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Annotated Bibliography of Gamma-Ray Methods Applied to Gold Exploration

by

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INTRODUCTION

Gamma-ray methods in base- and precious-metals exploration have had very little use in the west, judging from published material. Yet, there is ample geochemical evidence that the method could be an important tool for exploration and mine development. Boyle (1979, p. 481), in his classic paper on gold, lists only nine references to gamma-ray techniques, eight in the Russian literature, and only one study from Canada. Preliminary studies by the U.S. Geological Survey have shown that radioelement measurements employing gamma-ray spectrometers have promise as a tool in base- and precious-metal exploration. This technique is a cost-effective and rapid means for geochemical mapping of the radioactive elements potassium, uranium, and thorium. Because the measurements may be made by airborne instruments, they have applicability to regional and district scale exploration programs, as well as deposit scale work.

Potassium haloes around base- and precious-metal deposits are well known from standard geochemical studies. Potassium metasomatism associated with mineralizing systems can double the potassium concentration of even high-potassium host rocks. Boyle (1979) cites numerous examples of potassium haloes, defined by standard geochemical methods, surrounding gold mineralization in various types of deposits. Because potassium flooding usually occurs throughout a much larger volume of host rock than economic gold mineralization, potassium gives a broader and more easily detected target for exploration. Uranium often is enriched in gold deposits; the Witwatersrand District, S. Africa (Boyle, 1979, 1989) and Central City, Colorado (Sims, and others, 1963) are examples from genetically distinct types of deposits where uranium is associated with gold. Uranium, however, is fairly mobile in an oxidizing environment and not completely predictable as a pathfinder element. Thorium is generally considered very immobile, although Tammemagi and Smith (1975) report that kaolinized granites in the southwest part of England are depleted in uranium and thorium relative to fresh granite. They suggest that this may be due to weathering. Boyle (1982) notes that thorium forms a number of organic and inorganic complexes that can make the element relatively soluble and mobile under certain natural conditions. He also notes that thorium complexes are generally more stable than those of uranium. However, the stability is poorly known. Thorium may also be mobile as a colloid (Boyle, 1982). There does not appear to be a large amount of data regarding thorium mobility or distribution in base and precious-metal systems.

PURPOSE AND SCOPE

This annotated bibliography was assembled as part of ongoing studies of geophysical methods that might be applied to precious-metal exploration and which are also directed at the geophysical characterization of various genetic types of ore deposits. The paucity of references makes this an easy task, although there are probably numerous references in the grey literature (theses, open-file reports, publications of limited distribution, etc.) that were not found. Although some of the references cited are from the grey

literature, no significant attempt has been made to locate such literature. It is hoped that this bibliography will point out the need for additional work, as well as point out opportunities.

Starting with the nine references of Boyle, a computer based routine was designed to search for additional references in March of 1988. Searches were made of the American Geological Institute GeoRef data base; American Chemical Society, Chemical Abstracts data base; and Geosystems, Geoarchive data base. The search was made for references published from 1950 in all languages. These searches turned up 12, 7, and 8 references respectively for a total of 27 references. Only one reference (Mwenifumbo and others, 1983) was found in all three data bases. Ten of the references were not germane to the subject.

References found in the data base search provided additional literature that was examined. This combined with the authors' knowledge of some grey literature gave a total of 46 citations for the bibliography.

In most cases the summary of the references was prepared by the authors of the bibliography. In a few cases the english abstract prepared by the authors of the referenced paper is used, and is indicated by "author's abstract" following the reference. Where editorial comments are made by the authors of this bibliography they are given by square brackets [ ].

SUMMARY

In the bibliography, the earliest reference found is Gross, 1952, followed by Sekine and Obi, 1960. The latter report no anomalies at the Nojiri mine, Japan. This may result from a lack of sufficient sensitivity in the instrument they used. Nothing more was found until 1970 when three Russian papers appear, Krendelev (1970), Ostrovskiy and others, (1970) and Zashchinskii and others (1970). These papers describe both airborne and ground measurements, indicating that the use of gamma-ray spectrometry was a well established tool in gold exploration in the USSR by this time. Thereafter papers appear in the Russian literature at a rate of about 1 per year. In all, half of the references, 23, are from the Russian literature.

In looking over the references it is clear that observed radioactive signatures of gold deposits tend to be quite variable. Potassium generally is the most useful pathfinder element because of its increase in altered rock surrounding the deposits forming an easily detected halo. In some cases (for example, Savosin and others, 1977) no potassium halo is reported. In some of the references sufficient detail is given to show radioelement distribution between ore and altered host rock. Where gold is hosted within quartz veins, typically the vein rock is low in the radioelements, but the hydrothermally altered host rock usually will have a distinct radioelement signature useful for exploration.

Next to elevated potassium values in hydrothermal alteration haloes adjacent to deposits, the most frequently cited radioelement characteristic is thorium depletion within the altered rock. This relates to the "antagonism" between potassium and thorium reported by Ostrovskiy (1975) and some other Russian authors. What the Russian authors mean by the "antagonism" between potassium and thorium is a depletion of thorium they note in some deposits

that accompanies an increase in potassium. However, in a number of deposits thorium is reported as increased within the ore zone or the alteration envelope. This suggests that thorium may be relatively mobile within the hydrothermal environment associated with some of the deposits. Boyle (1979, p. 481) suggests that pervasive alteration may remove uranium, thorium, and radium leaving negative aureoles.

Uranium increases are reported about as often as decreases in association with gold deposits. Grebenchikov and others (1977) identify 5 separate radioelement signatures associated with 5 types of gold deposits where the signatures appear to be related to a particular type of hydrothermal alteration assemblage. In a few cases radioelement content has been directly related to ore grade. Barreto (1974) notes a direct correlation of ore grade with total count radioactivity; Balykin and others (1973) note a direct correlation with potassium and uranium; and Krendelev and others (1976) note an inverse correlation with potassium.

From the references abstracted it is clear that no unique radioelement signature can be related to all gold deposits. For any deposit, or group of deposits, the radioelement distribution, at present, needs to be determined empirically, and used as an exploration guide. Unfortunately, the gold deposit type is not given or known for many of the references abstracted, so that no attempt has been made to try to relate radioelement signatures to particular gold deposit models. Clearly, much additional work is required before such characterization can be made.

Kochetkov and others (1987), Vasil'ev and others (1985), and Zlobin and Kurulenko (1981) discuss primarily the radioelement signatures of source rocks related to gold deposits. They note that the total count radioactivity, or thorium and uranium (Kochetkov and others, 1987) contents, are low in comparison to the potassium content in unaltered source rocks. This suggests that gamma-ray spectrometry may be useful in classifying all exposed potential source rocks.

Petrov and others (1972) imply that gamma-ray spectrometry is not useful in exploration for placer gold in the Patom uplands of the USSR.

While searching for references, an interesting indirect technique to find ore deposits high in radioactive minerals was reported by Cull and others (1988). They note that on the Stuart Shelf of south Australia, Tregolona shale that overlies the Olympic Dam deposit acts as a uniform blanket in which thermal gradient measurements can detect the excess heat production due to a 0.08% uranium ore body containing 0.6 gm/ton gold and 6 gm/ton silver.

We believe that examination of this annotated bibliography demonstrates that gamma-ray spectrometry can be a useful tool for exploration of many types of gold deposits, and that it should be considered for inclusion in most exploration programs. However, the geophysicist or geologist using the acquired data, must be aware of the many variables responsible for mobilization and fixing of the chemically distinct radioelements, and take them into account in interpreting the data. We hope that this bibliography will contribute to awareness of the varied radioelement signatures associated with gold mineralization, and contribute to the increased application of gamma-ray spectrometry in minerals exploration in the west.

References not cited in the bibliography

Boyle, R.W., 1982, Geochemical prospecting for thorium and uranium deposits: Developments in Economic Geology, no. 16, Elsevier, 498 p.

Boyle, R.W., 1987, Gold, history and genesis of deposits: Van Nostrand Reinhold, 676 p.

Cull, J.P., Houseman, G.A., Muir, P.R., and Paterson, H.L., 1988, Geothermal signatures and uranium ore deposits on the Stuart Shelf of South Australia: Exploration Geophysics, v. 19, no. 1/2.

Sims, P.K., Drake, A.A., and Tooker, E.W., 1963, Economic geology of the Central City district, Gilpin County, Colorado: U.S. Geolgoical Survey Professional Paper 359, 231 p.

Tammemagi, H. Y., and Smith, N. L., 1975, A radiogeologic study of the granites of SW England: Journal Geological Society, London, v. 131, p. 415-427.

BIBLIOGRAPHY

Balykin, P.A., Boroby'yev, V.I., and Krendelev, F.P., 1973, Gamma-spectrometric measurements of Clarkes of radioactive elements in gold deposits of the schist zone: Doklody Akademii Nauk SSSR, v. 209, no. 1, p. 190-192.

The authors compare results of laboratory and detailed field measurements along a cross-cut where gold distribution values were available from channel sampling. Measurements were made with an SP-3 spectrometer at 240 sites along the cross-cut. The distance between measurement sites is not given. The gold deposit consists of veins and stockworks in Proterozoic quartz-chlorite-sericite phyllite. Small amounts of sulfides, principally pyrite are present in the stockworks. They report that potassium, uranium, and thorium contents are low in the quartz veins, but that all three increase in the phyllite surrounding the veins. They also note that potassium and uranium concentrations correlate directly with gold content, with high values only found in gold-bearing zones. High thorium does not correlate directly with gold values.

Barreto, Pedro Trindade, 1974, Estudos das occurrencias de apatita de Gaviao e da jazida de ouro da Serra de Jacobina (Bahia) por meio de cintilometria e de espectrometria gamma. [Studies of the occurrences of apatite at Gavião and of a gold mine in the Serra de Jacobina, by means of gamma-ray scintillometry and spectrometry]: Thesis, Universidade Federal da Bahia, Salvador, Bahia, Brazil.

Studies at the Canavieras gold mine near the city of Jacobina, Bahia showed highly anomalous uranium and thorium associated with a gold and pyrite bearing horizon in the Serra do Corrego Formation. This is a Witwatersrand type quartz-pebble conglomerate deposit. In the ore zone uranium and thorium reach maximum concentrations of 735 ppm and 172 ppm respectively. Outside of the ore horizon concentrations of uranium and thorium were 2-10 ppm and 4-16 ppm respectively. Potassium was generally low, 0.3-0.9%, in the Serra do Corrego Formation, but could not be measured by gamma-ray methods in the ore horizons with high uranium and thorium. A linear correlation was made between ore grade and total radioactivity count rate. Barreto concludes that gamma-ray spectrometry could be used for exploration. It is interesting to note

that thorium was correlated with apatite at Gaviao, although this is not a gold district.

Berger, B.R., 1980, Geological and geochemical relationships at the Getchell mine and vicinity, Humboldt County, Nevada: Society of Economic Geologists, 1980 Field Conference Field Guide, Reno, Nevada, p. 111-135.

Based on the presence of chemically determined potassium and thallium enrichment in gold ore at the Getchell mine, an airborne magnetic and radioactivity survey was flown for exploration purposes. The presence of thallium, a radioisotope of the thorium-232 decay series, suggested that thorium may have been mobilized. Two plots, Bi^{214}/K^{40} (uranium/potassium) and Tl^{208} (thorium), are shown which indicate a trend along the Getchell fault zone at the mine, but not directly outlining ore. The Bi/K (uranium/potassium) ratio shows a zone of high values offset slightly to the east of the fault zone. The thallium (thorium) map is not as definitive, but highs are observed on or near the fault zone.

Blyumentsev, A.M., Khrust, A.R., and Chepizhnaya, E.A., 1974, Radioaktivnye elementy kak indikatory zolota v effuzivakh [Radioactive elements as indicators of gold in effusives]: Vsesoyuznyi Nauchno-Issledovatel'skii Institut Yadernoi Geofiziki i Geokhimii.

Radioelement investigations are described for two gold deposits in the southern Dzungar region hosted by intermediate to basic volcanic rocks (andesites, dacites, andesitic basalt). Gold is contained within low sulfide quartz and quartz-adularia veins within the volcanics. Gold content is reported to be very irregular and generally not over 10 gram/ton (gm/tn) with maximums of 17-20 gm/t. One figure shows a ground traverse across a deposit, and two figures show results of borehole investigations. The ground traverse shows uranium and thorium are reduced below background over the ore zone with uranium showing the greatest change. Potassium peaks are observed at each side of the ore zone with values exceeding 4%. The borehole data show potassium correlating directly with gold content, and uranium and thorium being reduced in the ore horizon. A table comparing the gold content of selected grades of ore with its uranium content shows that grades of less than 0.02 gm/t average 1.4 ppm uranium while grades greater than 10 gm/t average less than 0.3 ppm U. The authors believe that gamma-ray spectrometry can be effectively used in gold prospecting.

Boyle, R.W., 1979, The geochemistry of gold and its deposits: Geological Survey of Canada Bulletin 280, 584 p.

Referring to potassium enrichment in the wall rock of gold deposits, particularly in basic to intermediate volcanic and intrusive rocks, Boyle suggests that it "should be possible" (pg. 481) to detect high potassic zones which may be related to mineralization by use of gamma-ray methods. He also suggests that hydrothermal systems could have leached uranium, thorium and their daughter products giving a negative haloe. He then summarizes Ostrovskiy and others, 1970, Blyumentsev and others, 1974, Zashchinskii and others, 1970, Portnov and others, 1971, Grebenchikov and others, 1974, Zhokhov and others, 1975, Fel'dman and others, 1975, Krendelev and others, 1976, and Gross, 1952, all of which are included in this bibliography.

Collins, Steve, 1987, The geophysics of the Red Dome Gold mine and surrounding areas [ext. abs.]: Exploration Geophysics, 5th Geophysical Conference, Perth, Australia, v. 18, no. 1/2, extended abstracts, p. 19-20.

Gold mineralization is hosted primarily within a magnetite-garnet skarn adjacent to a rhyolite porphyry intrusion. Weathering of the skarn extends to 150 m depth and ore consists of ferruginous breccia derived from the skarn. The author gives a brief history of geophysical exploration in the Red Dome area and discuss results of gravity, magnetic, IP, and gamma-ray spectrometry measurements at the deposit. The gamma-ray results show high potassium associated with the outcropping porphyry, and weaker but positive potassium anomalies over altered ground. Unexpectedly, high thorium anomalies correlated exactly with known mineralization and revealed a previously unknown area of mineralization. IP is considered effective but expensive, gravity surveys are not considered effective for identifying the breccia because geologic mapping is as effective and cheaper. Magnetics is considered quite effective as the unweathered skarn produces large negative remanent magnetic anomalies. Exploration now relies on airborne magnetic and gamma-ray exploration for regional work followed by their application in ground follow up.

Costa, A.J.M. da, and Byron, C.L., 1988, Evolution of geophysical techniques over various types of archean gold occurrences on the farms Roodepoort and Eersteling, Pietersburg greenstone belt, South Africa [ext. abs.]: Geological Society of Australia, Bicentennial Gold 88, extended abstracts, p. 518-520.

The authors do not show any gamma-ray data. They state that "areas of deep or shallow soil cover were demarcated by radiometrics; anomalous K^{40} readings due to possible feldspar metasomatism were not associated to sulfide mineralization." Mineralization is in Archean greenstone terrain with gold occurring in a highly altered shear zone in quartz-chlorite-talc-carbonate augen schist in association with arsenopyrite.

Cui, L., and Zhang, W., (in press), Application of airborne gamma-ray spectrometry to geologic mapping and nonradioactive mineral prospecting.

This extended abstract uses 3-mile spaced Department of Energy National Uranium Resource Evaluation Program (NURE) data from the Salt Lake City, Utah area to discuss applications of gamma-ray spectrometry to geologic mapping. The authors then briefly discuss the application of gamma-ray spectrometry in gold prospecting in western China. No further identification of the area is given. The geologic setting is described as gold-quartz veins hosted in basalt-diabase units. The basalt bodies are distributed in clusters and along linear zones surrounded by tuffaceous sandstone. An airborne survey, combined magnetic, gamma-ray spectrometry, and electromagnetic, was flown in 1986 in western China at a 250 m line spacing and 70-80 m altitude. No further information is given on the geophysical instrumentation or the airborne platform. The prime objective of the surveys is to identify the basalt bodies. The basalt bodies are stated to be mapped by radioelement low and magnetic anomalies of several 10 to several hundred nT. The authors do not state whether the magnetic anomalies are positive or negative. A thorium contour map is shown with three gold deposits within, or adjacent to, zones of low thorium. The text also states that in the altered zone between the basalt and surrounding rocks radioelement highs are usually seen.

Cunneen, J.P., and Wellman, Peter, 1987, The use of airborne geophysics and ground gravity surveys in understanding the geology of the eastern gold fields of western Australia [ext. abs.]: Exploration Geophysics, 5th Geophysical Conference, Perth, Australia, v. 18, no. 1/2, extended abstracts p. 22-25.

The eastern gold fields is a 350,000 km^2 area of Archean greenstone terrain where a close spacial relationship is noted between gold mineralization in the greenstones and diapiric granitic intrusions. Combined, low level (60 m), and closely spaced (200 m) aeromagnetic and gamma-ray spectrometry are used for regional exploration in this environment. The gamma-ray survey used a 1024 cubic inch crystal, with sampling at 1 second intervals. The author's note only that gamma-ray results delineate high potassium zones related to sericitic alteration and help define lithologic boundaries.

Fel'dman, A.A., Slepnev, P.V., and Kul'kov, B.N., 1975, Primeneniye gamma-spektrometrii pri poiskakh zolotorudnykh mestorozhdenig blizpoverkhnostnogo tipa [Use of gamma spectrometry in prospecting for gold ore deposits near the surface]: Razvedka i Okhrana Nedr, no. 10, p. 59-60.

The authors describe the application of gamma-ray spectrometry to exploration for gold bearing quartz-sulfide veins in an unspecified region of the USSR. The gold mineralization results from hydrothermal alteration of granitic rocks with the localization of the veins along tectonic zones. Ground based measurements were made using an SP-3 spectrometer, but no other details are given for the spectrometer. Ground measurements were made at 20 m intervals and at 5 m intervals to detail anomalous areas. The authors use values of potassium and the ratio uranium + thorium/potassium (U+Th/K) to define areas of mineralization. Gold bearing quartz veins are defined by increased potassium, going to 5% against a background of 2%, and by minima in the ratio (U+Th)/K.

One illustration is presented showing potassium increasing along with gold values across a single vein. Dipole-dipole resistivity profile curves are also shown using an n of 3, and 10 meter? (scale is not given) dipole spacing. The resistivity curves show a 2000 ohm-m background and resistivities greater than 4000 ohm-m at the vein. The authors conclude that gamma-ray spectrometry is an effective technique in the search for near-surface deposits where cover is not in excess of 1.5-2.0 m.

Ferreira, Jorge, 1973, Estudo do thermoluminescencia do quartzito numa zona mineralizado em ouro e uranio (Canavieiras, Jacobina - Bahia) [A study of the thermoluminescence of quartzite in a zone mineralized in gold and uranium (Canavieiras, Jacobina - Bahia)]: Thesis, University Federal da Bahia, Salvador, Bahia, Brazil.

This thesis is principally concerned with thermoluminescence, but gamma-ray profiles were made at the Canavieiras gold mine where gold is directly associated with uranium in paleoplacers. Thermoluminescence of quartzite was directly correlated with uranium as measured by the gamma-ray surveys.

Ferreira, Clemiro; Barreto, Pedro Trindade; Torquato, Joaquin Ferreira, 1979, Reconhecimento gamametrico da regiao central da Bahia e da bacia do Reconcavo [Reconnaissance by γ-spectrometry of the central region of Bahia and the Reconcavo Basin]: Revista Brasileira de Geociencias v. 9, no.4, p. 249-266.

This report contains much of the same information as given by Barreto (1974).

Flanigan, V.J., and Pitkin, J.A., 1978, Airborne gamma-ray spectrometry survey of the Jabal Sayid area, Kingdom of Saudi Arabia: U.S. Geological Survey, Saudi Arabian Project Report 247, 34 p.

This report discusses an airborne gamma-ray spectrometry survey of 2750 km^2 on the Precambrian shield of Saudi Arabia. The surveyed area includes the ancient gold deposit at Mahd adh Dhahab associated with intrusive rhyolites. A radioactivity anomaly showing high potassium and uranium and potassium/uranium and potassium/thorium ratios of 1.6:1 and 16.3:1 respectively, were found over the rhyolitic unit at Mahd adh Dhahab. They suggest this pattern might be used for prospecting for other similar deposits in the area.

Grebenchikov, A.M., Khrust, A.R., and Chepizhnaya, E.A., 1974, Radigeokhimicheskiye osobennosti blizpoverkhnostnogo zolotorudnogo mestorozhdeniya i ikh poiskovoge znacheniye [Radiogeochemical characteristics of near surface gold-ore deposits and their prospecting value]: Izvestiya Vysshikh Uchebnykh Zavedeniy, Geologiya i Razvedka, v. 17, no. 10, p. 44-49.

This paper cites the papers of Ostrovskiy (1975;-originally published in Russian in 1973), Ostrovskiy and others (1970), and others, of the use of airborne gamma-ray spectrometry in prospecting for base- and precious-metal deposits. This paper continues the characterization of the distribution of uranium, thorium, potassium, and sodium in the vicinity of gold-bearing quartz veins within late Paleozoic tuffs, andesites and andesitic dacite. Element determinations were made by luminescence methods for uranium, photometric for sodium and radioactivity for thorium and potassium, on rock samples from outcrop and drill holes. Gold mineralization is contained within adularia-quartz, sphalerite-quartz and molybdenite-quartz veins that show distinct alteration haloes adjacent to the veins. Quartz-carbonate-hydromica metasomatism is found adjacent to the vein followed by carbonate-hydromica and propylitic alteration. Uranium and thorium are found to decrease as the vein is approached being minimum within the vein. Potassium increases to the quartz-carbonate-hydromica zone and drops to a minimum within the vein. Sodium is significantly depleted throughout the vein and altered areas.

The authors conclude that, 1) gamma-ray spectrometry can be recommended for identification of hydrothermal alteration related to gold mineralization, 2) radioelement haloes may be used in the search for alteration related to blind near-surface deposits, and 3) increased uranium and thorium contents may be used to define the distal parts of the zone of hydrothermal alteration.

Grebenchikov, A.M., Khrust, A.R., Buchenkova, Ye.I., and Rusinova, O.V., 1977, Radioactive and alkaline elements in metasomatites of gold-silver deposits of Kazakhstan: International Geology Review, v. 19, no. 2, p. 173-180.

This is a study of the radioactive element distribution associated with vein gold in late Paleozoic volcanics, generally of andesitic to dacitic composition. Pre-ore metasomatism has regionally altered the host volcanics to propylites, which coupled with ore related metasomatism has resulted in complex zonation patterns. The authors identify five types of gold deposits discovered in Kazakhstan based on their radiometric signatures.

1. All three elements, potassium, uranium, and thorium, are high, and are associated with adularia-quartz and quartz-hydromica assemblages.

2. Values of potassium are high, while uranium and thorium are depleted. This signature is represented by adularia-quartz veins in adularia-bearing chlorite-carbonate propylites, or quartz and adularia-quartz veins in carbonate-hydromica and quartz-hydromica metasomatites.

3. A high uranium and low potassium signature is associated with quartz bodies in quartz-pyrophyllite and quartz-kaolinite-pyrophyllite assemblages.

4. A signature showing all three elements low. This is associated with quartz bodies and veins in quartz-kaolinite, quartz-kaolinite-pyrophyllite and hydromica-quartz assemblages.

5. No specific gamma-ray spectrometric signature. This is associated with adularia free quartz veins in chlorite-carbonate propylites.

The authors note that sodium is anomalously depleted (10-100 times) in the high potassium anomalous zones which define the gold bearing zones.

Gross, W.H., 1952, Radioactivity as a guide to ore: Economic Geology, v. 47, no. 7, p. 722-742.

In this early paper determination of the uranium, and thorium content was by alpha methods. Unfortunately no element distributions are given, but only total count maps are shown. Gross studied nine intrusive bodies in Canada, some with and some without known associated mineralization. The Dome stock, Ontario, is most thoroughly described and has four associated gold mines. The mines are located within or near the eastern edge of the stock where silica, zirconia and radioactivity are higher than in other parts of the stock. Gross concludes that "stocks and batholiths of igneous or sedimentary origin are found to have a zone of higher-than-normal radioactivity in the vicinity of ore structures. Intrusives with no important structures close at hand have no such concentration. The determination of the distribution of the radioactive elements therefore, can be used as a general guide to ore structures. --- Furthermore, if no major concentrations [of radioactive elements] are found, the intrusive may well be eliminated from detailed prospecting".

Guzhova, N.G., and Chepizhnaya, E.A., 1979, Radioactive elements in the rocks of some near-surface gold-ore deposits: International Geology Review, v. 21, no. 6, p 687-694.

Measurements were made in the vicinity of six gold deposits in an unspecified region of the USSR. Gold was present in quartz veins, some containing adularia and/or sulfides. Host rocks were Paleozoic volcanics and sedimentary rocks which had been regionally propylitized. Gamma-ray spectrometry and chemical analyses were made on 300 rock and vein samples for potassium, uranium, and thorium. Values of all three radioactive elements were below regional background over the veins. From tabulated results, propylitized and metasomatized rocks adjacent to mineralization generally had high potassium, uranium, and thorium. The authors try to make arguments for minor differences in radiation patterns having some significance, but are not

very convincing. Individual minerals were examined to determine the contents of uranium and thorium. Pyrite in the metasomatically altered rocks carried the most uranium, and chlorite in the propylites was enriched in thorium.

Hoover, D.B., Smith, B.D., Grauch, V.J.S., and Podwysocki, M.H., 1987, Geophysical studies in the vicinity of the Getchell fault system Humboldt County, Nevada: U.S. Geological Circular 995, p. 31-32.

Studies were made along the Getchell trend, north-central Nevada, with a portable ground gamma-ray spectrometer, reading for five minutes per station. The radioelement signatures of local lithologies were defined. Paleozoic sedimentary rocks which host the ore are generally low in all three radioactive elements, 0.75% potassium, 3.3 ppm eU, and 4.2 ppm eTh. Ore and altered zones along the fault zone are distinctly higher in potassium, eU and eTh generally showing enrichment by more than two times. Ratios of these three varies considerably, however, and does not appear diagnostic.

Irvine, R.J., and Robertson, I., 1987, Interpretation of airborne geophysical data over the OK Tedi porphyry copper-gold ore body using image processing techniques [ext. abs.]: Exploration Geophysics, 5th Geophysical Conference, Perth, Australia, v. 18, no. 1/2, extended abstracts, p. 103-107.

The OK Tedi deposit, Papua, New Guinea is described as a leached supergene cap of gold mineralization over a copper skarn developed in shelf deposit sediments adjacent to the Mt. Fubilan monzonite porphyry. A combined magnetic, and gamma-ray survey was flown at 333 m line spacing and 100 m terrain clearance. The authors state that potassium, uranium, thorium, and total count radioactivity maps were all useful for geologic mapping in the area. However, the potassium map was most useful for identifying areas of hydrothermal alteration in the upper part of the porphyry system that may be associated with copper-gold mineralization. No significant uranium or thorium anomalies were noted associated with the high potassium zones. The combined use of magnetic and gamma-ray data was effective in distinguishing between intrusives and volcaniclastic sediments.

Kauahikaua, J.P., Hoover, D.B., and Pierce, H.A., 1986, Section on geophysical investigations at Rois Malk Republic of Palau, in Miller, W.R., Rytuba, J.J., Arnold, M.A., and Vercoutere, T.L., 1986, Investigations of the Rois Malk area, Republic of Palau: U.S. Geological Survey Administrative Report, 201 p.

Four traverses, about 500 m long, were made across the Rois Malk gold prospect using a 25 m station interval. Radioactivity, electromagnetic (EM-16R) and multifrequency telluric data were obtained on each traverse. Radioactivity and telluric data also were measured on a short line across a vein system at a 2.5 m station spacing. Known veins in the area showed potassium haloes, but no change in either uranium or thorium values. Potassium anomalies were identified which suggest the presence of unidentified mineralization. Host rock consists of deeply weathered basalt and basaltic andesite flows and flow breccias. Post mineralization sediments, in fault contact on the west end of the deposit, were easily identified by a significant increase in equivalent uranium and no change in potassium or thorium from background in the volcanics.

Kochetkov, A.Ya., Zlobin, V.A., and Popov, A.B., 1987, Radioactive elements and gold in Mesozoic magmatic rocks of central Aldan: Soviet Geology and Geophysics, Allerton Press translation, v. 28, no. 12, p. 34-42.

This paper discusses the radioelement signatures of magmatic source rocks for gold deposits in central Aldan, with very little discussion of the characteristics of the deposits themselves. They say little about potassium variation related to ore, but do note that there is in general no correlation between gold and uranium or thorium in gold rich altered rock. The authors' abstract follows:

> "Discussed are the petrochemical features and distribution of radioactive elements (uranium, thorium, potassium) and gold in mesozoic magmatic rocks of Central Aldan. Three formations are identified: monzonite-syenite, leucitite-alkaline syenite, and shonkinite-alkaline picrite. In their composition we identify individual petrographic rock types, subdivided into several age groups. New data are presented on the geological and radiological age of the latter. A typical radiogeochemical feature of the overwhelming majority of Aldan alkaline rocks is the decreased concentration of uranium and thorium, despite the sharply expressed potassium inclination; this makes these formations similar to basic and medium rocks and sodium granitoids which are widespread in many gold provinces. The mean gold concentrations range from 2.7 to 11.1 mg/ton. Increased gold concentrations are related to hydrothermally altered varieties of rocks of different formations."

Kremnev, I.G., Ostrovskiy, E. Ya., Portnov, A.M., and Kotlyarevskii, L.N., 1974, Vozmozhnosti aerogammaspektrometrii pri poiskakh korennykh zoloto-serebryanykh rudoproyavleniy v vostochnom Uzbekistane (Kochbulakskoye mestorozhdeniye) [Aerial gamma-spectrometric exploration for endogenic gold-silver deposits in eastern Uzbeckistan (Koteulaks deposit)]: Akademiya Nauk Uzbekskoy SSR Ministerstvo Geologii UzSSR, Uzbekskiy Geologicheskiy Zhurnal, no. 6, p. 45-49.

This paper presents the results of an airborne gamma-ray spectrometer survey over the Koteulaks deposit in eastern Uzbeckistan. An AGS-5 gamma-spectrometer was used, but no data are given on crystal volume, or flight specifications. Contour maps of thorium and potassium are shown in relation to zones of known gold mineralization, but no map scale is indicated. Some, but not all, mineralized zones show a correlation with potassium. Uranium is not associated with any known gold occurrences in the area. Two-element anomalies of potassium and thorium are associated with unaltered andesite and andesitic-dacite. Alteration of these andesitic rocks removes thorium giving a single-element potassium anomaly indicative of hydrothermal alteration.

Krendelev, F.P., 1970, Background radioelement levels in the Precambrian rocks of the Yenisey Ridge: Nauka, Moscow.

This paper has not been abstracted. It was referenced in Petrov and others, 1972, as identifying an association of uranium and gold that permits the indirect detection of gold.

Krendelev, F.P., Mironov, A.G., and Gofman, A.M., 1976, Use of gamma-spectrometric methods in contouring ore zones in the trans-Baikal region: Geologiya i Geofizika (8), p. 67-75.

The authors pioneered the use of gamma spectrometry in Transbaikal where ground studies were made at the Balei and Zamogta gold deposits and the Zhida Mo-W deposits. For laboratory measurements crystals of 150 x 200 mm were used. Minimum levels claimed for their measurements of potassium, uranium, and thorium are respectively 0.1%, 0.4 ppm, and 0.6 ppm for a 60 min integration time on 500 g samples. Field measurements are made with a 70 x 80 mm crystal linked by as much as a 1 km cable to the instrument. For 5 minute integration times minimum levels were 0.04%, 0.3 ppm and 0.4 ppm respectively for potassium, uranium and thorium.

The Balei epithermal gold deposit of Cretaceous age is contained within Mesozoic sedimentary rocks and granodiorite. Sulfide-poor quartz veins with hydromica, kaolinite, adularia and carbonate constitute the ore. Gamma-ray spectrometry is used principally to identify wall rock alteration, particularly adularized zones, related to mineralization. Potassium increase and thorium decrease is said to be characteristic, with little mobilization of uranium. One figure shows data for the Balei deposit and appears to be an idealized or averaged section rather than actual data.

The Zamogta deposit is hosted within acidic extrusives showing wide spread alteration with development of potassium feldspar and hematite. Gold is present in quartz-pyrite veins emplaced along structurally weak zones. Gamma-ray measurements were made at intervals of 0.5 m to 5 m. The entire area of felsic rocks studied has undergone potassium metasomatism showing an average of 6% potassium, no major change in uranium, and depletion of thorium. Individual quartz-pyrite veins, both rich or poor in gold show decreased contents of all three radioelements. In the veins the thorium/potassium and uranium/potassium ratios increase and maximum gold content correlates with minimum potassium. Thin mylonite zones adjacent to ore may be characterized by anomalously high uranium. One figure illustrates results in the Zamogta area and is the same as used by Mironov and others (1979).

Kuz'micheva Ye.V., Kondratenko A.K., Lukina O.P., and Rusinova O.V., 1981, The nature of aerial gamma-spectrometric anomalies: International Geology Review, v. 23, no. 11, p. 1321-1325.

This report discusses the radioelement signature of quartz-adularia vein deposits in volcanics of the Okhotsk-Chukotskiy belt. The mineral commodities of interest are not mentioned.

The authors discuss the "antagonism" between potassium and thorium reported by Ostrovskiy (1975), and show that for rocks in the region which have not been metasomatized there is in general an increase in potassium with increasing thorium. On the other hand for metasomatized units, as thorium increases there is essentially no significant variation in potassium. They conclude that during regional metasomatism potassium is redistributed and not added. However, narrow zones (several, to 10's of meters) associated with ore deposition show a doubling of the potassium oxide content to 7-9%. These narrow zones are not mappable by airborne techniques because of their thinness, but may be mapped by ground methods.

Mironov, A.G, Gofman, A.M., Yachmeneva, A.A., and Malyasova, Z.V., 1979, Radioaktivnye elementy v rudnykh polyakh mestorozhdeniy neradioaktivnogo syr'ya [Radioactive elements in ore fields of deposits of nonradioactive raw material]: Trudy Geologicheskogo Instituta Buryatskii Filial Sibirskoe Otdelenie Akademiya Nauk SSSR.

A brief history of the use of gamma-ray methods applied to ore deposits is given, including a reference to the work of Gross (see Gross 1952). From the literature cited it appears that extensive work by the Russians using gamma-ray methods for nonradioactive ore exploration began in the late 1960's, for the paper by Ostrovskiy and others (1970) is the earliest cited. The authors discuss the use of gamma-ray spectrometry in the exploration for various types of ore deposits in Transbaikal including: 1) molybdenite-wolframite, 2) pyrite-polymetallic and iron of the Ozernoe region, 3) pyrite-polymetallic of northern Transbaikal, 4) fluorite-beryl, and 5) gold in the Zamogta region (p. 96-99). For the Zamogta region, a table is shown listing the radioelement distribution for ore and host rock showing a depletion of all three radioelements within the ore zone and increase in uranium/potassium and decrease in thorium/uranium ratios within the ore zones. Their figure 39 shows two traverses across ore zones that do not clearly show depletion of the radioelements and a summary section that appears to be an idealized section of the radioelement distributions that does show low values over the principal ore zone and a distinct increase of uranium over what is called poor ore. In summary, the authors note the minimum potassium and reduced uranium associated with the rich ore zone and that the low-grade ore zones, high in uranium, are related to tectonic features and point to the presence of ore.

Mwenifumbo, C. J., Urbancic, T. I., and Killeen, P. G., 1983, Preliminary studies on gamma ray spectral logging in exploration for gold: Geological Survey of Canada Paper 83-1A, p. 391-397.

Author abstract

Several studies have indicated that the distribution of the naturally occurring radioelements (potassium, uranium, thorium) can serve as a useful guide to gold deposits. This is because most gold deposits are characterized by wall rock alterations (adularization and sericitization) in which potassium, including the radioactive isotope K-40 is considerably enriched. Theoretically it should be possible to outline areas enriched in potassium by gamma-ray spectrometry. Preliminary investigations have been conducted to observe and confirm this gold-potassium correlation and evaluate its usefulness in gold exploration. The distribution of the naturally occurring radioactive elements (potassium, uranium, thorium) has been determined by gamma-ray spectral logging in several boreholes intersecting gold mineralization in the Larder Lake area of Ontario. The orebodies in this area are of two types. The carbonate orebodies consist of irregular lenses of quartz stockworks lying within highly altered and brecciated carbonatized ultramafic rocks. The flow-type orebodies consist of pyritized and silicified zones lying within altered volcanic flows and tuffs. The present work was conducted in the flow-type orebodies. Most gold in this type of orebody is associated with pyrite mineralization. Preliminary gamma-ray spectral logging data indicate that, in the Larder Lake area there is not always a definite correlation between high gold values and an increase in potassium content. In some boreholes gold mineralization can be correlated with massive pyritization as well as an increase in potassium content. Logging of boreholes in the

quartz-carbonate stockworks seems to indicate that low potassium content is associated with the high gold content. In addition, to complicate matters, in some boreholes gold is found in zones without massive pyritization and without an increase in potassium. It is therefore likely that the distribution of the radioactive element K-40 can only be used as a guide in localizing zones with high gold content if additional information is available (e.g., pyrite content, and rock type). Ratios of the radioelements (Th/K, U/K, U/Th), which have sometimes been used as indicators of halos around certain types of deposits, could not be computed due to poor counting statistics in the uranium and thorium spectral windows.

Mwenifumbo, C.J., 1985, Application of borehole geophysics in exploration for gold: Transactions Society of Professional Well Log Analysts 26th Annual Logging Symposium, June 17-20, 1985, v. 2, p. 1-24.

Borehole geophysical logging was conducted in several holes at the Barber-Larder gold prospect, Larder Lake, Ontario, to map the stratigraphy, structures and alteration zones associated with gold mineralization. Natural gamma ray spectral logging, induced polarization (IP), resistivity, self potential (SP) and magnetic susceptibility logging were done.

Gold mineralization at the Barber-Larder prospect occurs within altered basic volcanic flows, tuffs and agglomerates which are overlain by metasedimentary rocks (graywackes) and underlain by fuchsite-bearing carbonate breccia. Alteration in the area includes pyritization, silicification, carbonatization and sericitization. Gold mineralization is mainly associated with pyritization. There is, however, a genetic as well as spatial relationship with the other types of alteration processes. A major feature within the area associated with the gold-bearing horizon is an extensive graphitic zone.

The stratigraphic units are defined by the natural gamma-ray spectrometry, IP, SP and magnetic susceptibility methods. The graywackes exhibits high radioactivity, low IP response, low susceptibility and no SP anomalies. The overall radioactivity within the volcanic rocks is lower than that observed in the graywackes. The graphitic zone can be easily delineated as a low resistivity, high IP zone at the contact between the graywackes and the volcanic rocks. The graphitic zone also exhibits a high negative SP anomaly. Within the altered volcanic flows, tuffs and agglomerates, the sericitized zones are characterized by high natural gamma-ray activity due to an increase in potassium. Pyritized zones are characterized by high IP response and zones with more than 10 percent pyrite have a corresponding low resistivity response. The silicified and carbonatized zones are characterized by low gamma-ray activity, low susceptibility and in some cases high resistivities. Generally the magnetic susceptibilities observed were fairly low. The basic volcanic flows showed higher susceptibilities than the graywackes. The susceptibility lows within the volcanic flows reflect carbonatized and pyritized zones. Slight increases in the magnetic susceptibilities within the volcanic sequence are related to the presence of minor pyrrhotite. The optimum geophysical parameters for delineating zones with a high probability of gold mineralization at this gold prospect are resistivity, IP, and gamma ray spectrometry. This applies to most gold deposits in Ontario where gold is associated with metallic sulphides and potassium metasomatism. The other geophysical parameters are, however, useful for stratigraphic and structural mapping.

Ostrovskiy, E.Ya., 1975, Antagonism of radioactive elements in wallrock alteration fields and its use in aerogamma spectrometric prospecting: International Geology Review, v. 17, no. 4, p. 461-468.

This report discusses the radiometric response of a variety of types of ore deposits such as; REE apogranites, carbonatites, polymetallic volcanic hosted deposits, and metamorphic hosted uranium deposits. Variations of potassium, uranium and thorium are shown over two gold-silver deposits in rhyolite. One shows a potassium halo adjacent to the vein, and high but slightly reduced potassium within the vein. Uranium shows limited depletion just outside the vein and limited increase inside with respect to regional background. Thorium shows a broad depletion around and within the vein. The other profile, over a quartz-adularia system, shows a distinct potassium high and diminished uranium and thorium in contrast to adjacent rhyolites.

Ostrovskiy, E.Ya, Portnov, A.M., and Drobkin, N.Ye., 1970, Aerogamma spectrometric prospecting for perisurficial deposits of gold in effusives: International Geology Review, v. 14, no. 7, p. 688-691.

The authors describe studies of gold mineralization associated with potassium metasomatism in the 3500 km long Okhotsk-Chukotka volcanic belt. Host lithologies for the gold are propylitized rhyolites, dacites and andesites. Geochemical studies of fresh and altered host rock and vein material showed that gold mineralization is associated with an increase in potassium, due to adularia, and decreases in uranium and thorium. Using these criteria for exploration, an airborne gamma-ray spectrometric survey is illustrated showing the successful application over two targets. The airborne survey was conducted by helicopter at 25-75 m altitude and flight-line spacing of 200-300 m. Adularized zones, which are the target of the survey, typically show a doubling of the potassium content in rhyolites and thorium decrease of 1/2 providing for relatively easy discrimination.

Petrov, B.V., Krendelev, F.P., Bobrov, V.A., and Tsimbalist, V.G., 1972, Behavior of radioelements and gold during metamorphism of sedimentary rocks in the Patom Uplands: Geochemistry International, v. 9, p. 647-655.

The authors note that in some regions of the USSR the association of uranium and gold has allowed the use of airborne gamma-ray spectrometry for the indirect detection of gold (Krendelev, 1970). In this paper geochemical and laboratory gamma-ray spectrometric results are presented on the distribution of gold and potassium, uranium and thorium in a sequence of metasedimentary rocks of the Patom Uplands. In this region, placer gold deposits have been related to regional metamorphism. Eight lithologies are sampled with metamorphic grades from greenschist to amphibolite facies. They conclude that gold is mobilized during metamorphism, being depleted in amphibolite facies. They also conclude that the radioactive elements were not mobilized, implying that gamma spectrometry is not useful.

Pitkin, J.A., and Long, C.L., 1977, Interpretation of data from an aerial gamma-ray survey in the Cripple Creek district, Teller County, Colorado: U.S. Geological Survey Open-File Report 77-534, 12 p., 5 pl.

This paper presents data from an airborne survey of about 1/2 of the Cripple Creek gold district. Flight elevation was 200 m or less with four 12.5 cm diam. by 10 cm thick crystals. Spectrometer integration time was one second and sample interval 0.4 sec. Flight line spacing was 0.4 km. Plates show geology and corresponding total count, potassium, equivalent uranium, and equivalent thorium maps. The volcanic cauldron was found to be higher in all three radioelements than the surrounding Precambrian granite, which has higher radioactivity than average granites. Radiometric highs of potassium and uranium correlated with geochemically determined regions high in gold, silver and tellurium.

Porter, E.W., 1984, Radioactivity as a tool for gold exploration [abs.]: Geological Society America Abstract with Programs, v. 16, no.6, p. 625.

Author's abstract

Scintillometry is suggested as a possible new tool in exploration for epithermal gold deposits. Recent models for both epithermal precious metal deposits and epithermal uranium deposits include near surface, low to moderate temperature environments, widespread disseminated ore and numerous small veins rather than massive rich veins, and low intensity geochemical and alteration haloes. As, Mn, Te and Tl are indicators for the precious metal environment. Epithermal uranium shares the first two, and Mo is a frequent associate in addition. These similarities suggest common transportation mechanisms and depositional conditions for two elements not frequently thought to be associated.

An important example of the association of gold and uranium in the eipithermal environment is the Mesquite or Big Chief deposit type north of Yuma, AZ, in the southeast corner of California, including the Glamis and Picacho Peak deposits. These large, low grade, bulk mineable, gold deposits were characterized during early uranium exploration as having radioactivity of six times background locally. Torbernite and autunite were identified on the outcrop.

Although this relationship between gold and uranium needs to be further substantiated, the use of radioactivity as a tool for gold exploration in some environments is of great potential importance.

Portnov, A.M., Ostrovskii, E.Ya., and Kolotov, B.A., 1971, Poiski blizpoverkhnostnykh zoloto-serebryanykh mestorozhdeniy aerogammaspektrometricheskim i gidrogeokhimicheskim metodami [Prospecting for near-surface gold-silver deposits by aerial gamma-ray spectrometric and hydrogeochemical methods]: Razvedka i Okhrana Nedr, no. 11, p. 13-16.

In this paper an airborne gamma-ray spectrometric survey is mentioned, but no figures illustrating results are given. About 1/2 page of text describes the gamma-ray work, with most of the text given to a description of the airborne equipment. This consisted of a AGS-4K system installed in an Mi-4 helicopter. Flight height was 30-75 m. A thallium activated sodium iodide crystal was used as detector but the crystal volume is not given. The spectrometer windows were set at 2.2-2.8 million electron volts (Mev), 1.6-1.9 Mev and 1.3-1.5 Mev to detect each of the three radioelements. The only result stated is that the quartz-adularia metasomatites could be clearly

distinguished by their accumulation of potassium and "antagonism" of thorium and potassium [see introduction]. Host rocks are dacitic volcanics within an eroded caldera that comprise the Karamkinsk gold-silver deposit.

Portnov, A.M., 1985, Osobennosti raspredeleniya toriya i kaliya v vertikal'nom razreze zoloto-serebryanykh mestorozhdeniy vulkanicheskykh poyasov [Distribution characteristics of thorium and potassium in the vertical cross section of gold-silver deposits of volcanic belts]: Geologiya Rudnykh Mestorozhdeniy, v. 27, no. 4, p. 113-15.

This paper does not present results of any gamma-ray spectrometer measurements, but presents results of chemical analysis of potassium, uranium and thorium contents of 206 samples of fresh and altered rock from a volcanic province of the USSR. The authors examine the radioelement variation from fresh rock, late Paleozoic and Mesozoic andesitic dacites, through potassium metasomatized units to gold- and silver-bearing quartz veins. Only one table is given showing the range of radioelement values, but not averages, in nine separate groups including adularia-sericite, hydromica-kaolinite, sericite, and kaolinite-quartz metasomatites. The author states that thorium and potassium contents are increased in the ore and in the altered rocks. Their table also shows that uranium is significantly enriched in some samples of ore and not in others. He suggests that increased thorium in surface rocks may indicate the presence of underlying gold-silver mineralization.

Portnov, A.M., Milovanov, A.E., and Kremnev, I.G., 1979, Indikatsiya metasomatitov zoloto-sere'ryanykh rudoproyavleniy pri AGSM-s'emke [Indication of metasomatic gold-silver ore appearance during AGSM (airborne gamma-ray spectrometric, magnetic) survey]: Razvedka i Okhrana Nedr, no.2, p. 36-9.

This paper describes airborne magnetic and gamma-ray spectrometry results in the Tien Shan region where gold-silver deposits occur in potassium metasomatized and argillized volcanic rocks of andesitic to dacite composition or in granite porphyry. Airborne magnetics is used to identify regional terraines favorable as hosts for ore, while gamma-ray spectrometry is used to identify specific sites of potassium metasomatism. The aeromagnetic survey is flown at 50-70 m flight height. It is presumed that the radioactivity survey is flown at the same time, but this is not specifically stated. The gamma-ray surveys are stated to give considerable information regarding ore deposits particularly zones where potassium metasomatism, quartz-adularia, quartz-sericite and quartz-hydromica occur. The AGS-5K gamma-ray spectrometer used employs two single crystals of NaI (Tl) measuring 200x150 mm each for a total crystal volume of 9500 cm^3. Windows used for measurement of the thorium, uranium, and potassium are 2.3-2.8 Mev, 1.65-2.0 Mev, and 1.35-1.55 Mev respectively. Both analogue and digital recording of the data are made during flying, with data being processed on a MINSK-32 computer. Flight-line spacing or other parameters are not given, but compilation of the data is done at 1:200,000 and 1:10,000 scales. Besides maps of the individual radioelements, a parameter suggested by E.Y. Ostrovskiy diagnostic of the "antagonism" between potassium and thorium in the ore deposit environment is also mapped. This parameter D_k is given by:

$$D_k = \left|\frac{q_k - \bar{q}_k}{\sigma_k} - \frac{q_{th} - \bar{q}_{th}}{\sigma_{th}}\right| \times e^{1-Q_{th}} \text{ where } Q_{th} = \frac{q_{th} - \bar{q}_{th}}{\sigma_{th}}$$

q is the local value of K or Th

$\bar{q}$ is the average value and

σ is the standard deviation

This paper gives a table showing chemical analyses of fresh and altered granite porphyry and andesitic-dacite. The analyses shows a loss of FeO, MgO, Na_2O and increase in Al_2O_3, K_2O and H_2O. A second table gives uranium, thorium, and potassium values for fresh and altered rock samples based on a radioactivity method of analysis. This table shows potassium increase and thorium decrease in quartz-adularia and quartz-sericite alteration. For quartz-sericite-kaolinite, quartz-alunite, and quartz-alunite-kaolinite alteration zones, no distinct pattern is seen in the radioelement data. The only gamma-ray data shown is a map, with no scale or locations, showing high potassium areas overlayed on a magnetic contour map. The potassic areas are said to correlate, in some cases, with low-sulfide gold-silver deposits, but no deposits are identified on the map.

Savosin, S.I., Chepizhnaya, E.A., and Guzhova, N.G., 1977, Raspredeleniye radioaktivnykh elementov v porodakh i rudakh nekotorykh zolotorudnykh mestorozhdeniy Uzbekistana [Distribution of radioactive elements in rocks and ores of some Uzbekistan gold-ore deposits]: Ysesoyuznyi Nauchno-Isledovatel'skii Institut Yadernoi Geofiziki i Geokhimii.

This paper describes ground radioelement surveys made over quartz, quartz-feldspar, quartz-carbonate, and quartz-carbonate-wollastonite veins enclosed within late Paleozoic volcanic and volcano-sedimentary rocks (granodorite and andesite) in Uzbekistan. Two figures are given showing a geologic section along with radioelement and gold distributions. In all cases the gold veins are associated with lows of all three radioelements. The profiles presented show no clear evidence for potassium enrichment adjacent to the veins nor do they show scales on ordinate or abscissa. A table compares averages and ranges of values of radioelements contained in ore and country rock and shows in most cases dramatic decrease in radioelement content within ore.

Sekine, Y., and Obi, I., 1960, Reconnaissance radiometric survey of the Nojiri gold mine and its neighborhood, Iwote prefecture: Japan Geological Survey, v. 11, no. 1, p. 29-33.

Gold occurs within scheelite-bearing quartz veins at the Nojiri mine, Iwote prefecture. The authors report no radioelement anomalies were found.

Stohl, Jaroslav, Gnojek, Ivan, and Dedacek, Karel, 1981, Prispevok leteckej magnetometric a gama-spektrometric k interpretacii metalogenezy stredoslovenskych neovulkanitov [Airborne magnetometer, and gamma-ray spectrometry interpretations of the metallogeny of the Central Slovakian neovolcanic region]: Zapadne Karpatz, mineralogia, petrografia, geochemia, metalogeneza, Geolozicky ustav Dionyza Stura, Bratislava, v. 8, p. 15-57 (author's abstract in english).

Author's abstract

The Central-Slovakian neovolcanic region comprises the Vtacnik Mts., the Kremnicke vrchy hills, the Stiavnicke pohorie Mts., the Pohronsky Inovec Mts. and mountain ranges Polana and Javorie. In their present erosive form they represent relicts of large volcanic structures. Neovolcanic rocks are products of intermediary and acid volcanism (andesites-rhyolites). Central parts of the volcanic structures consist of intrusive complexes, HDT-altered zones, occurrences of Pb, Zn, Cu, Au, Ag - and Fe-mineralizations in various forms.

In the years 1976-1978 airborne geophysical measurements were made simultaneously by magnetometry and gamma spectrometry in the northern part of the Central-Slovakian neovolcanic region. The measurements covered the surface of 2910 sq km and resulted in almost 600,000 of discrete values of ΔT anomalies of magnetic field, the same number of values of potassium, uranium, thorium-concentrations, and of total gamma activity.

From the data only those were used that were connected with metallogeny and ore prognoses. As for airborne magnetometry - we used data concerning physical-chemical character of hydrothermal alterations and the relationship of magnetic field to ore districts.

From gamma-spectrometric informations most interesting were data on qualitative and quantitative distribution of hydrothermal kalium [potassium] in relation to volcanotectonic and ore structures. We treated partly also distribution of uranium and thorium and their migration abilities in the course hydrothermal processes. Statistical analysis was used in judging the reliability of measured contrast data on altered and unaltered hydrothermal environments. Values of arithmetic mean, standard deviation, assymmetry and excess of flight values were calculated for 33 various rock types in ore districts. The values were compared and correlated in a series of frequency curves and diagrams.

Kalium [Potassium], Uranium, Thorium

The anomalous values 2% K in andesites and 3.5% K in rhyolites were determined according to calculated petrochemical values for the main rocktypes. Distribution of anomalous K and its relation to tectonics and ore districts are in Map 1. The relation of mean values of potassium, uranium, thorium to their standard deviations in hydrothermally altered and unaltered environments is in figure 1. The values of standard deviations of anomalous K are higher. Greater dispersion of the values of K in altered rock environment is due to uneven tectonics of the areas penetrating K-hydrothermae (fig. 3). The relation of uranium and thorium to hydrothermal processes is in figure 2 showing that in contrast to K, in the rocks of andesite type, uranium and thorium are not mobilized. Hydrothermal processes connected with rhyolite volcanism mobilize U, Th, and K. It is presumed (including also geological aspects) that there are two different (both in genesis and in time) types of adularization in Central-Slovakian neovolcanic rocks. The later stage (Kremnica vein type Au-Ag±Sb) associated with rhyolite volcanism is characterized by increased uranium and thorium contents. The earlier adularization stage without any remarkable mobilization of uranium and thorium is associated with polymetallic mineralization of the Stiavnica type.

Frequency curves in figure 4 show dispersion of K values in rock types with the highest content of secondary K (the so-called Kalium-trachytes).

Figure 5 shows frequency curves of K-contents in areally propylitized pyroxene andesites. The curve showing increased K-content is asymmetrical. The curve has lognormal division with positive asymmetry. It is confirmed by calculated asymmetry and excess of flight values.

Figure 6 shows relationshipps between uranium and thorium and altered and unaltered sets rock.

Regional characteristic of distribution of K is indicative of a close relation between the secondary K and central volcanic zones in the western part of the Central-Slovakian neovolcanic rocks. Within regional anomalies are some lesser anomalies of possible practical significance for geological exploration. Kalium does not concentrate above ore mineralization of the porphyry type. No secondary kalium was found in the eastern part of the Central-Slovakian neovolcanic rocks (Polana and Javorie Mts.).
[The authors' abstract continues with a discussion of the magnetic field data. This section has been dropped]

Tihor, L.A., and Crocket, J.H., 1975, Gold distribution and gamma-ray spectrometry in the Kirkland Lake-Larden Lake gold camp: Report of activities, Part A, Geological Survey of Canada Paper 75-1A, p. 355-357.

The authors give preliminary results on potassium, uranium, and thorium laboratory analyses on rocks samples for the Kirkland Lake district to provide background values for study of enrichment and depletion of rock elements around the gold deposits. Surface and underground measurements were also made at the Kerr-Addison and Cheminis mines. They report that preliminary results suggest a positive correlation between gold and potassium and uranium, and negative correlation with thorium.

Thomson, Ian, 1980, Gamma-ray mapping of alteration zones associated with gold-bearing horizons, Orientation studies of the Kerr Addison Mine, Virginiatown, District of Timiskaminy: Ontario Geological Society Miscellaneous Paper 96, p. 145-149.

At the Kerr Addison mine three types of gold ore are recognized; 1) flow ore probably related to silicified tuffs and interbedded pillow lavas containing pyrite, 2) carbonate ore in sericitic and fuchsitic dolomitized ultramafic volcanics in which gold occurs in quartz veins, and 3) low grade dike ore occurring in albitite dikes post dating the carbonate-potassic alteration of type 2 ore. The authors used a Scintrex GAD-6 spectrometer and a 348 cm^3 crystal to measure underground on four different levels. Measurements were generally made at 7.5 m intervals, using a 100 sec counting time. Their conclusions are reported below.

1) The gamma-ray spectrometer can be used to map potassic alteration and the distribution of characteristic rock types within the Kerr Addison Mine.

2) The present survey has demonstrated that potassic alteration within the mine is bilaterally symmetrical, is probably zoned, and transgresses mapped rock types and structures. It is characterized by a gross increase in potassium with associated low values of thorium, thus giving rise to anomalously high potassium/thorium ratios.

3) The potassic alteration occurs as a pipelike body elongated with the plane of the ore zones parallel to the Larder Lake Fault. The alteration post dates the more extensive carbonate alteration and lies roughly centered within the carbonatized zone. The potassic metasomatism is, in turn, cut by later albitite dikes.

4) The carbonate gold ore zones occur where potassic alteration is strongest and most extensive. Individual ore bodies appear to be localized on the flanks of the potassic alteration pipe within or close to steep gradients in potassium concentration.

5) Gamma-ray mapping could be used to examine other areas of carbonate alteration in the Larder Lake area. It represents a rapid technique for identifying and localizing potassic alteration which, in turn, appears to have a spatial control on the deposition of carbonate gold ore of the Kerr type. Rapid recognition of the form and symmetry of alteration zones could aid in locating new gold ore bodies on the flanks of alteration pipes.

6) Because of the very low count rates, this approach can only be employed underground in an environment free of background cosmic radiation. It is thus confined to mapping boreholes and underground development drives.

Urbancic, T.I., and Mwenifumbo, C.J., 1986, Multiparameter logging techniques applied to gold exploration, in Killeen, P.G., ed., Borehole Geophysics for Mining and Geotechnical Applications: Geological Survey of Canada Paper 85-27, p. 13-28.

Author's Abstract

Several boreholes intersecting gold mineralization at the Barber Larder gold prospect, Larder Lake, Ontario were logged with gamma ray spectral, induced polarization (IP), resistivity, self potential (SP), and temperature methods in an attempt to delineate favourable lithologic units. The gold mineralization at this prospect occurs within highly altered, pyritized, brecciated and carbonatized volcanic rocks of Archean age. The gold is associated with pyrite mineralization.

A qualitative interpretation of the borehole logging data indicated that SP and gradient SP logs were useful in outlining the known favorable sections of volcanics. Further detailed investigations were carried out in these sections. Zones of gold mineralization within the volcancis were found to correlate with increased apparent conductivity values and in some cases, decreased potassium values. High apparent conductivities are due to increased pyrite content. Abnormally low potassium content is generally associated with high potassium enveloping halos, that are due to an increase in sericite. In general these zones also exhibit low or near zero temperature gradients. Temperature anomalies encountered in these zones are probably due to fracture zones and water movement along the borehole.

Vasil'ev, B.D., Zlobin, V.A., Pavlova, L.K., Ponomareva, A.P., and Shirokikh, I.N., 1985, Radiogeochemical properties of magmatic rocks in gold regions of Kuznets Altau: Soviet Geology and Geophysics, Allerton Press translation, v. 26, no. 1, p. 45-54.

This paper presents the radioelement signatures of magmatic rocks from ten gold producing regions of the Kuznets Altau, Siberia, and discusses their variations and significance for each area. The magmatic rocks in the region

show an increase in thorium and thorium/uranium values with increasing potassium content. The magmatic rocks most closely associated with gold ore are characterized by low radioactivity and thorium/uranium ratio (1.5-2.5) suggesting the source rock was of "basic-intermediate" composition.

Zashchinskii, L.A., Kortunov, V.A., Nomokonova, G.G., and Turysheva, T.I., 1970, Use of potassium radiometric survey during study of ore-controlling factors in the Darasan gold field: Izvestiya Tomskogo Politekhnickeskogo Instituta, v. 239, p. 436-40.

This paper reports on results of geochemical and gamma-ray spectrometric measurements in the Darasan gold field USSR. Geochemical data shows that potassium is concentrated along fracture zones that acted as channels for ore-bearing solutions that altered surrounding host rock, and adjacent acidic dikes. Gamma-ray spectrometric surveys are used to identify the major tectonic fracture zones that served as conduits for the mineralizing solution.

Zhokhov, G.A., Klimov, V.I., Karimov, Kh.K., and Abbosov, I.M., 1975, Radioktivnye elementy vo vmeshchayushchikh i gidrotermal'no izmenennykh porodakh kokpatasskogo rudnogo polya [Radioactive elements in country rocks and hydrothermally altered rocks of the Kokpatos ore field]: Akaemiya Nauk Uzbekskoy SSR, Ministerstvo Geologii Uzbekskoy SSR, Uzbekskiy Geologicheskiy Zhurnal, v. 19, no. 5, p. 32-36.

The authors discuss the application of ground-based and borehole gamma-ray spectrometry to identification of hydrothermally altered rock in the Kokpatas district. Finely dispersed gold is found with disseminated pyrite-arsenopyrite in hydrothermally altered late Proterozoic sediments and volcanics. The authors compare quantitative results of potassium, uranium and thorium chemical analyses against quantitative gamma-ray measurements for a large number of rock samples. The results show a 1:1 relationship substantiating the use of gamma-ray spectrometry for quantitative radioelement measurements.

Results of field surveys shows that potassium increases significantly within the altered rocks but no consistent or noticeable change is reported for uranium or thorium. However, one illustration (fig. 4) shows similar variations for potassium and thorium across an ore zone. In near-surface altered rocks uranium was also reported elevated and attributed to alteration of pyrite and absorption of uranium by the resulting iron hydroxides.

They conclude that, 1) in the Kokpatas district hydrothermally altered rock may be clearly distinguished by its increased potassium content and by no substantial change in content of uranium or thorium, 2) that uranium is only concentrated in iron hydroxides in the superficial part of the deposit, and 3) that utilization of gamma-ray spectrometry permits simple mapping of hydrothermally altered rock that localize the gold-sulfide ore.

Zlobin, V.A., and Kurulenko, R.S., 1981, Formation conditions and features of gold-containing granitic rocks on the basis of radiogeochemical data: Geologiya Geofizika, v. 4, p. 68-74.

This paper is principally a radioelement study of the Shartash granite massif and related dikes which occur within the Berezovskii gold district.

Gold mineralization occurs 1.7-3.5 km distant from the Shartash massif, and this study addressed the relationship of magmatism to gold mineralization. They state that the connection between granitic magmatism and gold mineralization has not been "solved conclusively" in any of their districts. No details are given of the deposits themselves, but they appear to be hosted in volcanogenic sediments into which ore bearing dikes have been intruded, and along which silicification and quartz veins have developed. Quartz veins and silicified units show low levels of radioelements, but late stage dikes and veins are said to have the highest uranium content. The increased uranium content, along with an increase in potassium, is related to postmagmatic alteration ("beresitization").

Comparisons are made between the radioelement characeristics of "gold bearing" intrusives [the source rock is implied here, ed.] at Shartash and other gold producing regions of the Urals. they conclude:

1. According to radiogeochemical data the intrusive phases of the Shartash massif, the dike rocks which cut it, and dikes of the Berezovskii field are similar.
2. In the process of formation of the Shartash intrusive and associated dike complex there was directed enrichment of the dike vein rocks by uranium, which suggests the accumulation of volatile components in the crystallized magmas.
3. In terms of radiogeochemistry, the Sartash granitoid massif and the dikes of the Berezovskii field are similar to many gold-bearing granitoids of the Urals and other gold provinces.
4. In terms of radiogeochemistry the adamellites of the Shartash massif and the dikes of the Berezovskii field are comparable to the volcanogenic rocks of medium-acid composition, which suggests the relationship of the magmas which formed the volcanogenic series and the gold-bearing intrusives of the granodiorite-plagiogranite (tonalite-granodiorite) composition.
5. Radiogeochemical signatures of gold-bearing granitoids, according to study of the Shartash massif, the Berezovskii dikes, and other massifs, are the decreased concentrations of radioactive elements and the low thorium/uranium ratio.