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## NEUTRON-CAPTURE, GAMMA-RAY PROSPECTING METHOD

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The present invention pertains to a method of locating ore deposits, and more particularly relates to locating anomalies in the degree of igneous and metamorphic rock mineralization or other forms of alteration commonly associated with ore bodies by neutron-capture, gamma-ray spectrometry.

This application pertains to subject matter related to that disclosed in U.S. application Serial No. 599,650, entitled "Induced Gamma Activity Prospecting Method", filed July 23, 1956, by Earley, Graham, and Tittle.

The invention is predicated upon the discovery that with respect to many important types of igneous or metamorphic rock alteration, notably mineralization, a specimen of altered rock will produce, upon being subjected to a flux of slow neutrons, neutron-capture gamma rays having energies in excess of at least 2.23 mev. and preferably above about 3 to 4 mev. at a rate that is markedly different from the rate at which such gamma rays are produced upon identical treatment of a relatively unaltered specimen of the same rock body or mass. Such rate of producing neutron-capture gamma rays has been found to vary in a manner generally linear with respect to the degree of alteration (especially mineralization), and in a sense dependent upon the specific nature of the alteration.

Also, rock alteration processes which have resulted in, or which are related to prior or contemporary mineralizing processes resulting in commercially important ore bodies have also apparently caused varying degrees of rock alteration for substantial distances outwardly from the ore body proper, with the degree of alteration usually decreasing with increasing distance from the ore body proper. The zone (referred to herein as the "halo") surrounding the ore body proper having a gradually and outwardly diminishing degree of alteration can be partly or entirely due to natural processes operating after the formation of the ore body.

The halo normally will involve varying concentrations of the commercially important component of the mineral ore body; however, such variations in concentration of the commercially significant component of the ore body is frequently accompanied by or substantially entirely replaced by a composition anomaly of some other component that can be in itself indicative of the existence of and location of the ore body. Accordingly, the expression "halo" is also meant to include the zone of composition variations surrounding an ore body, whether the composition varies as to the significant component of the ore body (anomaly of the first kind) or as to another component of the igneous or metamorphic rock (anomaly of the second kind). Thus, the halo zone includes any composition anomaly in the region of an ore

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body, and the present invention is concerned with locating composition anomalies that may be halos.

Though rocks within a halo zone normally are mineralized to a far lesser degree than to be even of trivial commercial interest, and are frequently if not always mineralized or otherwise altered to such a slight degree as to escape visual detection thereof by the most experienced prospector; the subject invention pertains to securing valuable information indicative of both the existence of and the actual location of ore bodies, though the latter may be at a substantial depth below the earth's surface, by detecting and locating composition anomalies of the sort characterizing halos as specified above in the igneous or metamorphic rock body.

According to the invention, such valuable information is obtained by locating anomalies, either of the first or second kind, in the degree of alteration of a rock body over an area of the earth's surface. Also, according to the principles of the invention, both kinds of such anomalies are ascertained by procuring a plurality of surface, or preferably near-surface (when weathering effects are negligible) rock samples of equal weights from spaced points situated over an area of a rock body under investigation, preferably according to a grid pattern. The relative degree of alteration, notably mineralization, of the samples is obtained by subjecting individually each sample to a fixed or standard flux of slow neutrons and concurrently measuring the rate at which gamma rays (pre-eminently neutron-capture gamma rays) having energies in excess of at least 2.23 mev. and preferably above about 3 to 4 mev. are produced by the sample. The so-measured rates of production of gamma rays of the plurality of samples, which are indicative of the relative degrees of alteration or mineralization, are then correlated with the locations from which the samples were initially procured. Such correlation is preferably done by plotting such measured rates upon a map conforming to the area from which the samples were initially procured, and then optionally additionally marking isograms upon the map relative to the values of the plotted rates.

The anomalies in the degree of rock alteration or mineralization indicative of the possible presence and the location of ore bodies is ascertained upon reference to the rates, or a plot thereof and preferably upon inspection of suitably short interval isograms of the rates.

A more specific aspect of the invention involves measuring with respect to a plurality of samples solely the rate at which neutron-capture gamma rays of a specific energy level or of a specific range of energy levels are produced, and correlating such measured rates with the locations from which the samples were procured, usually by plotting such rates on a map and optionally additionally marking isograms upon the map. This aspect of the invention is particularly adapted to ascertain concentration anomalies of a selected class or classes of atomic nuclei.

The invention will be more fully understood in the light of the following detailed description thereof taken together with the accompanying drawings illustrating preferred apparatus for practicing the invention wherein:

Figure 1 is a sectional view of apparatus for subjecting a sample to a flux of slow neutrons and a detector for detecting gamma rays produced by the sample, with rate measuring means being shown diagrammatically and,

Figure 2 is a representation of isograms indicating an anomaly.

Referring to Figure 1, the numeral 10 designates a

vessel preferably comprised of a material productive of few if any neutron-capture gamma rays, which can conveniently be fabricated of aluminum or steel. The vessel 10 is filled with water (neutron moderator) to the level indicated at 12, the water preferably being distilled water, and in any event is substantially free of materials having a high cross section for neutrons or which are reactive with neutrons to produce hard gamma rays.

Supported by suitable means, not shown, within the upper central portion of the vessel 10 is a receptacle or well 14, fabricated of a substantially slow neutron transparent material preferably such as a plastic (polymerized methyl methacrylate—a resin plastic sold under the trademark "Lucite"). A neutron source 16, such as radium-beryllium or polonium-beryllium (though an ion-accelerator type of neutron source, not shown, could be used where an especially prolific source of neutrons is required or deemed necessary), is disposed within the lower portion of the receptacle 14, and is surrounded by gamma-ray shielding 18, preferably of lead. In the preferred construction, a further block of gamma-ray shielding 20 is disposed upon the shielding 18, the shielding 20 being preferably bismuth.

A platform 22, which transversely fills the receptacle 14 rests upon the gamma-ray shielding block 20, such platform 22 being comprised of bismuth of sufficient thickness that the same in conjunction with the shielding 18 and 20 substantially attenuates gamma rays originating from the neutron source 16 from passing upwardly from the platform 22.

Resting upon the platform 22 is a toroidal-shaped sample container 24 that is also preferably fabricated of "Lucite" so as to be substantially transparent to slow neutrons as well as gamma rays. The container 24 is adapted to contain a crushed and weighed sample of rock 26 with respect to which measurements are to be made. For the purposes of the invention, satisfactory results can be obtained with a sample 26 weighing from about one to five pounds, though lesser and greater amounts can be used. A two pound or larger sample 26 is preferred being sufficiently large so as to balance out any errors that could be introduced by a lack of homogeneity in the rock sample. For a sample 26 of such size a radium-beryllium source 16 can be on the order of about 0.1 curie or greater to be adequate for rapid measurements of good statistical accuracy.

The numeral 28 indicates generally a combined photomultiplier tube and scintillation crystal of conventional character, the scintillation crystal thereof being preferably a thallium-activated sodium iodide crystal and occupying the position indicated in dashed outline at 30 so as to be disposed centrally of the toroidal-shaped container 24 and the sample 26. The photomultiplier tube and scintillation crystal 28 are, in the preferred construction, provided with a boron shield 32 to shield such equipment from slow neutrons.

The output of the photomultiplier tube and scintillation crystal 28 is fed to an amplifier 34 by leads 36 and 38, with the output of the amplifier 34 being in turn fed to a pulse-height analyzer 40 by leads 42 and 44. The pulse-height analyzer 40 is conventional in character and is adjusted to pass only electrical pulses having predetermined heights. The pulse-height analyzer 40 is normally adjusted to pass only such electrical pulses that correspond to detected gamma rays having energies in excess of 2.23 mev. or preferably in excess of about 3 to 4 mev.; however, the pulse-height analyzer 40 can for specific purposes be adjusted to pass electrical pulses having a predetermined range of heights that correspond to detected gamma rays having a selected energy or range of energies.

The electrical pulses passed by the pulse-height analyzer 40 are fed to a conventional scaler 46 by means of leads 48 and 50. A conventional timer 52 is connected to the scaler 46 by leads 54 and 56.

The operation of the apparatus shown in Figure 1 will be readily understood. Neutrons produced by the source 16 pass outwardly therefrom into the water contained in the vessel 10 and are therein moderated in energy to what is known as slow (epithermal and thermal) energy levels, it being understood that the spacing between the vessel 10 and the receptacle 14 is in the neighborhood of one foot or more so that sufficient moderation of neutron energies to thermal levels is assured. Neutrons moderated in the water diffuse throughout the water, and a portion of such slow neutrons re-enter the receptacle 14 and pass into the sample 26 contained within the toroidal-shaped container 24, it being noted that the receptacle 14 is sufficiently deeply immersed in the water in the vessel 10 that the container 24 is disposed substantially below the upper surface 12 of the water.

Slow neutrons entering the sample 26 react with constituents thereof to produce neutron-capture gamma rays at rates and energy values determined by the character of and the concentrations of constituents of the sample 26. A portion of the neutron-capture gamma rays produced in the sample 26 as a consequence of the latter being subjected to a flux of slow neutrons is detected by the photomultiplier tube and scintillation crystal combination 28 to produce electrical pulses having heights dependent upon the energies of the individual gamma rays detected. The electrical pulses produced by the photomultiplier tube and scintillation crystal combination 28 are amplified by the amplifier 34 and fed to the pulse-height analyzer 40.

As mentioned previously, the pulse-height analyzer 40 is adjusted to pass pulses having heights of a selected height or range of heights, with the pulses passed by the pulse-height analyzer 40 being fed to the scaler 46 for counting. The counting operation of the scaler 46 continues for a set time interval controlled by the timer 52 in a conventional manner.

It will be noted that the upper end of the receptacle 14 is open, so that the sample container 24 can be readily removed therefrom for emptying and charging with a new sample upon either disconnecting the photomultiplier tube and scintillation crystal combination 28 from the amplifier 34 or removing the photomultiplier tube and scintillation crystal combination 28 from the receptacle 14. Though not shown, it will be evident to those skilled in the art that the apparatus shown in Figure 1 can be shielded so as to protect operating personnel and also reduce the effects of background gamma rays. Such shielding can be of conventional character for slow neutrons and gamma rays and include removable covers of shielding material for both the vessel 10 and the receptacle 14.

Proceeding now to a description of the method for prospecting for ore bodies or locating anomalies in the degree of alteration or mineralization of an igneous or metamorphic rock body indicative of the presence of and location of an ore body, a plurality of rock samples is procured from spaced points about an area to be investigated. The samples are preferably collected or procured from points that are spaced according to a geometric pattern such as from the intersections of a grid such as that shown in the grid map of Figure 2. Each of the procured samples is sufficiently broken up for a weighed portion thereof to be placed in the sample container 24 and tested in the apparatus shown in Figure 1 or an equivalent thereof so as to determine the rate at which such samples produce gamma rays of a particular energy or range of energies upon being subjected to a flux of slow neutrons. Needless to say, the measurement of such rates is not restricted to the particular form of the preferred apparatus shown in Figure 1.

If the samples represent an area containing all or part of an anomaly, such fact can be ascertained by reference to the measured rates; preferably however, after the rates of the various samples have been measured, the value

of such rates is correlated with the locations of the positions from which the samples were initially procured by plotting the measured rates upon a map of the area from which the samples were procured. Thus, with reference to the grid map representing the area under investigation shown in Figure 2 where the samples were procured from the intersections of the vertical and horizontal elements of the grid pattern, the measured rate values would be plotted in a manner analogous to which elevations are plotted for topographical maps or barometric pressures for meteorological maps.

Upon the measured rates being plotted, inspection of the map can reveal variations in plotted rates and serve to identify readily any anomaly; however, an additional optional step is preferably taken which comprises marking upon the map isograms such as are indicated in Figure 2 by numerals 58, 60, 62, 64, 66 and 68, which are lines marked through approximate positions from which samples presumably would produce equal measured rates when such rates are determined according to the procedure that the plotted data was obtained. It will be evident that such isograms are analogous to the isobars of meteorological maps or the contour lines of topographical maps.

Anomalies in measured rates over the area under investigation are obvious upon visual inspection of the isograms, and such anomalies can be of substantial interpretive importance irrespective of whether such anomalies are of a positive or a negative character.

With further reference to Figure 2, it will be clear that the isograms, particularly isograms 58 and 60, clearly define an anomaly possibly indicative of the presence of an ore body. Clearly, the isograms 58, 60, 62, 64, 66 and 68 make visually apparent variations in the composition of the rock body that can very well warrant in view of the localization of such variations as defined by the isograms 58 and 60 a further investigation perhaps by analysis of samples from such portion of the area by conventional chemical or spectrographic procedures supplemented also perhaps by core drilling.

As stated previously, an anomaly such as shown in Figure 2 can be of interpretive importance whether of a positive or negative nature, that is, the isograms shown in Figure 2 are of interpretive importance irrespective of whether the isograms 58, 60, 64 and 68 represent measured rates of increasing or decreasing values.

The interpretive significance that can be placed upon results obtained by the practice of the invention will be clarified upon reference to Tables I to III presented hereinafter.

With respect to Table I, the sensitivity of gamma-ray measurements of the character defined above with respect to silica sand with and without a minor proportion of a number of metallic compounds was established by a series of tests, the results of such tests being tabulated in Table I. The apparatus used in making the tests was similar to that shown in Figure 1 of the drawings, the vessel 10 being a 55 gallon steel drum filled with water. The pulse-height analyzer 40 was adjusted to pass only pulses having heights corresponding to gamma rays of 4.0 mev. and higher energies. Energy calibration was made by use of the iron neutron-capture gamma ray at 7.64 mev., which produces a prominent pair line at 6.62 mev. The neutron source 16 employed was a 200 milligram radium-beryllium neutron source. A two pound sample was used in each of the tests, and the measured rate of gamma-ray production made with respect to each sample was corrected by subtracting therefrom the rate of gamma rays measured when the toroidal-shaped container 24 was empty, so as correct insofar as was possible for background gamma rays, gamma rays inherently produced in the apparatus, etc.

A corresponding series of tests was made with respect to two pound samples of the usual constituents of igneous rocks. Results of such tests are tabulated in Table II,

which also includes the percentage by weight of such rock components in average igneous rock.

Based upon the assumption that the counting rate obtained as in the tests above is proportional to the amount of the particular element under consideration present, and upon the further assumption that the counting rate is proportional to the neutron-gamma cross section of the particular element for thermal neutrons and inversely proportional to the molecular weight of the compound of the element, the expected count of a number of elements has been predicted. Such predicted counts are tabulated in Table III presented hereinafter with such predicted values being labeled as "expected" counts. The basis for the predicted counts consists of the assumptions mentioned previously correlated with the response of chlorine which was used as a standard of comparison.

The "expected" counting rate should be at least for the most part within a factor of two or three of the actual counting rate. Also included in Table III is the actual observed counting rates for the listed compounds for purposes of comparison of the "expected" counting rate to the actually observed counting rate. Inasmuch as the gamma radiation from heavy nuclei tends to be softer than that from light nuclei, the "expected" counting rates for elements having atomic numbers above 30 have been arbitrarily reduced in Table III by a factor of 2.

TABLE I

Neutron-capture gamma ray net integral count above 4.0 mev. pulse height

| Composition, Percent by Weight |                                  | Net Counts per Minute with Probable Error |
|--------------------------------|----------------------------------|-------------------------------------------|
| Sand <sup>a</sup>              | Other                            |                                           |
| 100                            | 100 Marble Chips <sup>b</sup>    | 111±8                                     |
| 98                             | 2 Fe <sub>2</sub> O <sub>3</sub> | 122±6                                     |
| 98                             | 2 V <sub>2</sub> O <sub>5</sub>  | 144±7                                     |
| 98                             | 2 TiO <sub>2</sub>               | 155±7                                     |
| 98                             | 2 WO <sub>3</sub>                | 164±7                                     |
| 98                             | 2 MnO <sup>c</sup>               | 140±7                                     |
| 98                             | 2 Ag <sub>2</sub> O <sup>d</sup> | 203±10                                    |
| 98                             | 2 HgO                            | 218±7                                     |
| 98                             | 2 Cl <sup>e</sup>                | 550±10                                    |
| 98                             |                                  | 667±11                                    |

<sup>a</sup> Ottawa silica sand (essentially pure silica—SiO<sub>2</sub>).

<sup>b</sup> Essentially pure calcite.

<sup>c</sup> As MnO<sub>2</sub>.

<sup>d</sup> As AgNO<sub>3</sub>.

<sup>e</sup> As C<sub>2</sub>Cl<sub>6</sub>.

TABLE II

Neutron-capture gamma ray net integral count above 4.0 mev. pulse height

| Substance                      | Percentage by Weight Present in Average Igneous Rock <sup>a</sup> | Net Counts per Minute with Probable Error |
|--------------------------------|-------------------------------------------------------------------|-------------------------------------------|
| SiO <sub>2</sub>               | 59.14                                                             | 122±6.                                    |
| TiO <sub>2</sub>               | 1.05                                                              | 2,440±30.                                 |
| Al <sub>2</sub> O <sub>3</sub> | 15.34                                                             | 200±13.                                   |
| Fe <sub>2</sub> O <sub>3</sub> | 3.08                                                              | 1,000±20.                                 |
| FeO <sup>b</sup>               | 3.80                                                              | 1,110±25.                                 |
| MgO <sup>c</sup>               | 3.49                                                              | 55±9.                                     |
| CaO <sup>d</sup>               | 5.08                                                              | 198±14.                                   |
| Na <sub>2</sub> O <sup>e</sup> | 3.84                                                              | 322±24.                                   |
| K <sub>2</sub> O <sup>f</sup>  | 3.13                                                              | 1,030±27.                                 |
| H <sub>2</sub> O               | 1.15                                                              | O (estimated).                            |
| P <sub>2</sub> O <sub>5</sub>  | 0.30                                                              | negligible (estimated).                   |
| SO <sub>3</sub> <sup>g</sup>   |                                                                   | 163±8.                                    |
| S                              |                                                                   | 407±20.                                   |
| Cl <sup>h</sup>                |                                                                   | 27,500±700.                               |

<sup>a</sup> After Clark; from Pettijohn, Sedimentary Rocks, p. 82; published by Harper and Brothers.

<sup>b</sup> As Fe<sub>2</sub>O<sub>3</sub>.

<sup>c</sup> As Mg.

<sup>d</sup> As CaCO<sub>3</sub>.

<sup>e</sup> As Na<sub>2</sub>CO<sub>3</sub>.

<sup>f</sup> As K<sub>2</sub>CO<sub>3</sub>.

<sup>g</sup> As S.

<sup>h</sup> Estimate based on last item of Table I.

TABLE III

"Expected" and observed counting rates above 4 mev. for two-pound samples of various elements and oxides

| Atomic Number | Compound or Element            | Counts per Minute |          |
|---------------|--------------------------------|-------------------|----------|
|               |                                | "Expected"        | Observed |
| 1             | H or H <sub>2</sub> O          | a 0               |          |
| 3             | Li <sub>2</sub> O              | 68                |          |
| 4             | BeO                            | 11                |          |
| 5             | B <sub>2</sub> O <sub>3</sub>  | <35               |          |
| 6             | CO <sub>2</sub>                | 3                 |          |
| 7             | N                              | 220               |          |
| 8             | O                              | <4                |          |
| 9             | F                              | 15                |          |
| 11            | Na <sub>2</sub> O              | 490               | 322      |
| 12            | MgO                            | 24                | 55       |
| 13            | Al <sub>2</sub> O <sub>3</sub> | 130               | 200      |
| 14            | SiO <sub>2</sub>               | 82                | 122      |
| 15            | P                              | 190               |          |
| 16            | S                              | 470               | 407      |
| 17            | Cl                             | b 27,500          | 27,500   |
| 19            | K <sub>2</sub> O               | 1,300             | 1,030    |
| 20            | CaO                            | 240               | 198      |
| 21            | Sc <sub>2</sub> O <sub>3</sub> | 5,800             |          |
| 22            | TiO <sub>2</sub>               | 2,200             | 2,440    |
| 23            | VO <sub>2</sub>                | 1,800             |          |
| 24            | Cr <sub>2</sub> O <sub>3</sub> | 1,200             |          |
| 25            | MnO                            | 5,500             | 4,000    |
| 26            | Fe <sub>2</sub> O <sub>3</sub> | 940               | 1,000    |
| 27            | Co <sub>2</sub> O <sub>3</sub> | 13,000            |          |
| 28            | Ni <sub>2</sub> O <sub>3</sub> | 1,700             |          |
| 29            | CuO                            | 1,400             |          |
| 30            | ZnO                            | 400               |          |
| 31            | Ga <sub>2</sub> O <sub>3</sub> | 490               |          |
| 32            | GeO <sub>2</sub>               | 350               |          |
| 33            | As <sub>2</sub> O <sub>3</sub> | 640               |          |
| 34            | SeO <sub>2</sub>               | 1,600             |          |
| 35            | Br                             | 1,300             |          |
| 37            | Rb <sub>2</sub> O              | 120               |          |
| 38            | SrO                            | 170               |          |
| 39            | Y <sub>2</sub> O <sub>3</sub>  | 190               |          |
| 40            | ZrO <sub>2</sub>               | c 20              |          |
| 41            | Nb <sub>2</sub> O <sub>5</sub> | 140               |          |
| 42            | MoO <sub>3</sub>               | 260               |          |
| 44            | RuO <sub>2</sub>               | 280               |          |
| 45            | Rh <sub>2</sub> O <sub>3</sub> | 18,000            |          |
| 46            | PdO                            | 13,000            |          |
| 47            | Ag <sub>2</sub> O              | 8,000             | 4,900    |
| 48            | CdO                            | 290,000           |          |
| 49            | In <sub>2</sub> O <sub>3</sub> | 21,000            |          |
| 50            | SnO <sub>2</sub>               | 70                |          |
| 51            | Sb <sub>2</sub> O <sub>3</sub> | 680               |          |
| 52            | TeO <sub>2</sub>               | 440               |          |
| 53            | I                              | 820               |          |
| 55            | Cs <sub>2</sub> O              | 3,200             |          |
| 56            | BaO                            | 120               |          |
| 57            | La <sub>2</sub> O <sub>3</sub> | 850               |          |
| 58            | Ce <sub>2</sub> O <sub>3</sub> | 70                |          |
| 59            | Pr <sub>2</sub> O <sub>3</sub> | 1,000             |          |
| 60            | Nd <sub>2</sub> O <sub>3</sub> | 4,000             |          |
| 62            | Sm <sub>2</sub> O <sub>3</sub> | 580,000           |          |
| 63            | Eu <sub>2</sub> O <sub>3</sub> | 400,000           |          |
| 64            | Gd <sub>2</sub> O <sub>3</sub> | 3,800,000         |          |
| 65            | Tb <sub>2</sub> O <sub>3</sub> | 3,700             |          |
| 66            | Dy <sub>2</sub> O <sub>3</sub> | 91,000            |          |
| 67            | Ho <sub>2</sub> O <sub>3</sub> | 5,200             |          |
| 68            | Er <sub>2</sub> O <sub>3</sub> | 13,000            |          |
| 69            | Tm <sub>2</sub> O <sub>3</sub> | 9,300             |          |
| 70            | Yb <sub>2</sub> O <sub>3</sub> | 2,800             |          |
| 71            | Lu <sub>2</sub> O <sub>3</sub> | 8,400             |          |
| 72            | HfO <sub>2</sub>               | 8,400             |          |
| 73            | Ta <sub>2</sub> O <sub>5</sub> | 1,500             |          |
| 74            | WO <sub>3</sub>                | 1,300             | 3,200    |
| 75            | ReO <sub>2</sub>               | 5,900             |          |
| 76            | OsO <sub>2</sub>               | 1,000             |          |
| 77            | IrO <sub>2</sub>               | 30,000            |          |
| 78            | PtO <sub>2</sub>               | 550               |          |
| 79            | Au <sub>2</sub> O <sub>3</sub> | 6,600             |          |
| 80            | HgO                            | 27,000            | 21,500   |
| 81            | Tl <sub>2</sub> O <sub>3</sub> | 220               |          |
| 82            | PbO                            | 12                |          |
| 83            | Bi <sub>2</sub> O <sub>3</sub> | 2                 |          |
| 90            | ThO <sub>2</sub>               | 350               |          |
| 92            | UO <sub>2</sub>                | 110               |          |

a Gamma rays too soft to detect by spectrometer set to record only pulses above 4 mev.

b Used as standard of comparison for computing "expected" counts.

c Usually occurs with three percent HfO<sub>2</sub>, the combination having an "expected" count of 350.

It will be noted upon inspection of Table I that silica sand and marble chips produce gamma rays respectively at rates of about 111 and 112, whereas sand including only a minor percentage of the listed metallic compounds or chlorine produces gamma rays at substantially higher rates.

Upon reference to Table II, it will be noted that rela-

tively very high counting rates were obtained with respect to compounds of titanium, iron, sodium, potassium, sulfur, and chlorine, while the counting rate associated with a magnesium compound is particularly low,

Based upon the assumption that the counting rate of a rock specimen of known composition could be computed by multiplying the fractional amount of each constituent present by the counting rate attributable to such a constituent, such as those given in Table II and adding the products, it was predicted that an artificial sample of igneous rock prepared by mixing the substances listed in Table II, with the exception of H<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub>, in the amounts given for average igneous rock would have a counting rate of 259±6. The actual rate of gamma-ray production was counted at 260±9, which agrees exceedingly well with the predicted counting rate. Accordingly, a variation in the composition of an igneous rock with respect to any of the constituents listed in Table II other than silicon, calcium, aluminum, and phosphorus will produce a markedly different counting rate that would constitute an anomaly with respect to the counting rate of an igneous rock more closely representing an average specimen thereof.

Upon consideration of the "expected" counting rate values tabulated in Table III, it will be evident that much greater counting rate differences can be expected from those shown in Tables I and II upon the inclusion in the samples various other elements to which the above-described method of analysis is extremely sensitive. Among such elements to which the method is extremely sensitive are some of the rare earths, notably samarium, europium, gadolinium, and dysprosium. It is estimated that the presence of as little gadolinium as 0.0005 percent would account for a difference in counting rate of about 40 counts per minute. It is also computed that as little as 0.008 percent of europium would cause a corresponding difference in counting rate. Similarly, a very small concentration of cadmium will account for a large difference of counting rate.

The "expected" counting rates tabulated in Table III are of value in interpreting the results obtained upon correlating measured rates with respect to the locations from which samples of rock are obtained.

Assuming that the isograms of Figure 2 pertain to measured rates of gamma rays having energies in excess of 2.23 and preferably in excess of about 3 to 4 mev., and further assuming that the anomaly is of a positive character (isogram 58 representing measured rate values higher than those of isogram 60), the same can be interpreted as probably defining a zone or area of rock wherein the naturally occurring nuclei of one or more of the following elements occurs in greater abundance than in adjacent parts of the rock body:

chlorine, sulfur, sodium, potassium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, molybdenum, silver, cadmium, tantalum, tungsten, gold, mercury, samarium, europium, gadolinium, dysprosium, and others. This is true for the reason that each of such elements will produce gamma rays of the above-specified

energy range at a substantially greater rate than will the major metallic constituents of igneous or metamorphic rocks, namely, silicon, calcium, and aluminum, as well as the usual major nonmetallic constituents, oxygen and carbon. It should be noted that the usual major metallic constituents, silicon, calcium, and aluminum are similar in their rate of production of gamma rays having energies of the specified range upon being subjected to slow neutrons. Accordingly, the elements silicon, calcium, and aluminum provide a relatively constant background upon which the relatively more positive or alteration signal of the above-listed elements can be said to ride. It should also be noted that the usual major nonmetallic constituents, oxygen and carbon, are virtually nil in their response to a flux of slow neutrons insofar as the pro-

duction of gamma rays of the above-specified energy range at a substantially greater rate than will the major metallic constituents of igneous or metamorphic rocks, namely, silicon, calcium, and aluminum, as well as the usual major nonmetallic constituents, oxygen and carbon. It should be noted that the usual major nonmetallic constituents, oxygen and carbon, are virtually nil in their response to a flux of slow neutrons insofar as the pro-

duction of gamma rays of the above-specified energy range at a substantially greater rate than will the major metallic constituents of igneous or metamorphic rocks, namely, silicon, calcium, and aluminum, as well as the usual major nonmetallic constituents, oxygen and carbon. It should be noted that the usual major nonmetallic constituents, oxygen and carbon, are virtually nil in their response to a flux of slow neutrons insofar as the pro-

duction of gamma rays of the specified energy range is concerned.

It should also be mentioned that while hydrogen captures thermal neutrons to produce gamma rays, such gamma rays are of 2.23 mev. energy and are therefore excluded to a substantial extent in the measured rates since the latter apply only to gamma rays possessing energies in excess of at least 2.23 and preferably in excess of about 3 to 4 mev. Variations in the amount of hydrogen in igneous or metamorphic rocks is often not associated with ore bodies. The magnitude of the interference due to hydrogen if the neutron-capture gamma rays thereof are not substantially excluded would be such as to mask substantially and probably obscure composition variations of much greater fundamental or interpretive importance. It is primarily for these reasons that gamma rays having energies of 2.23 mev. are excluded from the measured rates so as to omit interference by the slow neutron response of hydrogen.

Most, if not all, direct interference by hydrogen can be eliminated by measuring the gamma rays of the specified range of values. As igneous and metamorphic rocks contain only minor quantities of hydrogen, any secondary interference due to displacement or dilution of other rock constituents is relatively small. Hydrogen in the form of water or in the form of water of crystallization is present to a much greater and variable extent in sedimentary rocks, and it is for this and other reasons that the method of this invention is ordinarily of vastly more value in investigating igneous and metamorphic rock bodies than sedimentary rock bodies.

From the above list of elements especially productive of positive anomalies, it will be noted that all of such elements are metals with the exception of chlorine and sulfur. That sulfur and chlorine will produce positive anomalies does not mitigate substantially against a positive anomaly being interpreted as indicating an area of greater mineralization of the igneous rocks, for the reason that the presence of a higher concentration of either of such elements can indicate the presence of a metallic compound, the metallic constituent of which might in itself be relatively incapable of indicating its presence by a positive anomaly, particularly when such element is in a small concentration. Examples of such metallic elements are lead, bismuth, and zinc. Thus, for example, a positive anomaly due primarily to sulfur could be due to galena and therefore be indicative of the possible presence of galena.

On the other hand, negative anomalies can be of considerable significance as to the degree of mineralization of a rock body. For example, a mineralized rock body of a nature containing relatively high concentrations of hydrogen, lithium, beryllium, boron, carbon, fluorine, magnesium, zirconium, tin, cerium, lead, oxygen or bismuth will result in negative anomalies for the reason that these elements either have exceptionally low neutron absorption cross sections, or are not productive of gamma rays having energies in excess of about 3 to 4 mev. to as great an extent as silicon, calcium, and aluminum during such absorption.

In view of the foregoing, adjustment of the pulse-height analyzer 40 to pass pulse heights corresponding to only those gamma rays having energies in excess of at least 2.23 and preferably in excess of about 3 to 4 mev. produces results interpretable generally with respect to the degree of alteration and particularly of the degree of mineralization of a rocky body according to the above-described method.

It is clear then that in the great majority of cases, mineralization of igneous and metamorphic rock bodies will produce a positive counting rate anomaly. The sensitivity to some elements is particularly striking. For example, a few parts per million of certain of the rare earths will produce a detectable increase in counting rate. These quantities are far beyond the limit of de-

tection by ordinary chemical or spectrographic methods, and needless to say, visual detection by a "prospector."

A few hundredths of one percent of any elements whose "expected" counting rate as set forth in Table III exceeds 10,000 would produce a noticeable increase or anomaly in counting rate. These elements include chlorine, cobalt, rhodium, palladium, cadmium, indium, samarium, europium, gadolinium, dysprosium, erbium, iridium, and mercury; and if "expected" counting rates of 5,000 rather than 10,000 are considered, also included in the list would be scandium, manganese, silver, holmium, thallium, lutetium, hafnium, rhenium, and gold. Also, it will be observed that even when present in amounts of only a few tenths of one percent potassium, titanium, vanadium, chromium, iron, nickel, copper, selenium, bromine, cesium, praseodymium, terbium, tantalum, tungsten, and osmium would give a noticeable increase in counting rate above the background of the counting rate of the usual silicon, calcium and aluminum bearing compounds present in igneous or metamorphic rocks.

It is also within the province of the invention that the method can be employed in a more restrictive manner so that anomalies with respect to the concentration of a particular class of atomic nuclei can be detected. Such more specific application of the principles of the invention is based upon the fact that certain elements, such as titanium, iron, chlorine, cobalt, and manganese; especially iron and manganese, produce upon being subjected to a slow neutron flux neutron-capture gamma rays having particularly distinctive energies. For example, the method can be made substantially specific with respect to locating anomalies in the concentration of titanium in rocks by adjusting, as will be understood by those skilled in the art, the pulse-height analyzer 40 or a combination of such analyzers or equivalent discriminators, not shown, to pass only those pulses having heights corresponding to gamma rays having energies of any one or all of the values 6.76 mev., and 6.41 mev.; of iron in rocks by adjusting the pulse-height analyzer 40 to pass only those pulses corresponding to gamma rays having energies of any one or all of the values 6.0, 7.64, and 9.3 mev.; of chlorine in rocks by adjusting the pulse-height analyzer 40 to pass only those pulses corresponding to gamma rays having energies of any one or all of the values 5.01, 6.12, and 7.77 mev.; of cobalt in rocks by adjusting the pulse-height analyzer 40 to pass only those pulses corresponding to gamma rays having energies of any one or all of the values 6.5-6.9, 7.20, and 7.49 mev.; of manganese in rocks by adjusting the pulse-height analyzer 40 to pass only those pulses corresponding to gamma rays having energies of any one or all of the values 6.78, 7.05, and 7.26 mev. In an analogous manner, the pulse-height analyzer 40 or analyzers can be adjusted to pass only those pulses corresponding to gamma rays having energies corresponding to one or more characteristic gamma rays of any selected element, so as to render the method preferentially sensitive to the selected element, as will be appreciated by those skilled in the art.

As in the case of the first-described embodiment of the invention, the measured counting rates where the pulse-height analyzer 40 is adjusted to obtain a response preferentially dependent upon the concentration of a selected element is correlated with the positions from which the samples were initially procured. Such procedure will usually make clearly apparent anomalies in the concentration of the selected element. However, it should be noted that in the practice of this specific embodiment of the invention, normally only positive anomalies will be of special interest.

To those skilled in the art, it will be apparent that the practice of the invention can be accomplished in the field, that is, the samples of rock can be obtained and tested on location, as the apparatus can be easily trans-

ported by a small vehicle or diminutive forms thereof can be transported by men, particularly where water of suitable character is locally available. Ordinarily, the method will be practiced in portable field laboratories situated at or adjacent the area under investigation. However, in some cases the method will be practiced in a centrally located permanent laboratory probably removed from the area under examination.

The principles of the subject invention are believed especially well suited in exploration programs as an intermediate step between the conduction of reconnaissance mapping and of gravitational or magnetic surveys, as with the airborne magnetometer, and the much more intensive and localized surveying methods such as core drilling.

It is to be particularly observed that the detection of anomalies caused by elements of relatively slight commercial importance can nevertheless be of substantial importance insofar as geological interpretation of such anomalies is concerned, especially with a view to geological interpretations relating to alteration processes that can have resulted in or be related to ore deposits. For example, sodium concentration is important in the delineation of some types of metasomatic halos in rocks, since sodium is quite commonly added in amounts of one to 10 percent during extensive hydrothermal or deuteric alteration which is often related to ore deposition.

The illustrated embodiment and described modes of practice of the invention are readily susceptible to numerous variations without departing from the spirit of the invention. For example, inasmuch as the rare elements (gold, silver, mercury, rare earths, etc.) tend to be strong neutron absorbers, and since strong neutron absorbers tend to produce neutron-gamma spectra characterized by relatively low energy gamma rays closely spaced energywise (in the range of 3 to 5 mev.); the pulse-height analyzer can be adjusted so as to pass solely the range of pulse heights corresponding to the closely spaced low energy gamma rays characteristic of the listed elements, so that the counting rate tends to be more of a function of the concentration of such listed elements as a whole. In a similar manner, since the relatively more frequent elements of distinct commercial value (nickel, chromium, cobalt, manganese, titanium, copper, zinc, and even cadmium and tungsten) produce neutron-capture gamma rays in a relatively higher energy range, say 5 mev. and above, which even though resolution of such gamma rays may if at all be resolved with considerable difficulty, some basis for grouping as a whole is available upon corresponding adjustment of the range of heights of pulses counted.

Upon the measured rates being plotted, inspection of the map can reveal variations in plotted rates and serve to identify such variations with particular geographical areas shown on the map; however, an additional optional step is preferably taken which comprises marking upon the map isograms such as are indicated in Figure 2 by numerals 58, 60, 62, and 64, which are lines marked through positions from which samples would produce equal measured rates when such rates are determined according to the procedure that the plotted data were obtained. It will be evident that such isograms are analogous to the isobars of meteorological maps or the contour lines of topographical maps.

Anomalies in measured rates over the area under investigation are obvious upon visual inspection of the isograms, and such anomalies can be of substantial interpretive importance irrespective of whether such anomalies are of a positive or negative character, as stated previously.

The preceding will make it evident that composition anomalies with respect to any one of the majority of elements can be expected to be detectable as an anomaly in the practice of the invention. Anomalies detected by

measuring only gamma rays having more than at least 2.23 and preferably above about 3 to 4 mev. will be relatively minor for relatively large variations in the concentration of silicon, calcium, and aluminum, which indeed is an advantage for the reason that composition anomalies with respect to such elements can be expected to occur quite frequently with only a minor proportion of such anomalies being associated with ore bodies. Thus, the relative insensitiveness of the method with respect to composition anomalies of silicon, calcium, and aluminum is a marked advantage for the reason that a higher proportion of anomalies detected by the method can be expected to be related to ore bodies. With the exception of the elements silicon, calcium, and aluminum, there are relatively very few elements with respect to which composition anomalies will result in little likelihood of detection according to this embodiment of the invention. For all practical purposes, only the elements rubidium, barium, and uranium fall into this classification. Even here, composition anomalies can possibly be detected by limiting the detection of gamma rays to selected gamma-ray energy levels.

In the method wherein gamma rays having energies in excess of 2.23 and preferably in excess of about 3 to 4 mev. are measured, it will be understood that the precise discrimination level is not sharply critical, it being understood that the level is selected so as to substantially exclude from the count gamma rays produced by neutron capture in hydrogen, while at the same time including in the measurement neutron-capture gamma rays produced by other elements to the fullest possible extent. Also, while the method has been described as including in the measurement all gamma rays having energies in excess of the discrimination level selected to exclude the effects of hydrogen, it will be evident that an upper limit, say of about 10 mev., can be set, although ordinarily no useful purpose would be served thereby for the reason that most, if not all, of the neutron-capture gamma rays produced in the samples would have lesser values. For example, though not preferred, an upper limit of about 6 mev. can be set, as the upper limit of the energy of the gamma rays to be measured where it is desired to reduce somewhat the sensitivity of the method to the effects of composition anomalies with respect to chlorine; however, such limitation as to the energies of gamma rays detected is not desirable for the reason that the effects of composition anomalies of other elements, such as iron, manganese, and potassium would be reduced.

It will be evident to those skilled in the art that the described preferred modes of and apparatus for practicing the invention are subject to numerous variations without departing from the spirit of the invention. For example, means other than those shown in Figure 1 can be employed for producing slow neutrons and for detecting and measuring gamma rays. For instance, any form of gamma-ray detector that makes possible differentiation between gamma rays of different energies can be employed, such as a proportional counter of conventional character, though the illustrated and described scintillation counter is preferred for reasons of sensitivity and resolution of gamma-ray energy levels. Also, other means of recording or making visually apparent the rate at which gamma rays passed by the pulse-height analyzer (or discriminator) can be employed, such as the oscilloscope, mask and film apparatus disclosed in application Serial No. 400,956, entitled "Logging of Energy Distribution," filed December 29, 1953, by Charles W. Tittle, though of course it would not be necessary to provide means for moving the film. Correlation in this case can be made by visually comparing exposed and developed films.

Notwithstanding the fact that the invention has been described in very considerable detail, the invention is not



to be thereby inferred to be narrow in scope, attention being directed to the appended claims in order to ascertain the actual scope of the invention.

We claim:

1. A method for detecting an anomaly in the degree of alteration of igneous and metamorphic rock bodies which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having a predetermined range of energy levels, and correlating the measured rates with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the degree of alteration of igneous and metamorphic rock bodies.

2. A method for detecting an anomaly in the degree of alteration of igneous and metamorphic rock bodies which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having energies in excess of 2.23, and correlating the measured rates with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the degree of alteration of igneous and metamorphic rock bodies.

3. A method for detecting an anomaly in the degree of alteration of igneous and metamorphic rock bodies which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having energies in excess of about 3 mev., and correlating the measured rates with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the degree of alteration of igneous and metamorphic rock bodies.

4. A method for detecting an anomaly in the degree of alteration of igneous and metamorphic rock bodies which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having energies in excess of about 4 mev., and correlating the measured rates with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the degree of alteration of igneous and metamorphic rock bodies.

5. A method for detecting an anomaly in the degree of alteration of igneous and metamorphic rock bodies which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having a predetermined range of energy levels, plotting the measured rates upon a map corresponding to the area under investigation, and also marking isograms of the plotted rate values upon the map.

6. A method for detecting an anomaly in the degree of alteration of igneous and metamorphic rock bodies which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having energies in excess of a selected energy level, and concurrently with the sample being subjected to the flux of slow neutrons measuring the rate at which gamma rays are produced by the sample having energies in excess of an energy level

higher than said selected energy level, and correlating the difference between the measured rates made with respect to each sample with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the degree of alteration of igneous and metamorphic rock bodies.

7. A method for detecting an anomaly in the concentration of nuclei of naturally occurring titanium in an igneous or metamorphic rock body which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having energies of about 6.76 mev., and correlating the measured rates with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the concentration of nuclei of naturally occurring titanium in an igneous or metamorphic rock body.

8. A method for detecting an anomaly in the concentration of nuclei of naturally occurring iron in an igneous or metamorphic rock body which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having energies of about 7.64 mev., and correlating the measured rates with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the concentration of nuclei of naturally occurring iron in an igneous or metamorphic rock body.

9. A method for detecting an anomaly in the concentration of nuclei of naturally occurring chlorine in an igneous or metamorphic rock body which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having energies selected from the group consisting of about 7.77 mev. and about 7.42 mev., and correlating the measured rates with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the concentration of nuclei of naturally occurring chlorine in an igneous or metamorphic rock body.

10. A method for detecting an anomaly in the concentration of nuclei of naturally occurring cobalt in an igneous or metamorphic rock body which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having energies of about 7.20 mev., and correlating the measured rates with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the concentration of nuclei of naturally occurring cobalt in an igneous or metamorphic rock body.

11. A method for detecting an anomaly in the concentration of nuclei of naturally occurring manganese in an igneous or metamorphic rock body which comprises procuring equal weight samples of the rock body from spaced points over an area to be investigated, identically subjecting each sample to a fixed slow neutron flux and concurrently measuring the rate at which gamma rays are produced by the sample having energies of about 7.26 mev., and correlating the measured rates with the locations of the points from which the samples were procured to establish a relationship useful in the detection of an anomaly in the concentration of nuclei of naturally occurring manganese in an igneous or metamorphic rock body.

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