PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

General Discussion

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General discussion

L. R. Page (*P.O. Box* 171, *Melvin Village*, *New Hampshire* 03850, *U.S.A.*). I should like to make a statement related to the general subject of this meeting: how does one find a *new* uranium province?

This is an oversimplified set of criteria that have worked in the past in areas of no known occurrences of uranium minerals. Select, from library research: (1) a sedimentary basin containing coarse to medium grained epiclastic and volcaniclastic rocks interlayered with organic-rich rocks (or their metamorphic equivalents) that are cut by hyperbyssal igneous rocks, particularly the alkalic, mafic or ultramafic varieties; (2) areas within the basin that show evidence of either explosive activity such as cryptovolcanic structures (astroblemes?), breccia pipes, diatremes, etc., or large fault structures; (3) areas that contain evidence of hydrothermal (hot water) metamorphism in the form of chloritization, haematitization (as distinct from weathering or groundwater products), and silicification associated with carbonate veins. The alteration can be in separate zones or as a mixture, and in zones of nodules, concretions or veinlets.

In the field, check for radioactivity: (1) the organic matter, (2) fossils such as teeth, (3) iron oxide rich concretions, (4) dyke walls, (5) fault surfaces. Abnormal radioactivity in any of these areas should be followed up by the normal geological, geochemical and geophysical surveys to find the ore deposits.

J. E. Tilsley (*David S. Robertson & Associates Limited*, 65 *Queen Street West*, *Toronto*, *Ontario M5H 2M7*, *Canada*). During the first day of this meeting, Dr Michael Davies expressed a concern that this meeting might not produce what he felt was the desired result of advancing the understanding of uranium geology in regard to our ability to identify uranium provinces and thereby, presumably, to find more ore. Dr Davies was, unfortunately, unable to attend all of the first day's meeting, nor was he able to be present on the second day. Had he been, we are sure he would have had the pleasure to find that, although not all the field geology problems have been satisfactorily resolved, and though, perhaps, the laboratories have not provided the ultimate answer for which he called, we have had a useful exchange of ideas from both sides. Many of these ideas have evolved from work in what Professor Bowie aptly termed the best geological laboratory of all, the field. While we have in the past received valuable assistance from our colleagues in the laboratories, and indeed continue to look forward to much more such assistance, those of us actively involved in uranium exploration feel compelled to do our part in the development of the understanding of the 'scientific' aspects of uranium geology. We can judge by the presentations at this meeting that both groups are contributing well.

There seems, however, to be a vague feeling that uranium exploration is a rather inexact science. If fact, one can sometimes sense that, even among Earth scientists, luck is considered to be a major factor in exploration success. Be assured that this is not the case.

Most uranium exploration programmes are based on very definite concepts and models. Many of these concepts and models have been illustrated in the papers given during this meeting. In our consulting group we have a particular perception of uranium geology. Our exploration philosophy reflects this perception. Study of the distribution of uranium in ores through

time shows that the major concentrations are time-bound. Conglomeratic ores of the Witwatersrand and Elliot Lake type lie within Proterozoic rocks older than 2200 Ma, but younger than about 2800 Ma. Palaeosurface-related vein-type deposits appear at about 1700 Ma and although age datings may indicate much younger movement of uranium, a minimum age of initial formation of about 1500 Ma appears probable. The third major uranium ore type, the Sandstone deposits, are for practical purposes restricted to young Phanerozoic rocks mostly younger than about 200 Ma. While it is true that 'fossil' sandstone deposits, the remnants of ores, have been identified in sediments having a variety of ages younger than 2200 Ma, the bulk of metal production has come from much younger rocks.

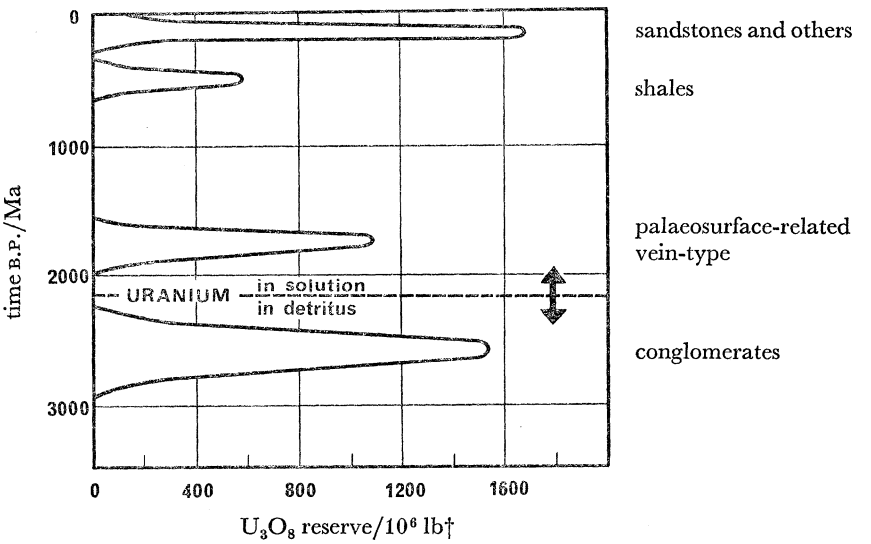

FIGURE 1. Time-bound character of uranium deposits. † 1 lb ≈ 0.454 kg.

These observations influence exploration for uranium in the following manner: Prospecting for conglomeratic ores is confined to Lower Proterozoic sedimentary rocks older than 2200 Ma. Although similar physical conditions of sedimentation can be found at later geological times, the sediments are red, pyrite is no longer present as a primary iron mineral, and uranium, if present, is contained in refractory minerals, not in the UO_2 form as in the Elliot Lake and South African conglomerates.

The major palaeosurface-related vein-type deposits have been located close to the present limit of eroding cover rock which has served to protect the uranium concentrations through time, since deposition at and adjacent to, a mature middle Proterozoic weathering surface. Although younger weathering surfaces warrant close study, the deposits of Northern Australia and northern Canada are related to a surface dated at about 1700 Ma. Exploration for similar deposits is directed first into areas having like surfaces of the same general age.

Sandstone ores are prospected for in rocks younger than about 200 Ma, always bearing in mind the special source rock – host rock topographic relations which seem necessary. Without going into great detail we can summarize nine uranium ore forming models.

Conglomerates

Detrital and geochemical concentration of UO_2 in pyrite-bearing conglomerates: formation of ore deposits is restricted to Lower Proterozoic sediments deposited on a stable plate segment

between the ages of 2800 and 2200 Ma. This is subsequent to the beginning of quartz-rich sedimentation and prior to a change in (atmospheric) conditions at about 2200 Ma after which red sediments (and haematitic iron formations) become common.

Palaeosurface-related vein-type deposits

Chemical concentration of uranium apparently released into solution in surface and ground water during long-term chemical weathering of Lower Proterozoic and older igneous and metamorphic terrain: our observations lead us to believe that the principal concentration mechanism is coincidence of significant drainage courses with a large-scale electrochemical cell. The uranium is essentially electroplated or electroprecipitated under the influence of appropriate current and voltage conditions related to conductive structures electrically connecting the oxidizing near-surface environment with the deeper reducing conditions.

Sandstone deposits

Uranium leached by rain and ground water from topographically high igneous rocks (granites or lavas) is carried in oxidizing aquifers into reducing conditions provided by organic matter, pyrite, H_2S, hydrocarbons, etc., within porous and permeable sediments where precipitation takes place. Roll fronts, tabular and channel deposits are formed.

To these three 'conventional' types of deposits, where concentration of uranium has an obvious surface relation, we may add the following:

Anatectic deposits

Deposits formed by anatexis of uranium-enriched rocks, probably shales, deposited under relatively shallow water (lagoonal) conditions during the Middle to Late Proterozoic or possibly more recently. The Rössing and Faraday deposits are examples.

Magmatic deposits

These include segregations of uranium-bearing minerals as a result of magmatic processes often during late stages of intrusion. They are commonly related to alkaline and carbonatite intrusions. The Kvanefjeld section of the Ilímaussaq intrusion, parts of the Zr–U-bearing syenite at Poços de Caldos and the Palabora complex would fall in this class.

Volcanogenic deposits

Violent magma degassing related to extrusive and shallow intrusive process sometimes results in concentration of uranium stripped from the magma by the fluids involved. Close to the parent magma, uranium may be found in gas breccias (tuffisite breccias – per Doris Reynolds) containing relatively refractory minerals, and as uraninite at more distant locations. These fluids may, with falling energy, report as classic hydrothermal solutions and deposit uranium as disseminations or in monometallic or polymetallic veins. Deposits of this type are known in the western United States, Poços de Caldos, Brazil and the Baker Lake region of northern Canada.

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Hydrothermal veins

Thermal anomalies related to a variety of causes may result in circulation of heated groundwaters in a fashion such that uranium (and other metals) may be leached from the rocks through which the waters pass, to be subsequently deposited in an open part of the system.

Black shales

The reducing conditions existing during formation of black shales are often responsible for the collection of uranium from fresh or brackish water flowing into a shallow water (lagoonal) environment. Uranium fixed in this manner will not be released again until the shale is subjected to anatexis to the point of remelting. Black shales of Proterozoic and Cambrian age are an enormous uranium sink. Some of these shales may be economic sources of uranium in the future. The Swedish alum shales are the best example.

Uranium in coal

During or shortly after deposition of coal beds, uranium being carried in stream and groundwaters flowing over the coal may be collected within the organic material. This uranium is usually difficult to recover. However, deposits of this nature are known in central Europe, Brazil and the U.S.A.

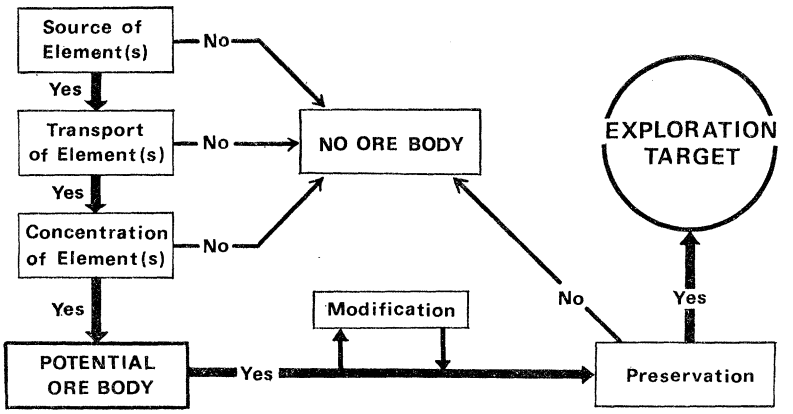

FIGURE 2. Conceptual model; formation of ore deposits.

Calcrete and gypcrete

Under appropriate desert conditions, metal leached from uranium-rich igneous and metamorphic rocks may be substantially concentrated in drainage channels due to chemical changes related to evaporation of part of the water involved. This problem is being studied in Australia and southern Africa and the chemical reactions involved are being reported upon. The Yeelirrie deposit in Australia is the best known example of this type of deposit.

Evaluation of exploration areas

Evaluation of any exploration area must include detailed study of all available geological information from the following points of view.

Ore bodies may be formed only if several indispensable conditions are met: (1) there must be a source of metal(s); (2) there must be a release and transport mechanism; (3) there must

be a concentration environment in which enrichment of the element sought may take place.

Should all of these conditions be met, the metal concentration must be preserved to the present day in order that we have a valid exploration target. Modification of the mineral concentration just short of dispersion is acceptable but is usually undesirable since it adds to a more than adequate list of exploration problems.

All uranium showings must be studied in these terms. Where any of the three conditions are found wanting, exploration priority is reduced. Should there be problems with preservation, emphasis is likewise modified.

This analysis assists in the most difficult of exploration decisions: when to stop exploring. The explorationist has ultimately both limited financial resources and limited time (i.e. working life). Perhaps misuse of time through over-exploring is a greater wrong than over-expenditure of financial resources.

The analysis described leads directly to the development of mineralization models. The descriptions of deposits given in this volume have all included genetic interpretations. The speakers have addressed the problems of where the uranium came from, how it was moved, how it was concentrated, and whether the concentration has been preserved. It is unfair to accuse any of them of being simply descriptive.

Papers have been presented on evolution of the crust and the changing behaviour of uranium with advancing geological time; we have been given details of the effect of metamorphism on uranium distribution; we have been instructed in the geochemical cycle of uranium and given the benefit of observations on, and interpretations of, the uranium content (or lack thereof) of various rocks.

Surely it is the responsibility of each one of us to process these data in our own way, using them to refine our general and particular models and understanding. These new or modified perspectives that result must be of benefit to the exploration process: undoubtedly more ore will be found. Even in advance of these expected discoveries, the meeting can be declared a success.

S. H. U. Bowie, F.R.S. I hope that we have gone some way to meet the views expressed by Dr Davis after Dr Jacob's paper. The later papers have tended to move away from magmatic differentiation to consider diagenesis, metamorphism and anatexis as processes capable of concentrating uranium. However, the swing was the other way in the presentation by Simpson *et al.* I should like to take this opportunity of saying that I think we tend to have too many models, none of which is based on adequate quantitative data and hence are most unlikely to stand the test of time. Nevertheless, it is clear that methods are currently being evolved that will throw new light on the processes that resulted in uranium deposit formation and preservation.

The fission-track method used by Simpson *et al.* should be applied on a much wider scale to study the distribution of uranium not only in granites and other igneous rocks, but in adjacent metasediments and sediments. Used in conjunction with neutron activation analysis this is an excellent method not only of measuring uranium with precision and accuracy, but of relating it to specific mineral phases.

Another method that shows promise, but which has not been mentioned during this meeting, is the measurement of lead isotopes in rock-forming minerals such as feldspar or in ore minerals

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such as galena as a means of determining whether or not the mineral comes from a uranium province. Research in the U.S.A. (Cannon *et al.* 1958) has shown that this might be an effective way of recognizing a uranium province.

It is also becoming clear that stable isotope determination has an important rôle to play in establishing the origin of uranium deposits, as does the study of fluid inclusions.

A final comment I should like to make is that we now have the methods of precision analysis such that it should be possible to determine whether there has been depletion or addition of uranium. Thus the problem of the derivation of uranium deposits from the weathering of tuffs, for example, should no longer be a matter for discussion. It could be proved one way or the other. There is an urgent need for the wider application of analytical techniques currently available as well as for other quantitative methods. If these are used to the full, I believe that many of the problems of the genesis of uranium deposits will become clearer in the near future and thus help us to find the additional reserves and resources that will be required towards the end of the century.

Reference

Cannon, R. S., Stieff, L. R. & Stern, T. W. 1958 In *Proc. 2nd Int. Conf. Peaceful Uses Atomic Energy, Geneva 1958*, vol. 2, pp. 215–232. New York: U.N.

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