ferred orientation is also shock-induced. However, it should not be concluded that recrystallization is necessarily the only mechanism by which this diffraction feature is formed. In meteoritic diamonds and in diamonds produced by anisotropic processes the preferred orientation apparently arises by preferential conversion of the basal planes of initially polycrystalline graphite to (311) planes of diamond (*9*). We can reasonably expect that, in addition to stony meteoritic minerals, terrestrial minerals from meteoritic impact sites and artifically shocked materials will also show crystallographic alteration.

M. E. LIPSCHUTZ
Physikalisches Institut der Universität Bern, Berne, Switzerland, and Department of Chemistry, Purdue University, Lafayette, Indiana 47907
R. R. JAEGER
Department of Chemistry, Purdue University

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Sediments from the Lower Columbia River and Origin of Graywacke

Abstract. *The mineral and chemical composition of sediments deposited in the three lowermost reservoirs of the Columbia River is remarkably similar to the composition of many graywackes. Lithic fragments are abundant. In comparison with an "average" sandstone, the sediments have low concentrations of silica and high concentrations of all other major constituents, except calcium. Sodium is more abundant than potassium. The sediments are generally better sorted than graywackes. If graywacke texture is post-depositional in origin, Columbia River-type sediments could be expected to form graywackes upon deep burial without any significant addition or removal of material.*

Interest in recent sediments has prompted attempts to recognize the modern analogs of ancient sediments now preserved as sedimentary rocks. Graywacke-type sands, characterized by very poor sorting, have seldom been identified (*1*). This is puzzling, in view of the widespread occurrence of graywacke throughout the stratigraphic column. Since many ancient graywackes are thought to have been deposited by turbidity currents in deep water (*2*), it is surprising that most sands on the deep ocean floor are relatively well sorted (*3*).

Cummins (*4*) has suggested recently that graywacke texture is post-depositional in origin and that it occurs when chemically unstable grains are partially or completely disintegrated and form matrix during weathering, deep burial, or low-grade metamorphism. If Cummins is correct and graywacke texture has little to do with primary sorting, then textural criteria are invalid for use in identification of modern graywacke-type sands; other criteria are needed. Two possible criteria are the mineral and chemical composition of the sediments.

The sand-size fraction of most graywackes is largely restricted to lithic fragments, quartz, and feldspar regardless of the age of the rock or its geographic locality (*5*). As might be expected, there is considerable variation in feldspar composition and type of lithic fragments in most graywackes.

Pettijohn states: "there are a considerable number of chemical analyses of graywacke in the literature which show a remarkable homogeneity of composition. Almost all these rocks would qualify as graywackes by any definition" (*5*).

The sediments carried by the Columbia River bear a striking mineral and chemical resemblance to many graywackes. Sediments were obtained by a Van Veen grab sampler in 1964 and 1965 from the bottom surface (to a depth of about 15 cm) of three downstream reservoirs of the Columbia River: Bonneville, The Dalles, and McNary. In all, 53 samples from the three reservoirs have been analyzed at least partially. The mean particle sizes of samples, in "phi units," the negative logarithm (base 2) of the diameter in millimeters, are: Bonneville reservoir (31 analyses), 2.45 ϕ; The Dalles reservoir (9 analyses), 3.79 ϕ; McNary reservoir (13 analyses), 3.75 ϕ. All are in the range of coarse sand to medium silt. The relatively coarse sediment in Bonneville, the lowermost reservoir, correlates with the greater current in that section of the river.

The range and mean of the sorting coefficients (σ_I) in each of the reservoirs are: Bonneville, 0.37 to 2.34 ϕ, 0.89 ϕ (moderately sorted); The Dalles, 0.26 to 2.49 ϕ, 1.42 ϕ (poorly sorted); McNary, 0.32 to 2.01 ϕ, 1.23 ϕ (poorly sorted). The sorting coefficient generally increases with decrease in grain size. Only the very fine-grained samples have sorting coefficients comparable to those of many recognized graywackes (*4*, Fig. 1).

Sedimentary structures were not observed in any of the samples because of the sampling method. A few samples showed stratified fine and coarse sediment (and were excluded in size analyses), but most were homogeneous.

Thin sections were made from 11 samples impregnated with epoxy resin, and a summary of modal analyses (by point-counting) is given in Table 1. Modal analyses of other samples (determined by inspection) do not differ greatly from those selected for point-counting, although the latter are not necessarily representative of each reservoir (only two samples were chosen from The Dalles). The modal analyses

Table 1. Mineral composition of Columbia River sediments, based on model analyses of four samples from McNary reservoir, two samples from The Dalles reservoir, and five samples from Bonneville reservoir.

Constituents	Composition (%)		
	McNary	The Dalles	Bonneville
Quartz	41	22	33
Plagioclase	13	13	14
K-feldspar	10	8	10
Lithic fragments	24	47	30
Opaque minerals	2	1	2
Mafic minerals*	9	8	10
Other	1	1	1

* Mainly hypersthene, augite, hornblende, biotite.

Table 2. Chemical analyses of sediments. Analyst: A. Stelmach; nd, no data.

Constituent	Percentage by weight			
	McNary, sample CC 21	The Dalles, sample CC 29	Bonneville	
			Sample CC 40	Sample CC 52
SiO_2	63.47	61.69	69.60	70.05
TiO_2	0.94	1.03	1.06	0.86
Al_2O_3	14.05	13.89	12.10	12.24
Fe_2O_3	3.47	3.82	2.77	2.31
FeO	2.07	2.20	2.57	2.05
MnO	0.09	0.11	0.08	0.06
MgO	2.06	2.02	1.95	1.61
CaO	3.04	3.10	3.54	3.50
Na_2O	2.35	2.20	2.85	3.13
K_2O	2.02	1.88	1.98	2.25
P_2O_5	0.25	0.25	0.16	0.15
H_2O	.96	1.81	.33	.33
L.O.I.*	5.14	5.99	.65	.99
BaO	nd	nd	.10	.10
S	nd	nd	.04	.12
Cl	nd	nd	.05	.05
Total	99.91	99.99	99.83	99.80

* Loss on ignition.

Table 3. Chemical analyses of Columbia River sediments (A, Bonneville; B, The Dalles; C, McNary; D, average of columns A, B, and C; Graywacke; F, Sandstone) compared with an "average" graywacke (E, *5*) and an "average" sandstone (F, *5*).

Constituent	Sediment					
	A‡	B§	C‖	D	E*	F†
	Percentage by weight					
SiO_2	66.91	67.32	68.95	67.73	66.7	77.6
TiO_2	0.83	0.80	0.75	0.79	0.6	0.4
Al_2O_3	13.59	13.63	13.66	13.63	13.5	7.1
FeO, Fe_2O_3¶	5.29	5.32	4.63	5.08	5.5	3.4
MnO	0.09	0.10	0.09	0.09	0.1	0.1
MgO	2.09	1.94	1.74	1.92	2.1	1.2
CaO	3.69	3.54	2.99	3.41	2.5	3.1
Na_2O	2.98	2.70	2.80	2.83	2.9	1.2
K_2O	1.99	2.03	2.20	2.07	2.0	1.3
H_2O	nd	nd	nd	nd	3.0	2.1
CO_2	nd	nd	nd	nd	1.2	2.5
Total	97.46	97.38	97.81	97.55	100.1	100.0
Na/K ratio	1.4	1.2	1.1	1.2	1.3	0.82
	Parts per million#					
B	<20	20	20	20		
Ba	1700	1600	1500	1600		
Co	10	10	10	10		
Cr	50	50	50	50		
Cu	20	30	30	30		
Ga	20	20	20	20		
Ni	30	20	30	30		
Pb	<20	30	40	30		
Sc	20	20	20	20		
Sr	430	430	480	450		
V	90	110	50	80		
Y	40	40	50	40		
Zn	<200	<200	200	<200		
Zr	160	160	185	170		

* Does not include P_2O_5, SO_3, S, or C. † Does not include P_2O_5 or SO_3. ‡ Av. of 27 analyses; mean size, 2.45 ϕ. § Av. of 14 analyses; mean size, 3.79 ϕ. ‖ Av. of 13 analyses; mean size, 3.75 ϕ. ¶ As Fe_2O_3. # Analyst: E. Bingham.

probably are not truly representative of the entire sample because of the difficulty in point-counting the silt and clay-size fraction.

Lithic fragments are largely basalt and andesite, but there is a small number of fragments from coarse-grained igneous, metamorphic, and sedimentary rocks. Quartz grains commonly show undulatory extinction, and about half of the plagioclase is zoned. Most of the minerals and lithic fragments are angular to subangular and appear unaltered, except for occasional amphibole and pyroxene crystals, which are etched in the direction of the *c* axis.

Four bulk sediment samples were analyzed by wet chemical methods (Table 2) and used as standards for analysis by x-ray emission spectrography (Table 3, col. A, B, C, D). The samples for x-ray analysis were fused by the method of Welday *et al.* (*6*). Trace elements were analyzed by optical emission spectrography at California Institute of Technology.

Chemical analyses of Columbia River reservoir sediments are remarkably similar to Pettijohn's analysis of "average" graywacke (Table 3, col. E) and to other analyses of graywackes (*5*). Compared with an "average" sandstone (Table 3, col. F), graywackes and Columbia River sediments are low in silica and high in all other major constituents except calcium. Especially notable is the excess of Na_2O over K_2O. According to Pettijohn, this is one of the most singular chemical attributes of graywacke (*5*).

The source rocks from which the sediments in the lower Columbia River reservoirs were derived are predominantly volcanic, coarse-grained igneous, metamorphic, and sedimentary rocks of the Cascade Range, and volcanic rocks of the Columbia Plateau. Much unconsolidated glacial and eolian sediment is present in parts of the drainage area and may also be a source of sediment. Ultimately, however, this unconsolidated sediment is derived mostly from igneous and metamorphic rocks.

The slight variation in sediment composition among reservoirs, despite the considerable variation in grain size, is evidence that the sediments were derived largely by mechanical weathering. In areas of widespread chemical weathering, composition is commonly related to grain size (*5*).

Some conclusions and inferences follow:

1) The mineral and chemical composition of Columbia River sediments reflects the volcanic, metamorphic, and igneous rocks of the source area. The result is a sediment with a mineral and chemical composition very similar to that of a graywacke. The composition is nearly the same for all samples, even though grain size and sorting vary widely.

2) A large percentage of the mafic minerals and volcanic lithic fragments present in Columbia River sediments is chemically unstable. Some, such as lithic fragments containing volcanic glass, are more unstable than others. During deep burial many of these grains and fragments would be expected to alter, and the resulting sedimentary rock *could* have the texture of a graywacke. The amount and type of lithic fragments and mafic minerals preserved in the graywacke would depend on the nature of the original detrital material, depth of burial, age, and other factors.

3) A high Na_2O/K_2O ratio in sediments or sedimentary rocks is not by itself evidence for soda metasomatism, for Na_2O exceeds K_2O in most basalts and andesites as well as in many coarse-grained igneous and metamorphic rocks. Sediments derived by mechanical weathering of these rocks would be expected to have high Na_2O/K_2O ratios.

4) Sediments from the Columbia River could be used in an attempt to produce a graywacke experimentally in the laboratory, and thereby test Cummins's hypothesis.

JOHN T. WHETTEN
Departments of Geology and Oceanography, University of Washington, Seattle 98105

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