sandstones. To employ the method, it is necessary to have major-element analyses of sandstones, and of rock and mineral fragments in the sandstones. Rock- and mineral-fragment compositions can be determined directly with an electron probe or estimated from published analyses of appropriate rocks and minerals. The most common detrital components that may recrystallize to become part of a sandstone matrix are feldspars and lithic fragments. Average major-element compositions of six possible detrital components are given in Table 1. If the major-element composition of a sandstone so dictates, other detrital components (such as carbonates) may be added to this group.

The geochemical calculation

Major-element concentrations in sandstones constrain the amount of specific detrital fragments that may have recrystallized in sandstone matrices. It is possible from major-element contents to calculate an upper limit of the amount of a specific detrital component present in an original sediment before recrystallization assuming *all* of a given major ele-

Table 1. Chemical composition of rock and mineral fragments used in geochemical matrix calculations.

	K	P (An2O)	AND	CAB	RH	SH
SiO_2	64.5	62.5	57.9	51.6	74.7	61.5
TiO_2	0	0	0.9	1.0	0.2	0.8
Al_2O_3	20.0	23.5	17.0	17.4	13.7	17.0
Fe_2O_3T	0	0	7.8	10.1	1.6	6.7
MgO	0	0	3.4	6.8	0.3	2.5
CaO	0.3	4.5	6.8	9.7	1.1	1.8
Na_2O	3.0	8.8	3.5	2.7	3.6	1.8
K_2O	12.0	0.6	1.6	1.2	4.7	3.5

Fe_2O_3T, total Fe as Fe_2O_3; K, K-feldspar; P, plagioclase; AND, andesite; CAB, calc-alkaline basalt; RH, rhyolite; SH, shale. Refs: Deer et al. (1963), LeMaitre (1976), Ewart (1979), Shaw (1956), Condie (1985).

ment resides in that component. The following relationship is used in such calculations,

$$d = (s/r) \times 100 \qquad (1)$$

where d is the percentage of a rock or mineral fragment in the original sediment, r is the concentration (in percent) of a specific major element (as the oxide) in a rock or mineral fragment, and s is the concentration (in percent) of the same major element in the bulk sandstone. The above calculation involves four steps: (1) determine the controlling element for each detrital component to be tested; (2) calculate the contributions of the controlling element in each detrital component and subtract these contributions from the corresponding bulk-rock concentration; (3) using equation 1, calculate the amount of each detrital component that may be in the matrix (d, eq. 1) using the amount of the controlling element remaining from step 2 and dividing it by the concentration of controlling element in the detrital component; and (4) add this amount to the preserved amount (from thin section modes) to determine an upper limit of each detrital component in the original sediment. The *controlling element* is the element that is first exhausted by adding a given detrital component to a sandstone matrix. It is determined by calculating the d value (eq. 1) for the detrital component with each major element, and the element with the smallest value of d is the controlling element. K_2O is commonly the controlling element for K-feldspar, micas, rhyolite and shale and either Na_2O or CaO for plagioclase, basalt and andesite. It is, of course, important that the controlling elements used in correcting the matrix calculations be relatively immobile during diagenesis and, if metasediments are studied, also during metamorphism. Although major elements tend to be relatively immobile during diagenesis and low to moderate grades of metamorphism (Schwarcz, 1966; Eade & Fahrig, 1971), element mobility may occur in some cases (Engel & Engel, 1961; Condie & Martell, 1983).

To illustrate the calculation for each of the detrital components given in Table 1, an example is appropriate. Average compositions and petrographically determined detrital modes for some typical Precambrian graywackes are given in Table 2. For a low-quartz-intermediate (LQI) graywacke (Table 2, col. 1), the controlling elements for the six types of framework grains given in Table 1 are K_2O (K, RHY, SH), CaO (AND, CAB) or Na_2O (P). The contributions of each preserved detrital component are given in Table 3 (using eq. 1). From thin-section study, Lv is assumed to be rhyolite fragments and Ls, shale fragments. The contribution of the controlling element (K_2O) is significant in terms of Lv ($0.168 \times 4.7 = 0.79$) and plagioclase is significant in contributing CaO ($0.13 \times 4.5 = 0.59$). The total percentage of the controlling element in petrographically observed detrital components is subtracted from the whole-rock concentration (W) to determine the amount of controlling element in the matrix (Table 3). This matrix contribution is then used to calculate an *upper concentra-*

tion limit (C*) of each detrital component that may have recrystallized to form matrix, assuming all of the controlling element resides in one detrital component only. For example, the maximum amount of K-feldspar (Table 4) allowed in the matrix of LQI is 4.3% ([0.52/12] × 100). C* ranges from 4 to 15% for the detrital components chosen for this example (Table 4). The C* values are added to the observed detrital modes C, as determined petrographically, to calculate an upper limit for the amount of a given detrital component in the sandstone (C + C*, Table 4). A 'corrected' detrital mode can be calculated using the C + C* values as illustrated for K-feldspar in LQI in Table 5. This corrected mode assumes only K-feldspar has contributed K_2O to the matrix and thus, represents an upper limit for the total contribution of K-feldspar to the original sediment. Similar corrected modes can be calculated for any number of different detrital components, each representing an upper limit for the contribution of a specific detrital component to the sandstone matrix.

Table 2. Average chemical compositions and detrital modes of various Precambrian graywackes.

	LQI	HQI	QR	QP
SiO_2	67.3	85.0	77.8	57.2
TiO_2	0.85	0.33	0.48	1.0
Al_2O_3	13.8	7.18	10.6	16.0
Fe_2O_3T	7.14	4.25	3.71	8.8
MgO	1.70	0.11	0.77	3.4
CaO	1.49	0.10	0.68	5.4
Na_2O	3.71	0.82	1.90	5.0
K_2O	1.65	1.66	2.52	0.7
MnO	0.07	0.01	0.05	0.12
P_2O_5	0.20	0.04	0.07	0.23
LQI	2.80	0.99	1.2	2.0
Qm	6.8	28.0	20.0	1.0
Qp	2.9	15.3	19.0	0.1
K	0.8	13.5	1.0	0
P	13.0	2.4	0.1	12.7
Lv	16.8	8.2	3.0	33.6
Ls	4.7	1.4	0	10.2
Matrix	55.0	31.2	56.9	42.4
n	4	2	36	10

n, number of samples; Fe_2O_3T, total Fe as Fe_2O_3; LQI and HQI, low-quartz and high-quartz intermediate graywackes from the Mazatzal Mountains, central Arizona (unpub. data of the authors, 1987); QR, quartz-rich graywacke (quartz wacke), from the Pinal Mountains, SE Arizona (Condie & DeMalas, 1985); QP, quartz-poor graywacke, Sierra Madre Mountains, SE Wyoming (Condie & Shadel, 1984). Graywacke classification scheme after Crook (1974). Qm monocrystalline quartz; QP polycrystalline quartz: Q = Qm + Qp; P plagioclase; K K-feldspar; F = K + P; Lv, volcanic/metavolcanic fragments; Ls sedimentary/metasedimentary fragments; L = Lv + Ls; Lt = L + Qp.

Table 3. Distribution of controlling elements in petrographically observed detrital components in LQI graywacke.

Identified Grains	Controlling element (as oxide)	
	K_2O (%)	CaO (%)
K	0.1	0.002
P	0.08	0.59
Lv	0.79	0.185
Ls	0.16	0.083
Total	1.13	0.86
W	1.65	1.49
Matrix (Total − W)	0.52	0.63

W, whole-rock concentration of controlling element from (Table 2); other symbols defined in Table 2.

Table 4. Summary of geochemical matrix calculations for LQI graywacke.

Component	K	P	AND	CAB	RHY	SH
C (%)	0.8	13	16.8	16.8	16.8	4.7
C* (%)	4.3	14	9.3	6.5	11.0	15.0
C + C* (%)	5.1	27	26.1	23.3	27.8	19.7

C, amount observed in thin section (col. 1, Table 2); C*, maximum amount recrystallized in matrix based on controlling element calculation; C + C*, upper limit of the amount in original sediment. Symbols defined in Table 1.

Table 5. Comparison of uncorrected and corrected detrital modes for K-feldspar in LQI graywacke.

	Uncorrected	Corrected
Q	6.8 + 2.9 = 9.7 (22)	6.8 + 2.9 = 9.7 (20)
F	13 + 0.8 = 13.8 (31)	13 + 5.1 = 18.1 (37)
L	16.8 + 4.7 = 21.5 (47)	16.8 + 4.7 = 21.5 (43)

Values in ( ) recalculated to 100% for plotting.

Application to triangular provenance diagrams

To illustrate the variation in plotting position of the detrital components for various upper-limit values, averages of four matrix-rich sandstones (Table 2) are corrected and plotted on two triangular provenance diagrams proposed by Dickinson & Suczek (1979) and revised by Dickinson (1985) (Figs. 1 and 2). Uncorrected detrital modes and modes with Q values corrected using the method of McLennan (1984) are also plotted for comparison. For the LQI graywacke described above, both uncorrected and corrected modes plot in the transitional-arc field on the QFL and QmFLt diagrams. The HQI graywacke illustrates a case in which the concentration of controlling elements (K_2O and CaO) in preserved detrital components exceeds that in the whole rock by a small amount (<0.5%). This probably means that the concentrations of these elements in one or more of the detrital components has been over-estimated. In this case, none of the detrital components given in Table 1 is allowed in the matrix and thus, the petrographically observed detrital components should represent an approximation of the true detrital proportions. In the case of QP graywacke, a very minor amount of K_2O (0.02%) remains after correcting for the preserved detrital components. Thus, K-feldspar, rhyolite, and shale, for which K_2O is the controlling element, cannot comprise a significant amount of the graywacke matrix and corrected modes plot at essentially the same positions as uncorrected modes. Only if sodic plagioclase is an important component in the matrix, does the corrected mode of QP

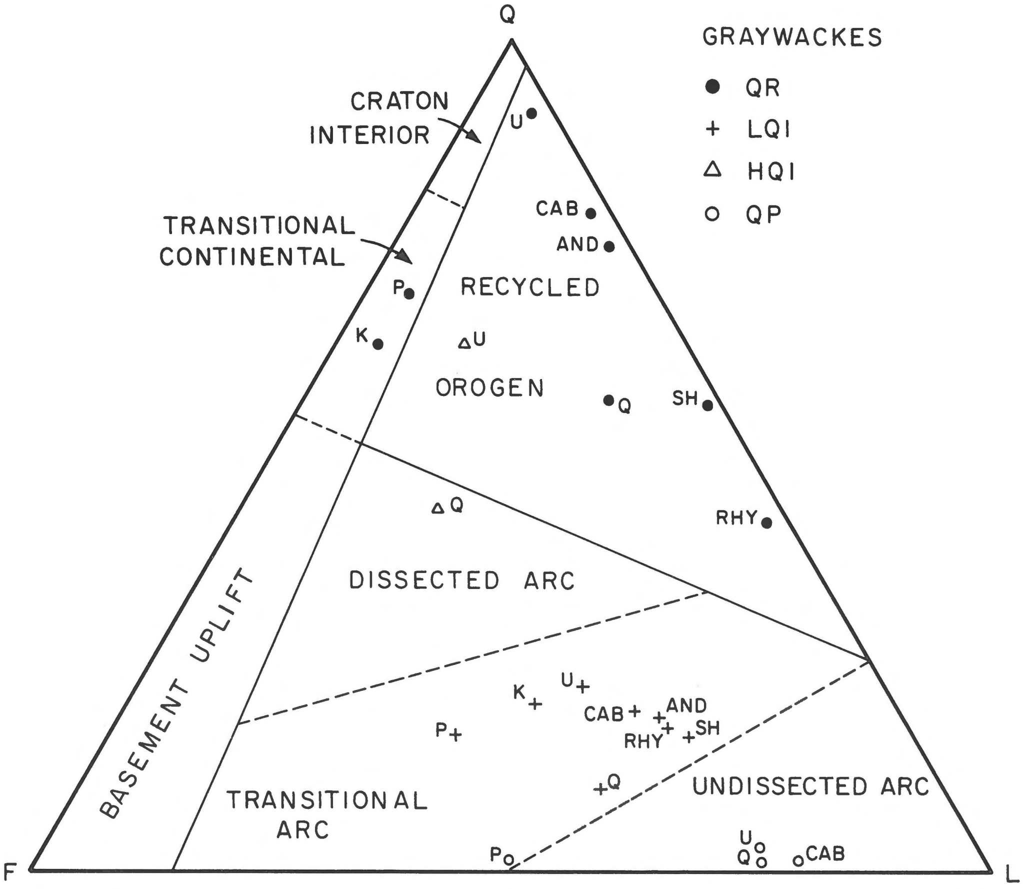

Fig. 1. QFL provenance diagram. Fields from Dickinson (1985). Detrital mode parameters defined in Table 2. U, uncorrected detrital mode; K, K-feldspar; P, plagioclase; AND, andesite; CAB, calc-alkaline basalt; RHY, rhyolite; SH, shale; Q, corrected mode using the method of McLennan (1984).

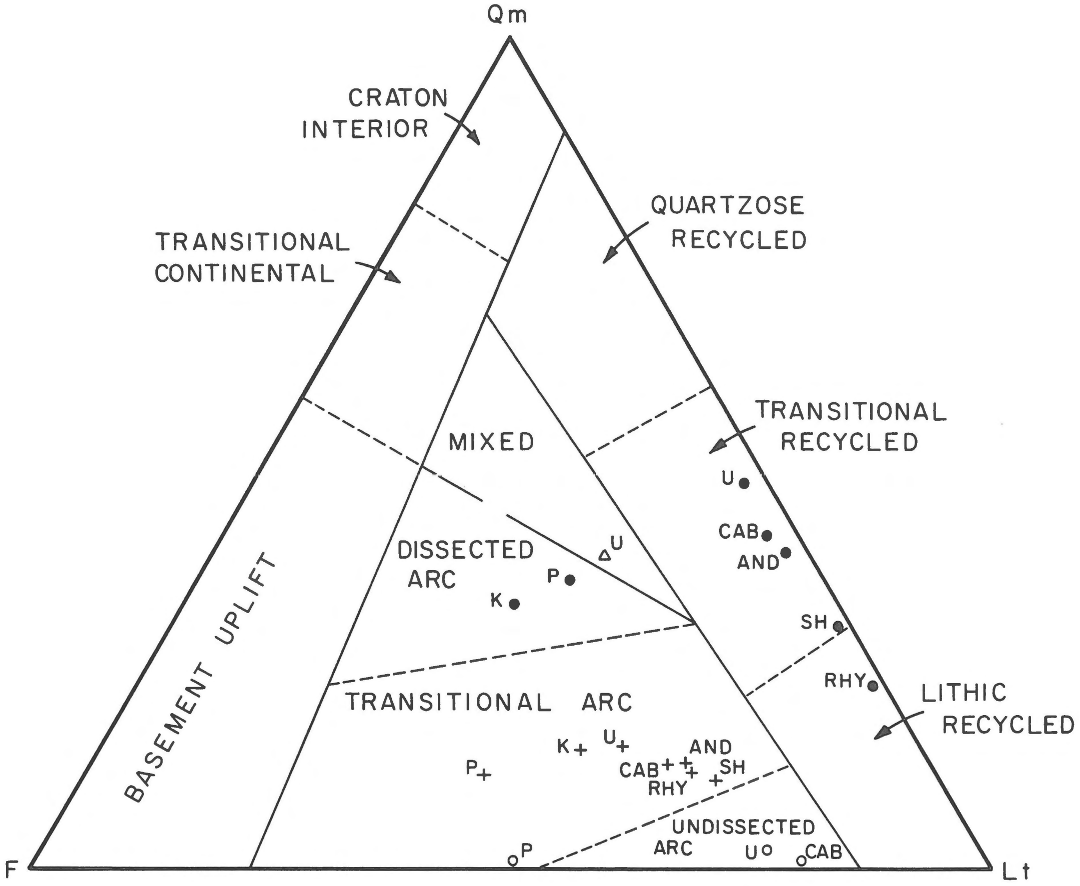

Fig. 2. QmFLt provenance diagram. Fields from Dickinson (1985). Symbols defined in Table 2 and Fig. 1.

graywacke plot in a significantly different position (Figs. 1 and 2).

All but the feldspar-corrected modes of a quartz-rich (QR) graywacke plot in the recycled-orogen field on the QFL diagram (Fig. 1), and in either the transitional- or lithic-recycled fields on the QmFLt diagram (Fig. 2). If feldspar is an important component in the matrix of these rocks, the points shift into the transitional continental field on the QFL diagram. It is important to recall that all of the chemically corrected modes are extremes and it is unlikely that many graywackes include only one detrital component. For graywackes that include only detrital components given in Table 1, the scatter shown on Figs. 1 and 2 is a *maximum* and the true detrital mode lies somewhere within the range of scatter. Perhaps the most remarkable feature illustrated in Figs. 1 and 2 is that the uncorrected detrital modes of graywackes generally result in the same provenance and tectonic setting interpretations as the corrected modes. The only exception is when detrital feldspar is an important component of the matrix.

Conclusions

From the major-element composition of matrix-rich sandstones, it is possible to constrain the original abundances of detrital components, provided the bulk composition of these components can be estimated. This extends the provenance interpretation of detrital sandstone modes to include a large and important group of sandstones including most graywackes and many subgraywackes.

The proposed matrix calculation method provides a means of estimating the *upper limit* of the abundances of various detrital mineral and rock fragments in graywackes. For instance, it is possible to constrain the abundance of andesite, basalt or komatiite in an original sediment while none of the actual rock fragments survives recrystallization. Relatively immobile trace elements (*viz.*, REE and high field strength elements) can be used in a similar manner provided their detrital component sites are known.

In addition, results of the proposed geochemical matrix calculations indicate that petrographic detrital modes of matrix-rich sandstones may provide accurate provenance and tectonic setting information provided recrystallized feldspars are not important matrix components.

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