RADIOMETRIC EVIDENCE FOR THE ORIGIN OF EUGEOSYNCLINAL MATERIALS

JOHN J. W. ROGERS
and
THOMAS W. DONNELLY
DEPARTMENT OF GEOLOGY
RICE UNIVERSITY, HOUSTON, TEXAS

CONTENTS

I. Abstract

Thorium and uranium contents of eugeosynclinal graywackes and associated volcanic rocks are similar and are in the range of 1-2 ppm thorium and 0.5-1 ppm uranium. These values are much lower than average concentrations in the continental crust and apparently indicate derivation of orogenic material directly from the upper mantle without contribution from the craton.

II. Introduction

During the past year the writers have participated in a joint study of orogenic volcanic rocks and their associated sediments. This combination of efforts arose out of the long-term project of one of the writers (TWD) to determine the evolution of the Caribbean island arc and out of the studies made by the other writer (JJWR) of radiometric properties of rocks in general and of the graywackes of western Oregon and Washington in particular. The results have been, and will be, published in a number of papers dealing with specific subjects, such as: the structure of part of the Caribbean arc (Donnelly, 1964); the geology of two of the Virgin Islands (Donnelly, 1966); the chemical petrology of the Caribbean volcanic rocks (Donnelly, in preparation; Lidiak, 1965); the radiometric properties of the Caribbean volcanic rocks (Donnelly and Rogers, in preparation); the radiometry of the graywackes of Oregon and Washington (Rogers and Richardson, 1964); and the petrology of the graywackes of Oregon and Washington (Rogers, 1966). This paper discusses primarily the radiometric properties of the volcanic wackes of the Caribbean island arc.

III. Acknowledgments

Radiometric work on this project was supported by Robert A. Welch Foundation Grant C-009 to John A. S. Adams and John J. W. Rogers. Work in the Caribbean has been supported by National Science Foundation Grants GP-1352 and GP-4695 to Thomas W. Donnelly. The writers thank Messrs. Kenneth J. Balacek and Willis Brimhall for assistance with the radiometric work.

IV. Geologic Settings

The geologic setting of the eastern Greater Antilles has been described by Donnelly (1964), and the following discussion is based largely on data and inferences presented in that paper. Basically, the island chain is an elongate, thickened, welt formed in response to sub-crustal drag, perhaps ultimately the product of convective or similar currents within the mantle. The line along which drag was manifested in thickening is an older boundary between evidently anhydrous oceanic crust and mantle and partially-hydrated Caribbean crust and mantle. Virtually every structural feature can be related to differential vertical movements of mobile, linear blocks within the welt. Except for a small fraction of biogenic carbonate rocks, all of the surficial rock materials of the island platform are either volcanic or are sediments derived from local volcanic sources and are of local origin. Recent sediments are also in part derived from quartz dioritic to granodioritic plutons injected into the volcanic material. The myth of a Caribbean continent must be excised from geological thinking, although it has been a dominant concept in the past and has persisted until the present day. Mattson (1960), however, clearly refuted the one bit of evidence in favor of such a continent by demonstrating that a presumed granite fragment derived from the continent was actually altered volcanic rock. The Caribbean orogen has created its own rock types, and its debris is moving away from it rather than toward it.

The Tertiary graywackes of western Oregon and Washington have accumulated in a typical eugeosynclinal trough. They are part of a sequence of clastic sediments and intercalated basaltic volcanic rocks with a thickness of some tens of thousands of feet in a zone approximately 500 miles long and 100 miles wide between the Pacific coast and the Cascade Mountains. The clastic sediments include graywackes and silty shales; sorting is poor, and graded bedding is common. The graywackes consist of approximately equal amounts of quartz, volcanic plagioclase, and clasts of basic volcanic rocks; very minor potassium feldspar is present, and the matrix is clayey. The general geology of the area is described by Snavely and Wagner (1964), and the graywackes are discussed by Rogers and Richardson (1964) and Rogers (1966).

V. Results of Correlative Studies

The various studies cited in the introduction have yielded a number of conclusions concerning the development of eugeosynclinal volcanic and sedimentary rocks. The major conclusions are:

1. Basalts and pyroxene andesites typical of eugeosynclinal environments are derived almost directly from primitive upper mantle material. This conclusion is based largely on a correlation of thorium, uranium, and potassium contents of the volcanic rocks with the abundances predicted for the upper mantle from heat flow studies. This conclusion is discussed by Rogers and Donnelly (1965) and Donnelly and Rogers (in preparation). Table 1 gives some average contents of radioactive materials in orogenic volcanic rocks.

2. Eugeosynclinal graywackes do not contain material derived from a continental, granitic craton. This conclusion is based largely on the absence of potassium feldspar from geosynclinal graywackes and the low content of radioactive materials in these rocks. The limited amount of "granitic" minerals, such as zircon and tourmaline, found in graywackes is presumably derived from quartz dioritic plutons within the orogen. The subject is discussed more completely by Rogers (1966).

3. Material of granitic composition does not develop in the geosynclinal column during the stages of orogenic evolution represented by major volcanic outpouring and deposition of graywackes. This conclusion is also based on the absence of granitic debris from the graywackes and by the fact that the intrusive rocks formed during these orogenic periods are generally quartz diorites with a low potassium content.

The preceding conclusions are based largely on the chemical composition of the orogenic igneous rocks. One problem in this interpretation is that the byproducts of solidification of hydrous, orogenic magmas may be chemically different from the magmas themselves. This problem is discussed by Donnelly (1966) and by Longshore (1965) and must be resolved in the interpretation of chemical data from any orogenic rock suite. Basically, there are two ways in which a rock may become compositionally different from its magma: 1) it may lose constituents completely to the environment; or 2) it may exchange constituents with the environment. There is abundant evidence that submarine volcanic rocks did both, losing a large part of their scanty content of potassium and acquiring some sodium in exchange from sea water. Large dioritic plutons in the West Indies also demonstrate exchange of some constituents with their wall rocks, acquiring alkalis (dominantly sodium) and losing divalent ions (dominantly magnesium).

Despite the difficulties discussed above, the possibility that exchange and loss have a major effect on the thorium and uranium contents of the Caribbean volcanic rocks can be disregarded for the following reasons:

1. Thorium and uranium concentrations in submarine and subaerial volcanic rocks are generally similar. For example, the subaerial, upper Tertiary basaltic andesites of St. Martin and other islands in the Lesser Antilles (Table 1) have average thorium and uranium contents of 1.73 ppm and 0.64 ppm, respectively; these values compare closely with thorium and uranium contents of 2.07 ppm and 0.93 ppm, respectively, in the dominantly submarine basaltic andesites of Puerto Rico (Table 1).

2. Longshore (1965) has demonstrated that concentrations of generally mobile constituents are similar in small and large intrusive bodies in the Caribbean island arc.

3. Thorium and uranium contents increase with time in both siliceous and mafic rock series just as they do in continental volcanic or plutonic series, thus indicating an absence of major secondary gain or loss (Donnelly and Rogers, in preparation).

As a test of the possibility of major exchange or loss of elements from volcanic rocks, the writers measured the thorium and

TABLE 1

AVERAGE THORIUM AND URANIUM CONCENTRATIONS OF OROGENIC IGNEOUS ROCKS*

	Th	U
West Indies		
Middle Cretaceous, Older Series		
Spilite, southwest Puerto Rico (1)	0.24	0.06
Spilite, Virgin Islands (5)	0.27	0.25
Quartz keratophyre, intrusive, Virgin Islands (5)	0.84	0.77
Quartz keratophyre, extrusive, Virgin Islands (4)	0.39	0.29
Quartz keratophyre, undetermined, Virgin Islands (3)	1.51	0.73
Middle Cretaceous, Younger Series		
Basaltic andesite, Puerto Rico (6)	2.07	0.93
Albitized basaltic andesite, Puerto Rico (2)	3.06	0.66
Upper Cretaceous		
Siliceous volcanic rocks, Puerto Rico (2)	2.61	0.98
Lower Tertiary (?)		
Diabase dikes, Puerto Rico and Virgin Islands (9)	1.30	0.62
Gabbro and quartz diorite, Puerto Rico, Virgin Islands, and St. Martin (5)	0.68	0.83
Granodiorite, Virgin Islands and St. Martin (3)	4.24	1.79
Upper Tertiary		
Basaltic andesite, St. Martin, St. Kitts, Montserrat, St. Lucia, St. Vincent (6)	1.73	0.64
Western Oregon		
Eocene		
Umpqua basalt (3)	0.53	0.45
Olympic Peninsula, Washington		
Lower Tertiary		
Diabase and albitized basalt (5)	1.67	0.24
Caledonides, Wales		
Lower Ordovician		
Diabase, spilite (4)	1.04	0.29

* All values are in parts per million of the metal.
Figures in parentheses represent numbers of samples analyzed.

uranium contents of suites of extrusive and intrusive keratophyres (Table 1). Although the extrusive keratophyres contained slightly lower concentrations of both elements, the concentrations in the intrusive keratophyres are comparable with the generally low thorium and uranium concentrations in other orogenic rocks.

VI. Graywackes of the Caribbean Island Arc

Table 2 shows the concentrations of thorium and uranium in a suite of graywackes from Puerto Rico and the Virgin Islands and, for comparison, the concentrations in the Umpqua graywackes of western Oregon. All measurements were made by gamma-spectrometric methods with the instrument described by Adams (1964); the results are generally reproducible to within 15 percent of the stated value.

The importance of the thorium and uranium contents in the Caribbean graywackes results from the fact that the graywackes are essentially a random sample of all material in the area. The clear evidence of rapid deposition and the abundance of clayey material in the graywackes preclude the possibility of selective sorting or extreme weathering of the source, both of which cause sandstones in other environments to be non-representative of their sources. As discussed, for example, by Adams *et al.* (1959), the majority of the thorium and uranium in shelf sediments is contained in shales with the sandstones being relatively impoverished in radioactive constituents. The lack of sedimentary differentiation in the Caribbean orogen and other geosynclinal areas, therefore, affords an opportunity to check the conclusions drawn from compositions of the volcanic rocks.

All of the Caribbean graywackes shown in Table 2 are mid-Cretaceous except the samples from the Eocene Augustinillo Formation. Petrographically the rocks consist solely of volcanic debris and may, in large part, be epiclastic. Crystal, vitric, and lithic components are all abundant, and the structures and textures are highly variable. Alteration to calcium carbonate is characteristic and is intense in some samples, particularly TD-63-24B, TD-63-49 and TD-63-50. As shown in Table 2, the thorium contents of the graywackes are in the range of 1 to 2 ppm, and the uranium contents in the range of 0.5 to 1 ppm.

The average thorium and uranium contents of the West Indian graywackes are clearly similar to the contents shown for the volcanic rocks in Table 1. Because graywackes and volcanic rocks constitute nearly the entire sequence of materials now ex-

Table 2
THORIUM AND URANIUM CONCENTRATIONS OF SOME GRAYWACKES*

West Indies			Th	U
Middle Cretaceous, Younger Series				
Fajardo Fm., Puerto Rico		TD-63-24B	1.08	0.82
Robles Fm., Puerto Rico		TD-63-31A	1.83	0.61
Tutu Fm., Virgin Islands		TD-63-101	0.91	0.85
		TD-63-101A	1.23	0.40
		TD-63-101B	1.05	1.06
		TD-63-103A	1.03	0.32
		TD-63-103B	0.91	0.73
Other, Puerto Rico		TD-63-1	3.45	1.05
		TD-63-3A	1.38	0.74
		TD-63-4	0.53	0.59
		TD-63-9A	1.29	0.71
Eocene				
Augustinillo Fm., Puerto Rico		TD-63-49	4.22	1.48
	(Duplicate)	TD-63-50	0.98	0.89
		TD-63-50	0.89	1.31
Western Oregon †				
Eocene				
Umpqua Fm.	(4 samples)		2.8	1.3

* All values are in parts per million of the element.

† From Rogers and Richardson (1963). The Umpqua Formation is petrographically the most characteristic of the geosynclinal formations studied in Oregon. The Tyee Formation, also reported by Rogers and Richardson, is abnormally rich in white mica and is not reported here.

posed in the area, the writers conclude that the material supplied to the West Indian orogen has a concentration of 1-2 ppm thorium and 0.5-1 ppm uranium. The significance of these values becomes apparent when they are compared with average compositions of other portions of the crust.

The values of thorium and uranium in crustal materials fall into three groups. The average continental values (largely based on granites and metamorphic rocks) are approximately 6 ppm thorium and 2 ppm uranium (Rogers and Adams, 1966 a & b). The typical mid-oceanic basaltic values are about 0.18 ppm thorium and 0.10 ppm uranium (Tatsumoto *et al.*, 1965). Therefore, concentrations in rocks of mobile belts of 1-2 ppm thorium and 0.5-1 ppm uranium may be explained as follows: The continental cratonic material represents successive waves of ancient magmatism, with relatively shallow melting in the presence of a high thermal gradient. Whatever thorium and uranium once existed in the upper mantle has been rather effectively incorporated in the surficial rocks produced by this magmatism, namely the continental shield areas. In the mid-ocean a layering of thorium and uranium exists in the mantle, with the bulk of these materials concentrated at relatively shallow depths. Present-day deep generation of magmas produces melts almost free of these elements, and the ascending magmas have a very limited opportunity to acquire more shallowly distributed minor elements prior to their eruption. Hence, most of the original thorium and uranium beneath the ocean is concentrated in the upper mantle, which probably has a markedly higher content than mantle beneath the shield areas. The mobile belts tap the upper mantle and generate melts richer than those of the mid-oceanic areas in the minor elements which are concentrated in the upper mantle. If deformation and magmatism persist through several cycles, then the concentration of minor elements in certain parts of the mobile belts might approach that of the shield areas. The two areas studied, the Pacific Northwest and the eastern West Indies, are, however, relatively juvenile in this regard.

The explanation given in the preceding paragraph clearly envisions upward movement of thorium and uranium, and presumably other materials, from the lower mantle during continental growth. The fact that rocks produced in orogenic belts marginal to the continents do not contain as much radioactive material as cratonic rocks, despite the apparent derivation of the orogenic lavas from relatively high levels in the mantle, indicates that cratonic rocks could not be differentiated solely out of the upper few tens of kilometers of the mantle. This reasoning is substantiated by finding metagraywackes and metavolcanic rocks of former geosynclinal belts in shields areas now underlain by granitic rocks. Apparently the formation of granite and construction of a craton follows the type of orogenic activity now found in the Caribbean area.

The two major conclusions which can be drawn from this study are:

1. The concentrations of radioactive elements in rocks of mobile belts are intermediate between concentrations in continental and in oceanic areas. This observation supports the concept that cratonic areas are formed as an end result of the orogenic process in geosynclines.

2. Mobile belts are largely filled with volcanic rocks and volcanic debris derived from the mantle and are not recipients of detritus from the craton.

VII. Literature Cited

Adams, J. A. S., 1964, Laboratory γ-ray spectrometer for geochemical studies: *in* J. A. S. Adams and W. E. Lowder (eds.), The Natural Radiation Environment, Univ. of Chicago Press, p. 485-498.

Adams, J. A. S., J. K. Osmond, and J. J. W. Rogers, 1959, The geochemistry of thorium and uranium: Physics and Chemistry of the Earth, v. 3, p. 298-348.

Donnelly, T. W., 1964, Evolution of the eastern Greater Antillean island arc: Amer. Assoc. Petrol. Geol. Bull., v. 48, p. 680-696.

Donnelly, T. W., 1966, Geology of St. Thomas and St. John, Virgin Islands: *in* Geol. Soc. America, Mem. 98, (in press).

Lidiak, E. G., 1965, Petrology of the andesitic, spilitic, keratrophyric flow rock, north-central Puerto Rico: Geol. Soc. America, Bull., v. 76, p. 57-88.

Longshore, J. D., 1965, Chemical and mineralogical variations in the Virgin Islands batholith and its associated wall rocks: Ph.D. Thesis, Rice Univ., Houston, Texas, 94 p.

Mattson, P. H., 1960, Geology of the Mayagüez area, Puerto Rico: Geol. Soc. America, Bull., v. 71, p. 319-362.

ROGERS, J. J. W., 1966, Geochemical significance of the source rocks of some graywackes from western Oregon and Washington: Texas Jour. Science, v. 18, (in press).

ROGERS, J. J. W., and J. A. S. ADAMS, 1966a, Thorium: Handbook of Geochemistry, Part II, Chapter 90, Springer Verlag, Berlin.

ROGERS, J. J. W., and J. A. S. ADAMS, 1966b, Uranium: Handbook of Geochemistry, Part II, Chapter 92, Springer Verlag, Berlin.

ROGERS, J. J. W., and T. W. DONNELLY, 1965, Radioactive constituents of West Indian orogenic rocks: Amer. Geophys. Union, Trans., v. 46, p. 548 (abs.).

ROGERS, J. J. W., and K. A. RICHARDSON, 1964, Thorium and uranium contents of some sandstones: Geochim. et. Cosmochim. Acta, v. 28, p. 2005-2011.

SNAVELY, P. D., JR., and H. C. WAGNER, 1964, Tertiary geologic history of western Oregon and Washington: Washington Div. of Mines and Geology, Report of Investigations 22, 25 p.

TATSUMOTO, MITSUNOBU, C. E. HEDGE, and A. E. J. ENGEL, 1965, Potassium, rubidium, strontium, thorium, uranium, and the ratio of strontium-87 to strontium-86 in oceanic tholeiitic basalt: Science, v. 150, p. 886-888.

June 11, 1966