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GEOLOGICAL SURVEY

Calcium-Phosphorus Relationships in Unconformity-vein Uranium Deposits, Alligator Rivers Uranium Field, Australia

by

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Abstract

Plots of whole-rock calcium vs. phosphorus for samples from the Ranger uranium orebodies, Australia, show that no altered rocks (carbonates excepted) contain any calcium- or phosphorus-bearing phases other than apatite. Calculations by Nash and Frishman (1982) showed that large amounts of P_2O_5 have been added to the volume of rock constituting the Ranger No. 1 orebody, and thus the phenomenon that formed the apatite is interpreted to be a metasomatic event that introduced phosphorus. The effects of this metasomatism cut across all lithologic and ore-grade boundaries. Whole-rock chemical data from the nearby Jabiluka orebodies show an identical pattern, and phosphorus metasomatism must have taken place there also. At both Ranger and Jabiluka, this metasomatism occurred after deposition of the fluvial sandstone that overlies the amphibolite-grade metamorphic rocks hosting the uranium ore and, at Ranger, almost certainly occurred long after the initial emplacement of the ore. Data compiled from the literature suggest that similar metasomatic events have taken place at Koongarra and Nabarlek, the other two uranium deposits in the district.

Introduction

The Alligator Rivers Uranium Field (ARUF) in the Northern Territory, Australia, hosts four important uranium deposits and scores of prospects that have not yet been drilled or are known from only very few drill holes (fig. 1). The significance of this major uranium district has been described many times and its importance in terms of world uranium resources need not be repeated here. In 1980, the U.S. Geological Survey began a study of the Ranger and Jabiluka deposits (fig. 1) as part of the National Uranium Resource Evaluation program (NURE). Our investigations were intended to provide descriptions of this important deposit type and to generate deposit models as an aid to U.S. explorationists. Nash and Frishman (1982, 1983), Nutt and Grauch (1983), and Nutt (1983, 1984) describe some of the results of these studies.

Most of the conclusions of this paper result from relationships we observed in whole-rock chemical data. The deductions leading to these

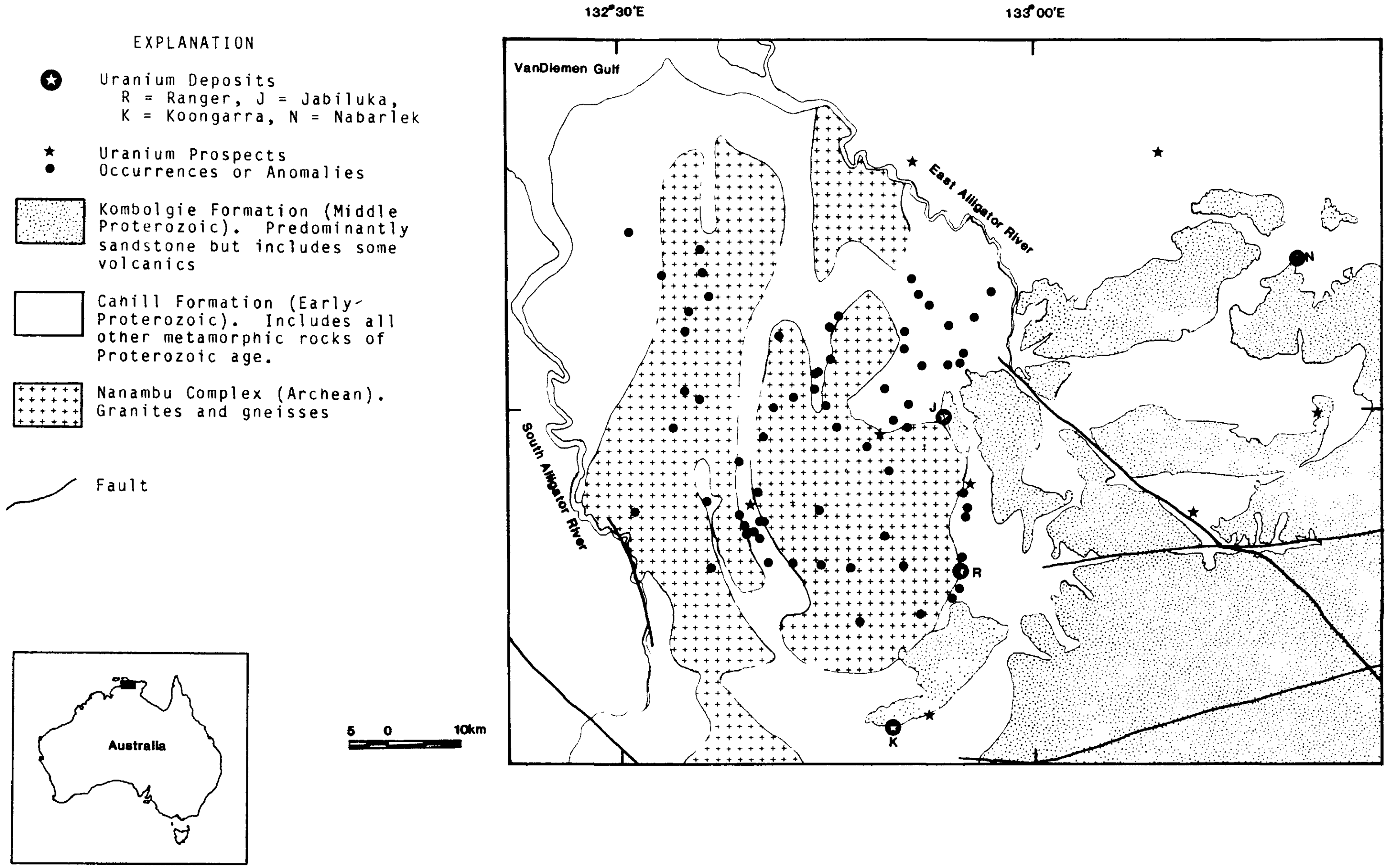


Figure 1. Generalized map of the Precambrian geology of a portion of the Pine Creek Geosyncline showing the location of the Ranger, Jabiluka, Nabarlek, and Koongarra uranium deposits and some of the nearby *uranium prospects and occurrences. Modified from Ranger Uranium Mines* (1979); the "prospects and occurrences" shown are those discovered by Ranger's initial airborne radiometric survey flown in 1970.

conclusions have been aided by our petrographic observations, but we do not intend here to fully describe the paragenesis of phosphorus-bearing phases in the deposits studied. Nash and Frishman (1982) provide some background information on how the sampling of the Ranger orebodies was conducted--the rationale described is broadly applicable to our sampling of the Jabiluka orebodies as well. Nash and Frishman (1983) describe details of sample preparation for whole-rock chemical analyses, give references for the analytical techniques used, furnish a table listing the analytical results for 370 of the Ranger samples, and present a preliminary statistical interpretation for the Ranger whole-rock analyses that includes minima, maxima, and mean abundances for the elements analyzed in the different rock types sampled, correlation and factor analysis matrices, and other information. Frishman (1984) presents an assessment of analytical errors.

Geologic Setting

The geology of the ARUF has been described by Needham and Stuart-Smith (1980) and Ewers and others (1984) and the geologic settings and geology of the Ranger and Jabiluka orebodies are described by Eupene and others (1975) and Hegge (1977), respectively. Brief descriptions of the four developed deposits in the district (Ranger, Jabiluka, Koongarra, and Nabarlek, fig. 1), plus a useful summary of geologic controls on uranium mineralization in the ARUF are provided by Eupene (1980). We present here only a generalized and extremely simplified summary of the geologic setting of the Ranger and Jabiluka deposits. To a limited extent, these general characteristics also describe the geologic settings of the Koongarra and Nabarlek deposits, although Nabarlek differs from the other three in some important respects (see Ewers and others, 1983, and Eupene, 1980).

At both Ranger and Jabiluka, ore occurs almost exclusively in a 3000-m thick sequence of lower Proterozoic marginal marine sediments (the Cahill Formation) that were metamorphosed to amphibolite grade around 1800 m.y. b.p. In the vicinity of the deposits, these rocks include quartz-feldspar-biotite schists, quartz-muscovite schists, dolomite and magnesite marbles, rare quartzites, and jasperoid units as well as intercalated pegmatites, granitic dikes, and diabase dikes and sills. Since the peak of metamorphism, this metasedimentary succession has undergone partial retrogressive metamorphism to a greenschist facies assemblage, has been planed off by a period of erosion, and has been covered by the fluvial quartz-rich sandstones of the Kombolgie Formation, also of Proterozoic age (1648 ± 29 m.y., Page and others, 1980). In addition to the regional retrogressive metamorphism mentioned above, both the Cahill and the Kombolgie Formations have locally undergone pervasive chloritization. Chloritization is a regional metasomatic phenomenon distinctly different from the regional retrograde metamorphic event and is not restricted to the vicinity of the uranium deposits, although all of the uranium deposits are extensively chloritized (Eupene, 1980). Additional chloritization has taken place within the uranium deposits at the time of mineralization.

The structural geology in the region surrounding the ore deposits is poorly known, largely because outcrops are quite sparse. Within the deposits themselves, drilling on 25 to 60 m centers precludes the definition of much structural detail, but Nash and Frishman (1982) speculated on the existence of low-angle faulting within the Ranger One orebody, and we believe that low-angle faults, expressed in drill core as pene-concordant breccia zones, are also an important ore control at Jabiluka. High-angle faults, which apparently offset ore, are shown on subsurface maps and in cross sections of the Jabiluka deposit published by Hegge (1977), Gustafson and Curtis (1983) and Nutt and Grauch (1983), and high-angle faults are required to explain the position of a block of Kombolgie sandstone in the No. 3 orebody at Ranger (see Eupene, 1980, figure 9). We have also observed the noses of small-scale, isoclinal folds in Jabiluka drill core and we are convinced that these fold noses are only the manifestation in hand specimen of much larger structures.

Terminology Used to Describe Alteration

We have already alluded to alteration events that affected the ARUF. Prograde metamorphism to an amphibolite facies mineral assemblage, regional retrograde metamorphism, regional chloritization, and alteration associated with uranium mineralization are each events whose areal extents can be delimited and whose chemical and mineralogic effects can be defined. However, within and near the uranium deposits, these events, plus others, have all been superimposed on one another and this has given rise to a somewhat complicated system of terminology. This terminology requires some definition, and what is set out below will, we hope, allow comprehension of the arguments to follow later in this paper with a minimum of confusion.

Types of Alteration

Retrogressed--applies to any rocks below the unconformity with the possible exception of some diabase dikes and sills (some of which were probably emplaced after the culmination of the retrograde metamorphic event). As used here, includes both altered and unaltered rocks. Retrogression is seen as a regional event and, at least for now, can be thought of as the result of regional tectonics and completely unrelated to any other process dealt with in this paper.

Unaltered = Fresh--for pelitic lithologies, means the rock contains feldspar and may contain relict garnet or recognizable garnet pseudomorph. Feldspar may be either pristine or partially saussuritized. For carbonates, "Fresh" means they contain no significant abundance of silicate phases. Here, we use this term indiscriminately to include both retrogressed and non-retrogressed lithologies although we realize that some "Fresh" rocks do in fact contain white mica and chlorite. We view this white mica and chlorite as being fundamentally different in origin, however, from that produced by alteration associated with uranium ore formation or that produced by any other deposit-specific alteration event.

Altered--for pelitic lithologies, means rocks in which all feldspar has been converted to other phases. For carbonates, "Altered" means they contain abundant silicates, most commonly chlorite. "Altered" includes all the terms defined below as well as some minor types of alteration not discussed here at all. Sample were assigned to the "Altered" or "Unaltered" category on the basis of visual inspection of drill core only.

Chloritized--for all lithologies, means the rock contains abundant chlorite. In part, this chlorite was produced by the regional retrogressive metamorphism or the regional chlorite metasomatism, but, within the orebodies, most of the chlorite is probably the product of alteration that accompanied the mineralizing event(s) and other episodes of alteration that affected the rocks in and close to the ore zones.

Sericitized--contains abundant white mica.

Silicified--textures or composition indicate the addition of SiO_2 to the rock. Most commonly used to describe the jasperoid units at Ranger (interpreted to be silicified marbles) but also applied to other units (e.g. the Kombolgie Formation, where appropriate).

Hematitized--rock contains abundant hematite. With the exception of some carbonates, hematitizaton is almost always superimposed upon another type of alteration.

Mineralized--rock contains greater than background abundances of U_3O_8.

Phosphorus metasomatism--addition of P but may include remobilization of P from other phases and its reconstitution into apatite. Inherent in the term is the assumption that addition of P_2O_5 was the controlling factor in the reaction and that sufficient calcium for the reaction to proceed was available from other phases. The necessity for and definition of this term are actually one of the conclusions of this study.

Previous Work on Ca-P Relationships in Uranium Deposits in the ARUF

A number of workers have observed the occurrence of apatite and the relationships between calcium and phosphorus in ARUF uranium deposits. As a result of their study of the Jabiluka deposit, Binns and others (1980) mentioned that accessory apatite is more abundant in retrogressed Cahill

Formation schists than in pristine schists and that, at Jabiluka, Ca and P are enriched in the basal few meters of the Kombolgie Formation overlying the uranium deposit (apatite replaces the sandstone matrix in these rocks). They also found that Ca and P are slightly enriched in disseminated ore at Jabiluka, due in part to concentration of apatite in breccia zones. Gustafson and Curtis (1983) noted that phosphorus abundance in the Kombolgie at Jabiluka was variable but that, overall, the sandstone was enriched in P. Their studies also suggested that mineralized Cahill schists were depleted in P and that phosphorus enrichment was observed in massive chlorite rocks near the unconformity but was not apparent in similar rocks at some distance from this surface (it is worth noting here that very preliminary graphs of our data from Jabiluka do not agree with this conclusion, but we have not yet done enough work on this aspect of the problem to disagree categorically and we will not consider this point further). Eupene and others (1975) noted the occurrence of localized high concentrations of apatite in the Ranger orebodies, and Nash and Frishman (1982) concluded that there had been a net addition of P_2O_5 to the rocks of the Ranger No. 1 orebody. Frishman and others (1983) presented earlier versions of some of the conclusions to be described later in this paper. Ewers and others (1983) discussed the occurrence of apatite at the Nabarlek deposit (fig. 1)--their results will also be discussed later in this paper.

Calcium - Phosphorus Correlations at Ranger and Jabiluka

Ranger

In their investigation of whole-rock chemical relationships at Ranger, Nash and Frishman (1983) assigned each sample to an alteration class based on which type of alteration seemed predominant in hand specimen--the alteration classes were essentially those described previously (e.g. samples were predominantly chloritized, silicified, sericitized, unaltered, etc.). Examples of both altered and unaltered rocks from Ranger are shown in figure 2, and, as a broad, oversimplified generalization, unaltered pelitic rocks may contain fresh to slightly saussuritized feldspar whereas altered rocks contain no relict feldspar whatsoever. The importance of this distinction between altered and unaltered lithologies will be addressed below.

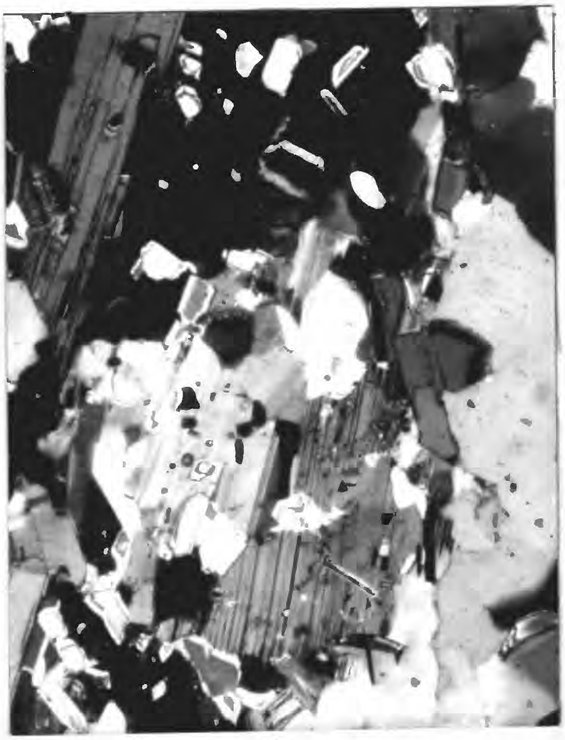
Figure 2. Photomicrographs of samples from the Ranger uranium deposit. The longest field of view in all photomicrographs is 0.35 mm.

a. Unaltered plagioclase-biotite gneiss from the Footwall Sequence of the No. 3 orebody; drillhole 83, 544.6 meters, crossed nicols.

b. Slightly chloritized Kombolgie Formation from the block of quartz sandstone in fault contact with the No. 3 orebody; drillhole 59, 30.6 meters, plane polarized light.

c. Chloritized Kombolgie sandstone from the hole adjacent to drillhole 59. Note the corroded and embayed margins on the quartz grains. Drillhole 97, 90.9 meters, plane polarized light. This sample is the one marked with the "◉" symbol in figure 5.

d. Subhedral apatite (white) set in a matrix of chlorite (mottled) and hematite (black). Ranger 1 drillhole 73, 44.1 meters, plane polarized light. Apatite also occurs as rounded to euhedral crystals embedded in a chlorite matrix (see figure 6 in Nash and Frishman, 1982).



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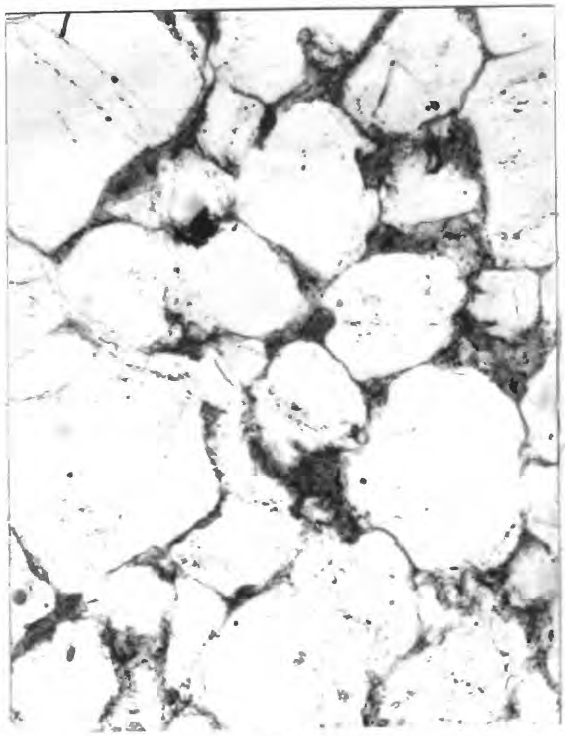

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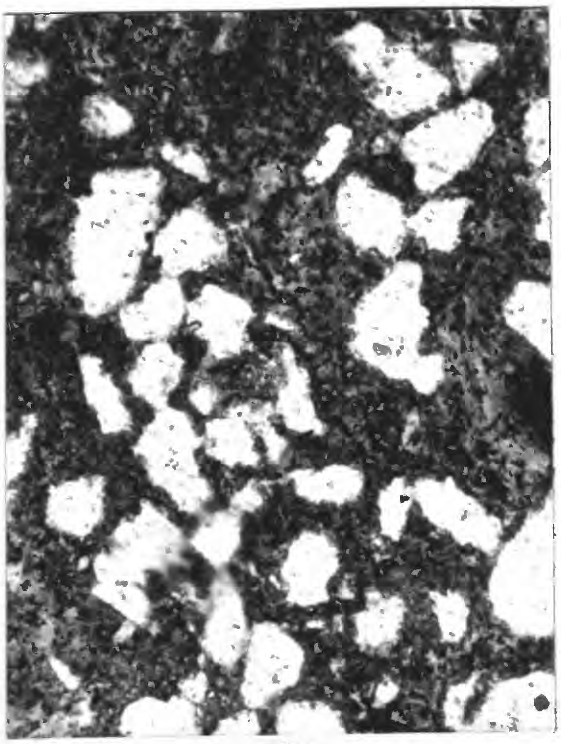

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Nash and Frishman (1982) noted abundant apatite in some samples from the Ranger deposits and calculated (for illustrative purposes only) that approximately 10,000 metric tons of P_2O_5 had been added to the volume of rock making up the No. 1 orebody. Further calculations have shown that, for all rocks types of generally pelitic composition in both the No. 1 and No. 3 orebodies, altered rocks at Ranger contain an average of approximately four times as much P_2O_5 as do unaltered rocks (0.47 vs. 0.13 weight percent, respectively). The precise magnitude of these numbers is not really important for the arguments to be presented here, but it should be clear that some sort of phosphorus metasomatism has taken place and that there has been a net addition of P_2O_5 to the rocks in the Ranger orebodies.

Figures 3 through 5 show the relationships between whole-rock calcium and phosphorus at Ranger. As far as we can tell, the remarkably straight lines defined by the points plotted in these figures are not a function of the particular samples we chose for analysis, analytical error, or creative drafting, but are instead a reflection of important geochemical processes that have occurred during the evolution of these ore deposits. The conspicuous inclined lines defined by the points plotted in figures 3 through 5 have a slope essentially indistinguishable from that which would be expected for a plot of Ca vs. P in apatite. A linear regression for the points plotted on figure 4 results in the equation $CaO = 1.348\ P_2O_5-0.006$, and the ideal formula for fluor-apatite can be expressed as $CaO = 1.317\ P_2O_5$ (we do not yet have any quantitative microprobe analyses of apatites from either the Ranger or Jabiluka deposits and do not, therefore, know which variety of apatite is present).

Noting the lithologic information plotted in figures 3 and 5, we can conclude that this metasomatic event has affected, to one degree or another, all of the rocks present in the vicinity of the Ranger orebodies. Comparing figures 3 and 4 shows that for virtually all of the samples, the most prominent difference between those samples that plot on this "apatite line" and those that do not is that when we were logging core at Ranger's core sheds, we described the apatite-bearing rocks as being "altered" in some respect. This difference between where altered and unaltered samples fall on the whole-rock Ca-P plot is all the more striking because, for most samples,

Figure 3. Plot of whole-rock calcium vs. phosphorus for all samples analyzed from the Ranger orebodies. 370 points; analyses are published in Nash and Frishman (1983). Only samples that help to elucidate the geochemical events we infer to have occurred are plotted with a special symbol indicating lithology--all others are simply plotted as "x".

Key to lithologic and ore grade symbols:

● = Kombolgie Formation sandstone

✷ = jasperoid or "chert"

■ = pegmatite or granitic dike

★ = massive chlorite-rock or "injected chlorite"

▲ = all other rocks of pelitic composition (Upper Mine Schists, Main Mine Series Schists, etc.)

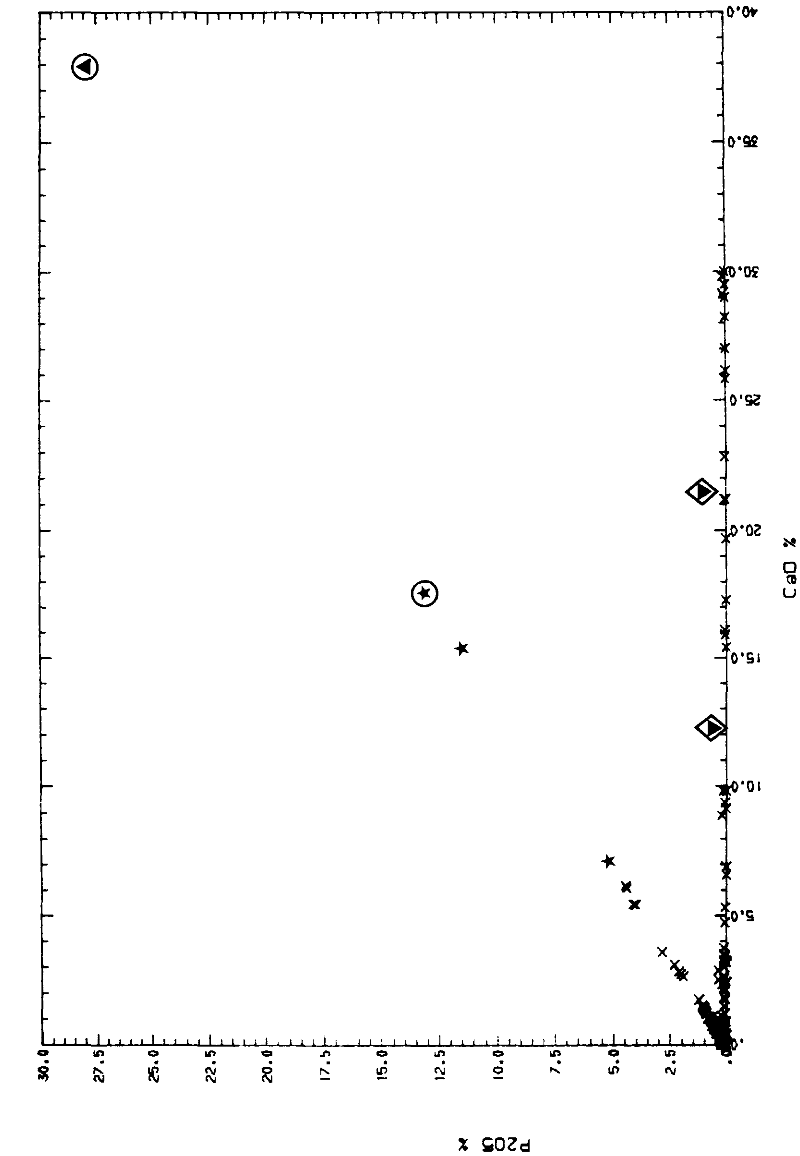
▼ = chloritized marble

○ = mineralized (> approximately 150 ppm U)

◇ = ore (> approximately 0.25% U)

× = undifferentiated rock types, including all those specified by the above symbols.

See Nash and Frishman (1982) and Nutt and Grauch (1983) for explanations of lithologic terminology.


P2O5 %
CaO %
30.0
27.5
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
35.0
40.0

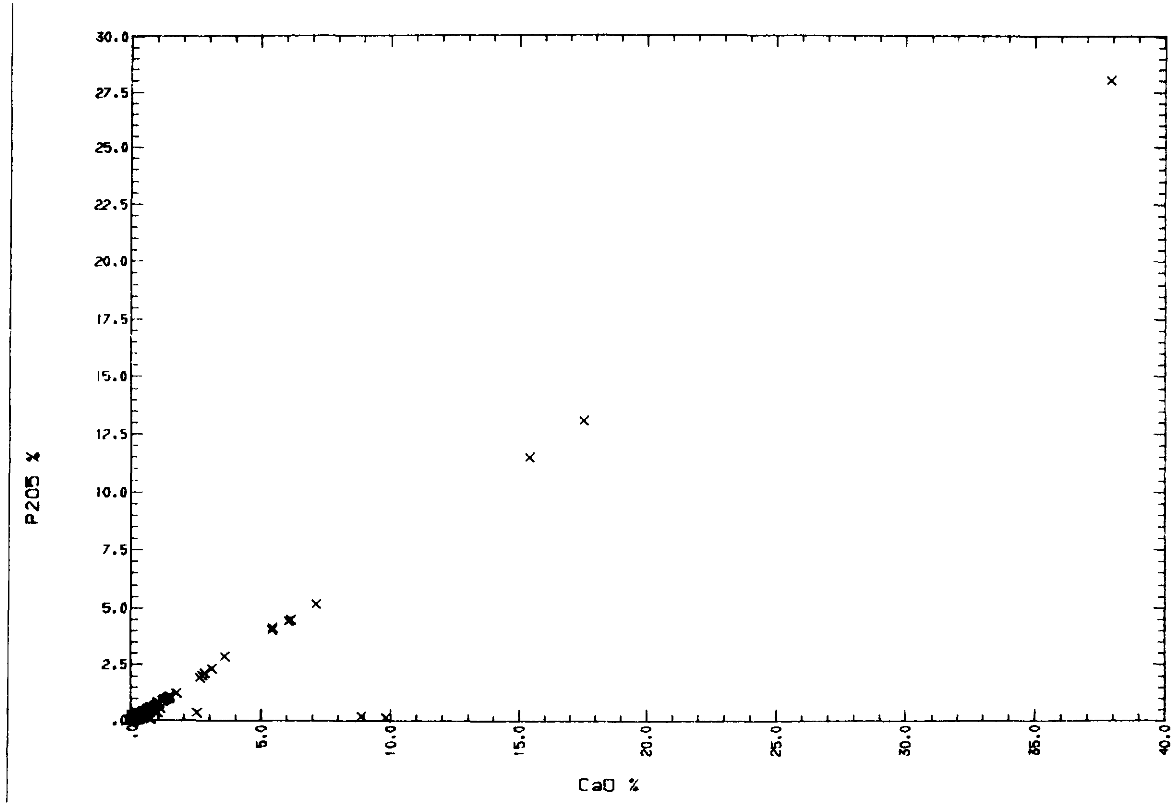


Figure 4. Same data as plotted in figure 3 except all samples described as "unaltered" when we logged the drill core and all carbonates, both altered and unaltered, have been excluded. Types of alteration include sericitization, chloritization, silicification, and hematitization. See Nash and Frishman (1982) for a more detailed discussion of alteration mineralogy. 288 points. The equation for the line defined by these points is $CaO = 1.348\ P_2O_5 - 0.006$, the ideal formula for fluor-apatite would be $CaO = 1.317\ P_2O_5$.

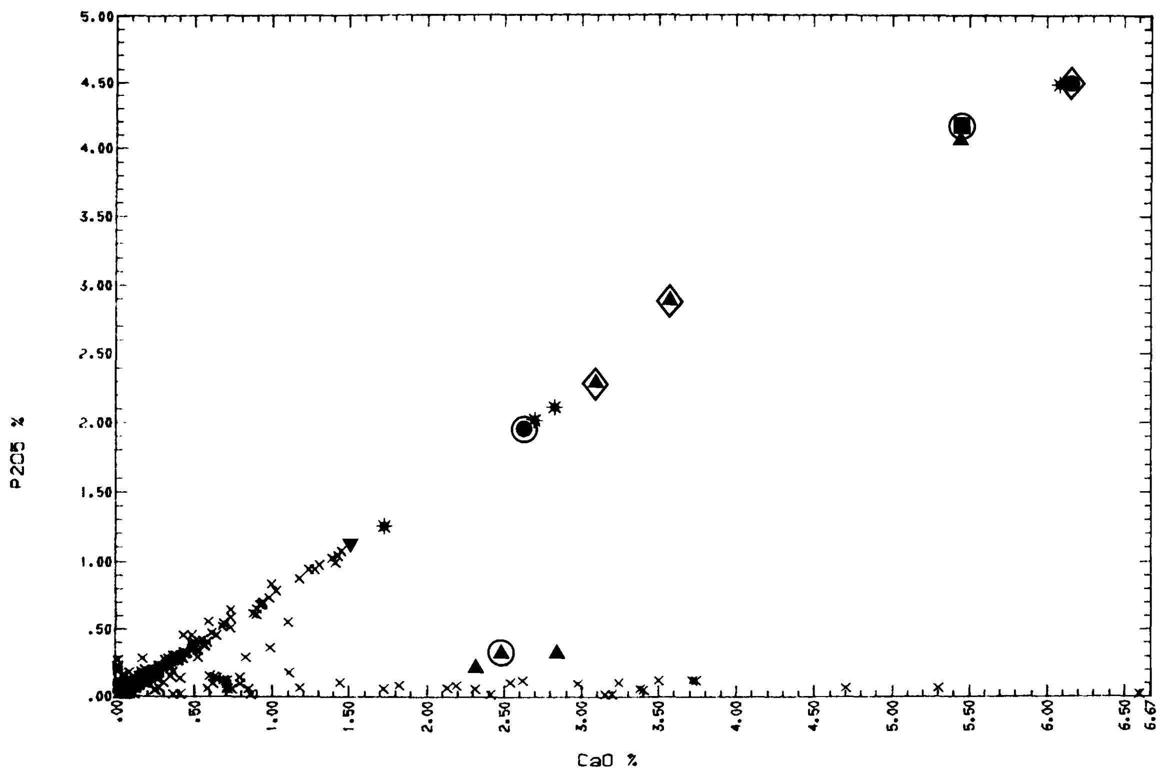


Figure 5. Same data as shown in figure 3 plotted with the scales expanded to show that the relationships depicted in figures 3 and 4 prevail at much lower concentrations of Ca and P. This relationship is still apparent in the data that falls in the tens to hundreds of ppm range.

the effects of the apatite introduction itself are too subtle to recognize in hand specimen and, in fact, we did not recognize that apatite had been added to theses rocks when we examined them in the field.

These data demonstrate that altered rocks at Ranger contain apatite, unaltered rocks do not, and, further, that altered rocks (carbonates excepted) do not contain any significant abundance of any mineral containing Ca or P other than apatite. Nutt (1983) has identified the cerium-aluminum phosphate florencite at Jabiluka and Ewers and others (1983) mentioned that the same mineral may occur at Nabarlek; it is apparently rare at both localities and we have not yet found any at Ranger. Additionally, hydrated uranium phosphates like those reported from weathered rock at Koongarra (Snelling, 1980) no doubt occur within the Holocene weathering profile developed over the Ranger orebodies also, but these secondary U^{+6} phases are not relevant to this discussion and we will not consider them further.

Uranium contents of the samples most enriched in P range from nil through low-level enrichment to minable ore (figs. 3 and 5). Radiographic studies indicate that the apatite itself contains very little uranium. Nash and Frishman (1983) concluded that there is no significant correlation between uranium and phosphorus for any rock type or subdivision of ore that we studied with the sole exception of the rather rare occurrences of ore in the chloritized intervals of the Lower Mine Series marbles (Nash and Frishman, 1983). This "significant correlation" in the marbles may be misleading, however, for it arises dominantly from the uranium-phosphorus relationship in only 3 of 28 samples. Uranium and phosphorus analyses for these 3 samples are listed below.

Sample No.	P_2O_5 %	U ppm
80 219.8	1.11	13.4
83 445.6	0.99	6300
82 419.6	0.54	9000

All other samples of marble, chloritized or not, contain less than 0.16 percent P_2O_5 and only one contains more than 50 ppm U (sample 81-183C with 173 ppm U). Because correlation coefficients are strongly weighted by highly deviant samples, we now feel that the uranium-phosphorus correlation is no more significant in the chloritized marbles than in any other lithologic grouping. Apparently, the effects of this phosphorus metasomatism cut across both lithologic and ore grade boundaries and the lack of correlation between these two elements implies either that phosphorus and uranium were added to the rocks during separate events or that they were differentially mobilized subsequent to their deposition.

The age of emplacement of primary ore at Ranger is still incompletely known. Studies in progress by Ken Ludwig of the U.S. Geological Survey should answer many of the questions that still remain, but the U/Pb isotopic work of Hills and Richards (1976) provides the best ages available to date. Hills and Richards point out that "none of the evidence from Ranger can be regarded as definitive....", but, based on concordia plots of pitchblendes and $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plots of pitchblendes and galenas, they conclude that 1700 to 1800 m.y. is the most probable age for primary mineralization at Ranger. If this age is correct, then the metasomatism that added the phosphorus to these rocks probably occurred very much later, for the phosphorus event also affects the Kombolgie Formation (fig. 5). Alternatively, it is possible that phosphorus was added before deposition of the Kombolgie Formation and merely remobilized at a later date. However, if this metasomatism took place after mineralization, then it also would be reasonable to expect that preexisting uranium ore would be remobilized, at least to some extent. We believe that this has occurred and that this late-stage remobilization is why minor amounts of ore occur in the Kombolgie Formation in the Ranger No. 3 orebody (Nash and Frishman, 1982).

Jabiluka

Figures 6 and 7 show calcium-phosphorus relationships in the whole-rock analyses from Jabiluka; the overall correspondence to the graphs of the Ranger data is self evident and the conclusion that Jabiluka has also gone through an episode of phosphorus metasomatism, or at least phosphorus remobilization, seems inescapable. Abundant apatite in samples of Kombolgie Formation from Jabiluka (figs. 6 and 7) means that, as at Ranger, this event must have occurred after deposition of the sandstone. Further, again by analogy with Ranger, these apatite-rich Kombolgie samples are permissive evidence that

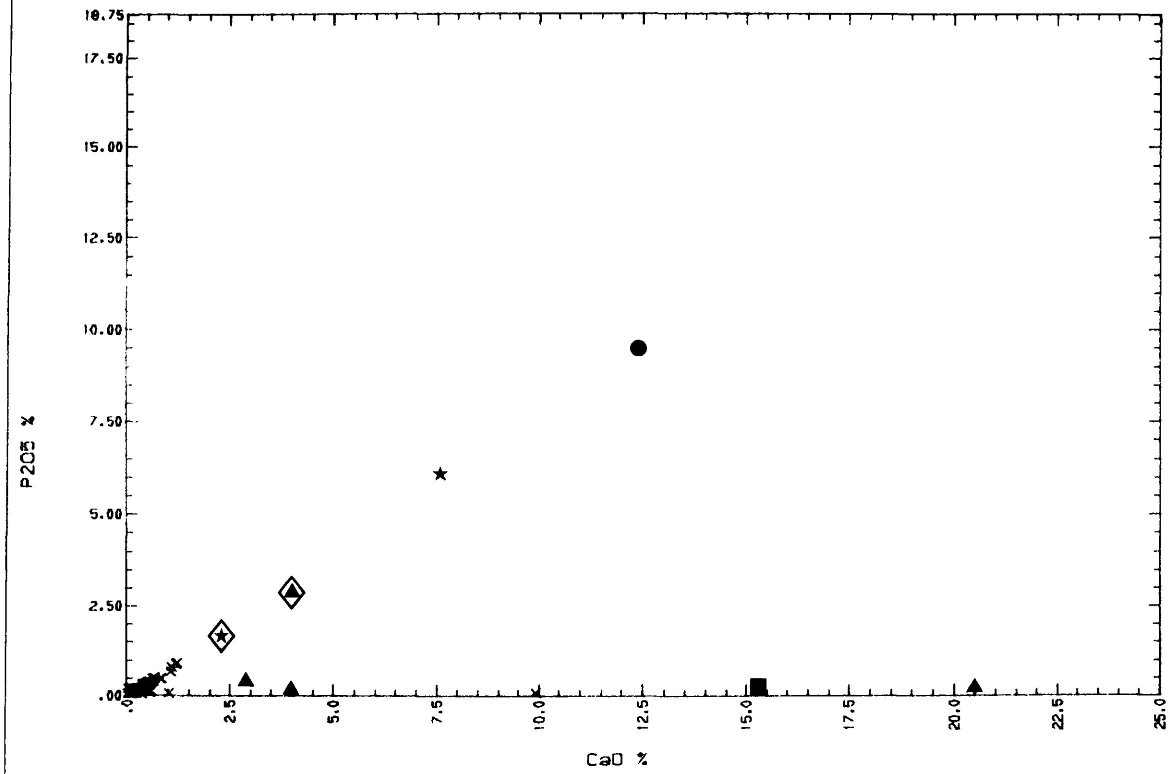


Figure 6. Plot of whole-rock calcium vs. phosphorus for all samples analyzed from the Jabiluka orebodies. 241 points. Plotting symbols are the same as those used in figure 3.

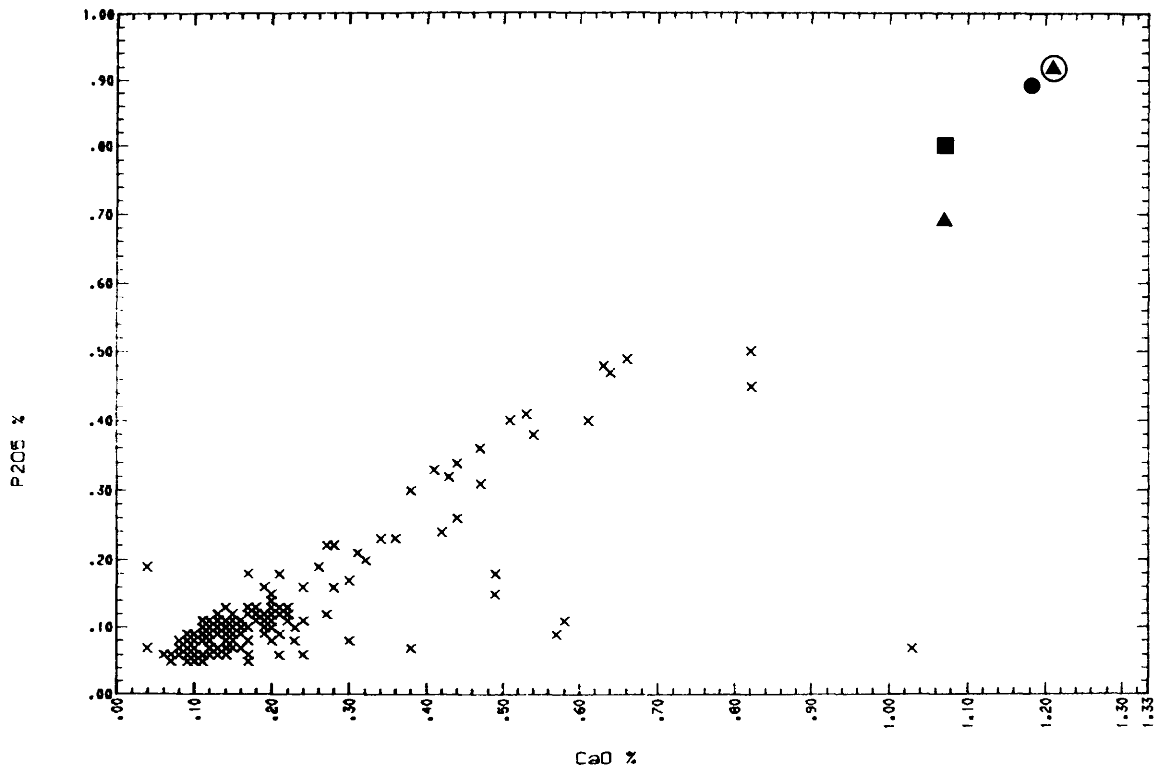


Figure 7. Same data as that plotted in figure 6 but with expanded scales, 232 points.

phosphorus has also been added to the rocks at Jabiluka and not just remobilized and concentrated in favorable traps. Geochemical studies of the Jabiluka sample suite are not yet far enough advanced for us to be able to quantify the amount of phosphorus that may have been added to the Jabiluka orebodies.

When studied in detail, however, there is a major difference between the Jabiluka and Ranger data that is at least as conspicuous as their similarity. In contrast to the Ranger data, the points plotted in figures 6 and 7 can not be separated into any simple groups. That is, we cannot yet define any macroscopically visible property that would allow us to differentiate apatite-bearing samples from those devoid of that mineral. Samples like those depicted in figure 8 may look very similar in hand specimen, and the "altered" versus "unaltered" classification that proved, ex post facto, to discriminate between apatite-bearing and apatite-free samples at Ranger does not apply at Jabiluka. Further, apatite paragenesis is apparently much more complicated (or the evidence for a complex paragenesis is better preserved?) at Jabiluka than at Ranger. On the basis of the presence or absence of hematite inclusions, we have identified at least two generations of apatite at Jabiluka, and differing textural relationships are clear evidence of more than one period of phosphorus mobility (Nutt, in press).

Calcium and Phosphorus in Other Uranium Deposits in the ARUF

As mentioned earlier, Ewers and others (1983) also found a good correlation between Ca and P in their study of the Nabarlek uranium deposit. Figure 9 is redrafted from their paper and looks very similar to, for example, our figure 7, although Ewers and others did not have the opportunity to analyze and subsequently plot any samples remote from ore and devoid of alteration. Nabarlek is dissimilar to the other three known uranium deposits in the ARUF in many respects, but it appears from the data plotted in figure 9 that Nabarlek also contains few calcium- or phosphorus-bearing phases other than apatite [the possible occurrence of florencite at Nabarlek was mentioned above, and Ewers (written communication, 1982) notes that uraninite in the five high-grade ore samples not plotted in our figure 9 may contain Ca in the

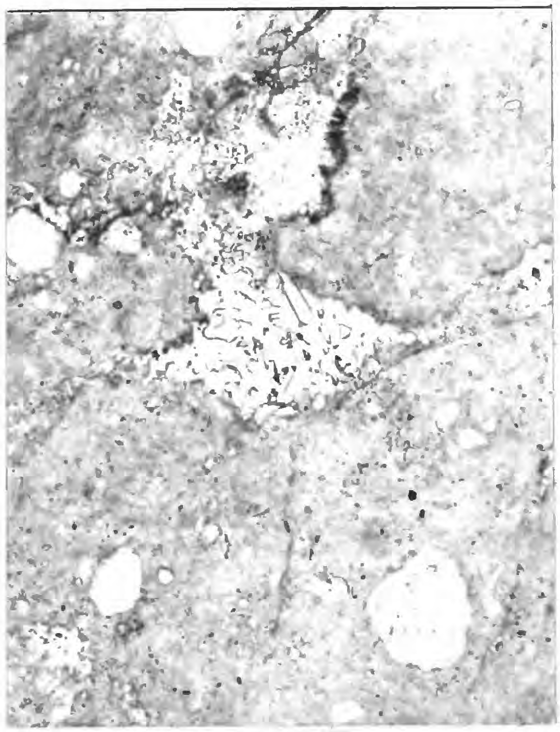
Figure 8. Photomicrographs of samples from the Jabiluka uranium deposit. The longest field of view in all photomicrographs is 0.35 mm. All thin sections depicted here are described more fully by Nutt (1983).

a. Fine-grained apatite (mottled) is interlayered with quartz (white) and pyrite (black). Drillhole T129V, 163.8 meters, plane polarized light. These apatite layers are both folded and, locally, broken indicating at least some deformation subsequent to their formation.

b. Euhedral apatite prisms (center) partially fill a vug in brecciated chlorite-quartz schist. Section is cut from the same hand specimen as "a", above; plane polarized light.

c. Unmineralized quartz-sericite-muscovite schist from the Footwall Schist Series beneath the Jabiluka II orebody. Drillhole T129V, 210.6 meters, crossed nicols. This sample is typical of many of both the mineralized and unmineralized schists at Jabiluka and contains low abundances of both phosphorus and calcium. Contrast with figure 2a.

A



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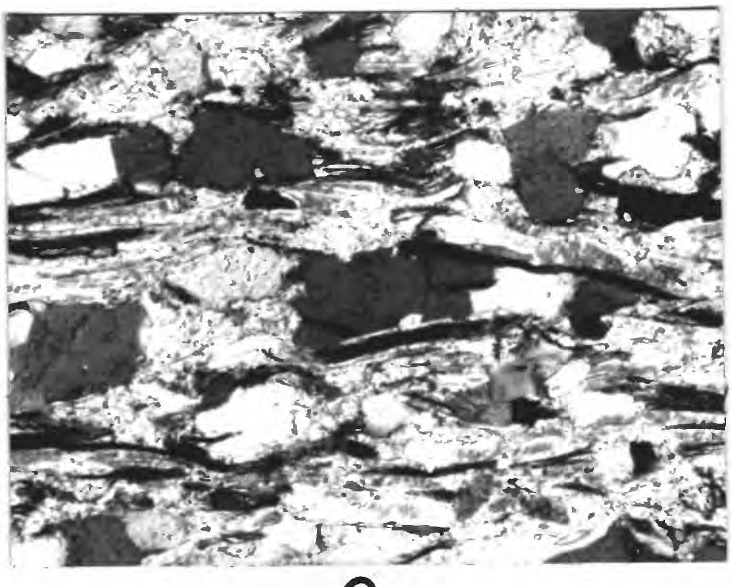

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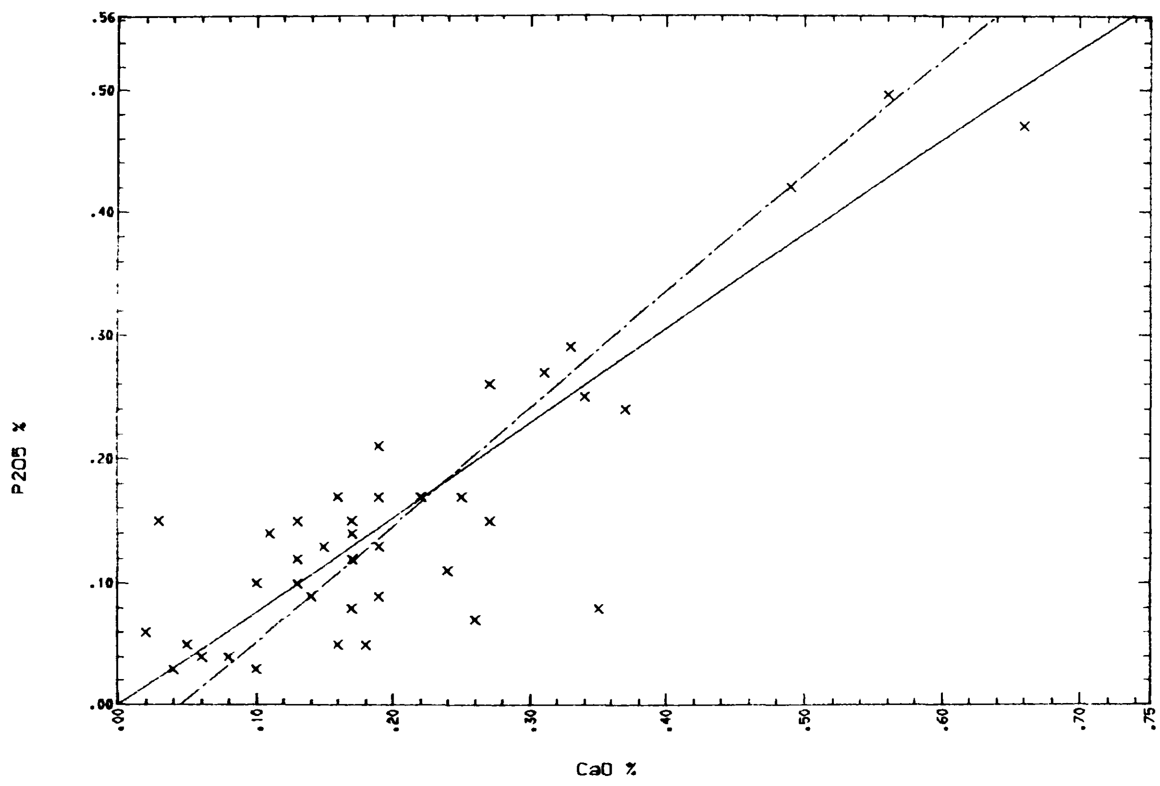


Figure 9. Plot of whole-rock calcium vs. phosphorus for 39 samples from the Nabarlek uranium deposit; data are taken from Ewers and others (1983). Five samples containing more than one percent CaO and with very low phosphorus abundances (shown by Ewers and others in their figure 8) are omitted from this graph--all five samples contain >20 percent U and also contain minor carbonate. A linear regression line (the dot-dash line) through the points plotted here has the formula $CaO = 1.06\ P_2O_5 + 0.05$. The solid line shows the stoichiometric proportions of CaO and P_2O_5 in apatite.

uraninite structure--see Berman, 1957]. It appears that Nabarlek too may have been affected by a phosphorus metasomatic event that has overprinted earlier ore-forming events.

Lastly, figure 10 shows all the relevant data of which we are aware for the Koongarra deposit. These data are compiled from the microfiche appendix included with Ferguson and Winer (1980) and, although those authors include some sample location data (drill hole number and depth) and a brief sample description (e.g. "chlorite-muscovite schist"), we have not yet been able to subdivide the samples into any meaningful groups. The lines shown on figure 10, a reference line representing the stoichiometry of Ca and P in apatite and a linear regression fit to the data, seem to at least allow the premise that phosphorus metasomatism and fixation of that phosphorus as apatite has also taken place at Koongarra.

Discussion

We have considered, but rejected, the possibility that the apatite is detrital. Figures 3, 5, and 6 show that some of the very apatite-rich lithologies include jasperoid and "chlorite-rock." Both of these rock types are interpreted to be largely of metasomatic origin; virtually all of the original rock constituents have been removed and the pelitic schist, dolomite-magnesite marble, or whatever rock was present has been almost totally converted to either jasperoid or chlorite. We have pointed out the consequence of these mass transfer reactions before (Nash and Frishman, 1982). The progressive development of these kinds of metasomatic lithologies is particularly well illustrated, at both Ranger and Jabiluka, by considering samples of altered Kombolgie Formation. For samples like those shown in figures 2b and 2c, we are fairly certain that the original lithology was essentially a quartzite with only minor amounts of chlorite, sericite, or clay. We do not think that the alteration easily discernable in samples like those shown in figures 2c, 2d and 8a through 8c is due solely to the metasomatic episode that added the phosphorus to the rocks--some of the chloritization, silicification and sericitization of the units that constitute the Ranger and Jabiluka orebodies certainly took place during uranium mineralization and some was probably produced during other alteration

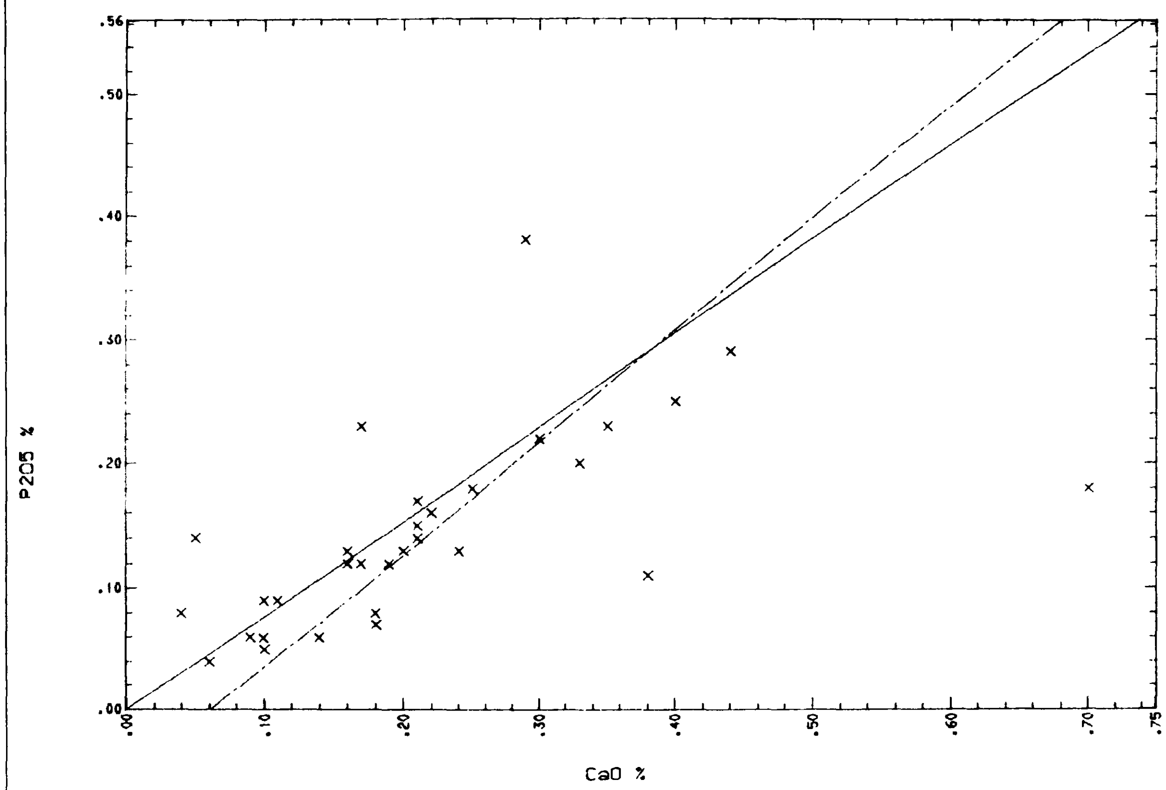


Figure 10. Plot of whole-rock calcium vs. phosphorus for samples from the Koongarra uranium deposit; data are taken from Ferguson and Winer (1980). The linear regression (the dot-dash) line through these points has the formula CaO = 1.10 P_2O_5+0.06; the solid line is a reference line representing the stoichiometric proportions of CaO and P_2O_5 in apatite.

events. We also do not think, however, that relict detrital apatite in the original amphibolite-grade assemblage or detrital apatite in the Kombolgie Formation (if any is present--none has been reported) would have survived these dramatic alteration events. Additionally, although we are reluctant to put too much weight on data as subjective as textural interpretation, many of the apatite textures do not look detrital (figs. 2d and 8b).

One obvious difference between figures 3 and 6 as compared to figures 9 and 10 is the lower absolute abundance, or at least lower maximum abundance, of phosphorus in samples from Nabarlek and Koongarra compared to those from Ranger and Jabiluka. This difference may merely be due to a difference in sampling. Ewers and others (1983) plot 44 points on their graph for Nabarlek and Ferguson and Winer (1980) provide 33 points for the Koongarra deposit, whereas the Ranger and Jabiluka data encompass 370 and 347 samples, respectively (although the number of points plotted in our graphs is in some cases smaller due to some samples falling below the limit of detection for one element or the other and because numerous data points plot at the same coordinates, particularly at low abundances of Ca and P). At Ranger, only 18 samples (or 5 percent of those we analyzed) contain more than 1.0 percent P_2O_5 and only 4 samples (1 percent) contain more than this amount at Jabiluka. The apatite present in the very phosphorus-rich rocks at the two deposits we studied is quite inconspicuous in drill core, and we did not identify it in the field. It is possible that rocks as rich in phosphorus as those we sampled at Ranger and Jabiluka do exist at Nabarlek and Koongarra but that they have not yet been recognized.

This possibility is emphasized when one considers figure 11. The graphs of CaO vs. P_2O_5 presented earlier were all plotted at scales designed to best represent the data for each ore deposit. For example, the data from Koongarra (fig. 10) were plotted with the CaO axis spanning the interval from 0 to 0.75 percent because no Koongarra sample analyzed contained more than 0.75 percent CaO. Figure 11 shows all the data sets at the same scales. Note that the conspicuous relationship between Ca and P shown by our data for Ranger and Jabiluka (figs. 11a and 11c) is also apparent in data for those deposits taken from Ferguson and Winer (1980) if one includes the samples rich in phosphorus (figs. 11b and 11d), but much less apparent if the scale on the axes is

Figure 11. Plots of whole-rock calcium vs. phosphorus for all four orebodies in the ARUF. For each data set, two graphs are presented, one at the scale of figure 4 (the expanded plot of our data from the Ranger orebodies) and one at the scale of figure 10 (the plot of the Koongarra data taken from Ferguson and Winer, 1980). The graphs show CaO from 0 to 6.67 percent vs. P_2O_5 from 0 to 5.00 percent and CaO from 0 to 0.75 vs. P_2O_5 from 0 to 0.56 percent. The scales chosen are such that the line representing the stoichiometric proportions of Ca and P in apatite runs approximately from the origin to the upper right-hand corner of each graph. The orebodies from which the samples came the sources of the data used, and the number of points plotted are:

A and A'--Ranger, this study, 337 and 273 points.
B and B'--Ranger, Ferguson and Winer, 1980, 37 and 27 points.
C and C'--Jabiluka, this study, 338 and 335 points.
D and D'--Jabiluka, Ferguson and Winer, 1980, 63 and 50 points.
E and E'--Nabarlek, Ewers and others, 1983, 39 points in each graph.
F and F'--Koongarra, Ferguson and Winer, 1980, 33 points in each graph.

Fewer points than the number indicated appear in some of the graphs because, in some cases, numerous values plot at the same position.

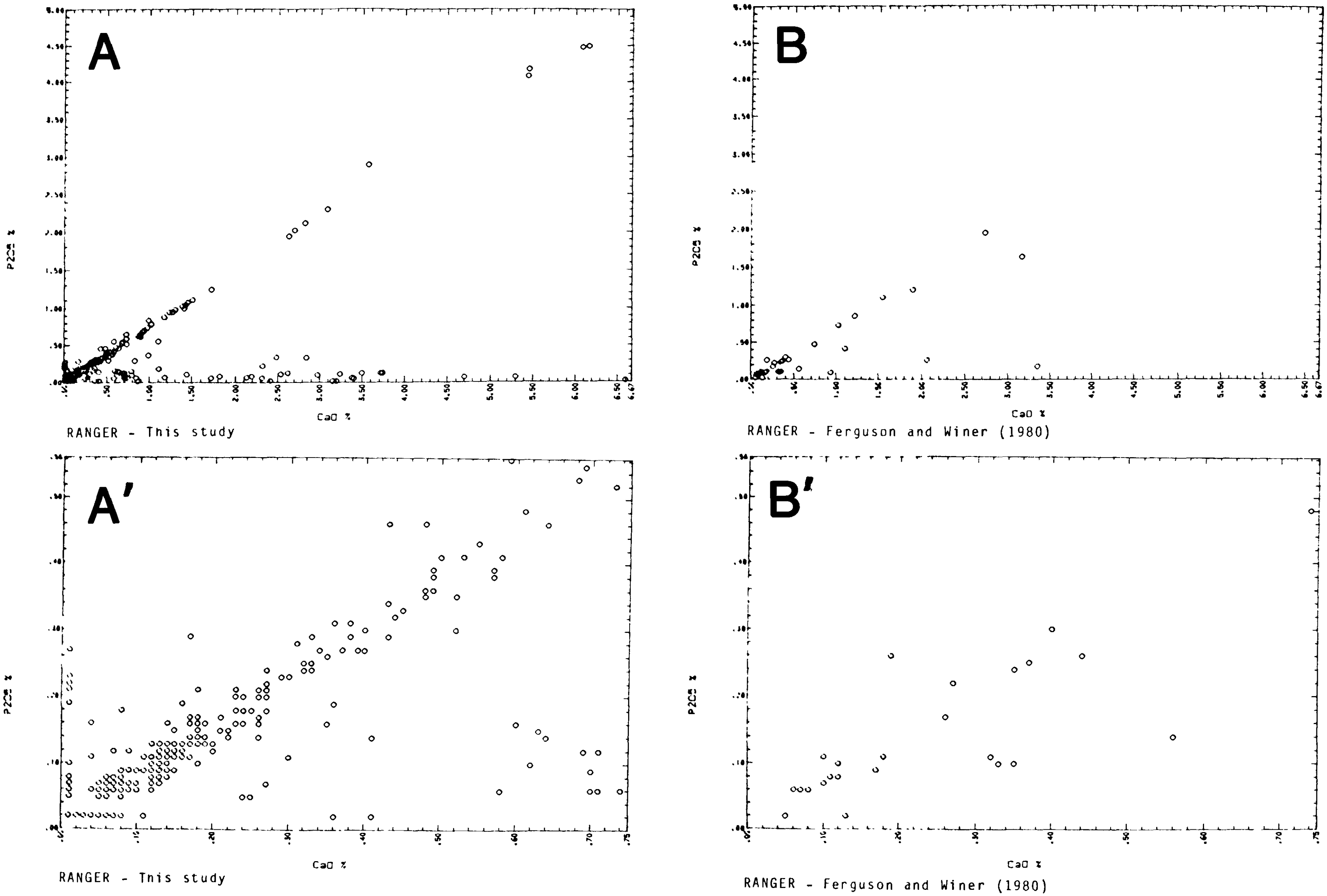


Figure 11 (Cont'd.)

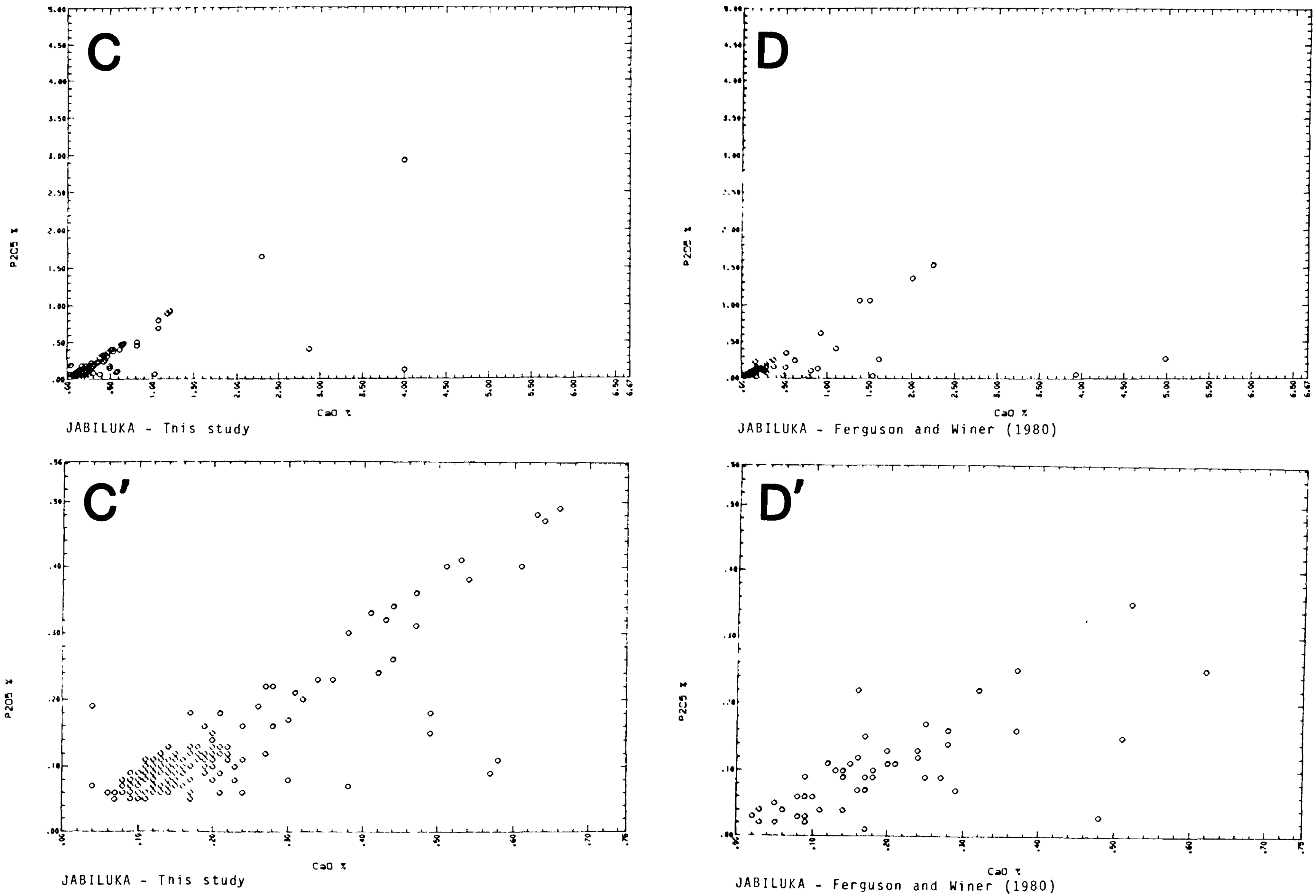
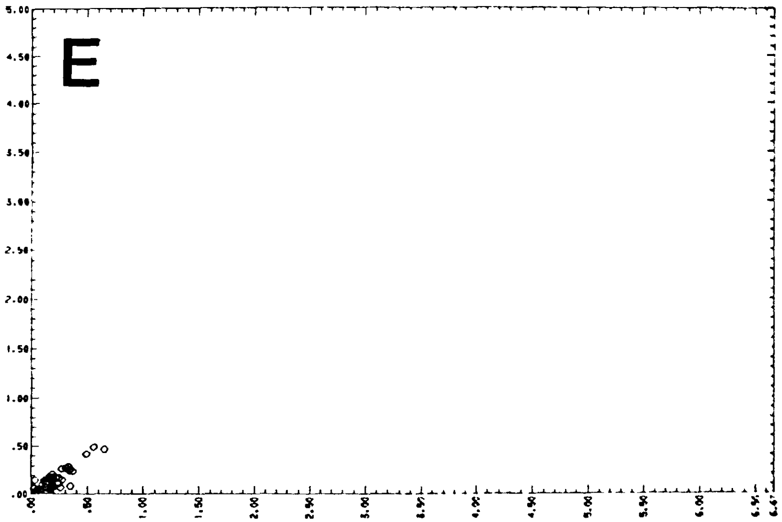
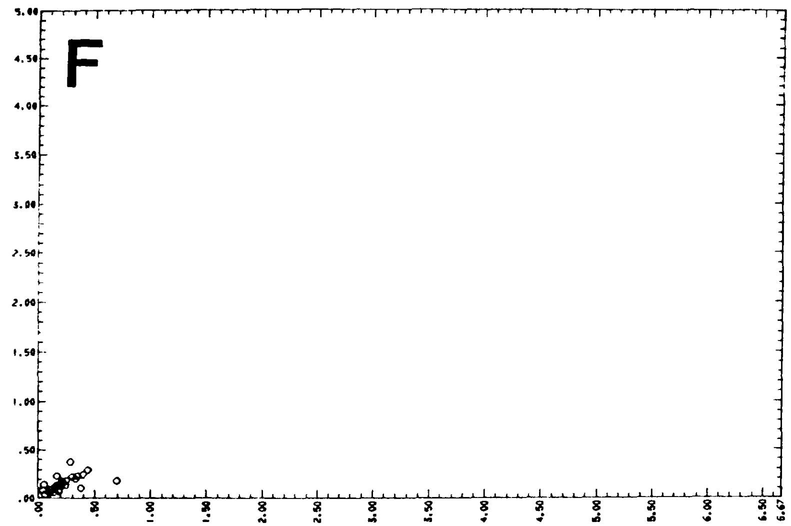


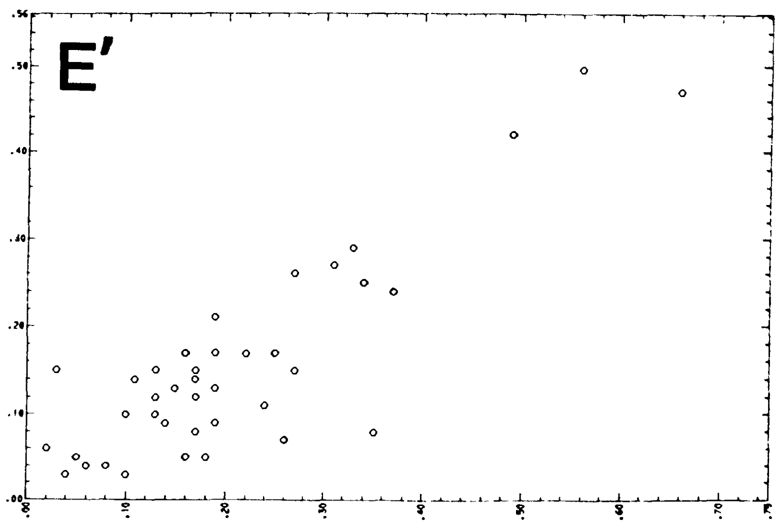
Figure 11 (Cont'd.)



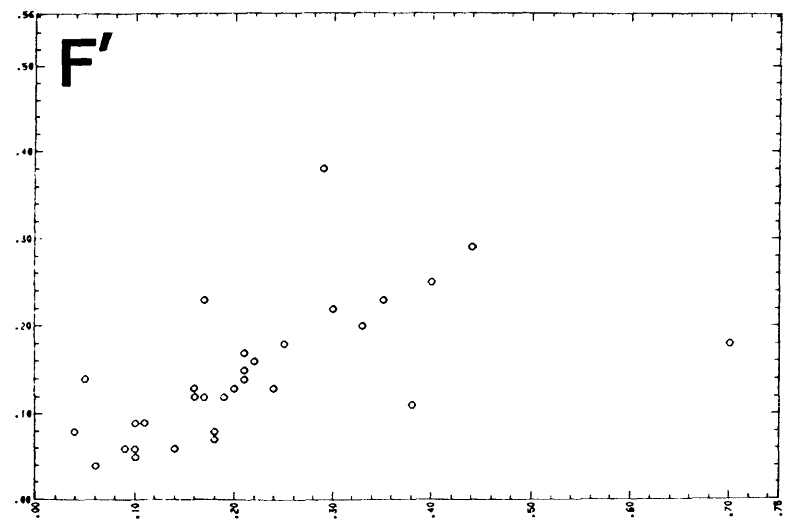
NABARLEK - Ewers and others (1983)



KOONGARRA - Ferguson and Winer (1980)



NABARLEK - Ewers and others (1983)



KOONGARRA - Ferguson and Winer (1980)

Figure 11 (Cont'd.)

expanded and only the low phosphorus samples are shown (figs. 11b' and d'). This is noteworthy because, considering Ferguson and Winer's Jabiluka data, of the 5 samples containing more than 0.5 percent P_2O_5 (fig. 11d), three of them come from an interval less than one meter thick in a single drillhole (DDH 226 from 271.6 to 272.3 meters). If those authors had not sampled DDH 226, the Ca-P trend on figure 11d would be clearly defined by only two or three points and, in that case, a graph of the entire data set from Jabiluka would begin to closely resemble the data for Koongarra and Nabarlek. Comparing figures 11a' and 11b' with 11e' and 11f' (the low-phosphorus plots for two sets of Ranger data and the Nabarlek and Koongarra data sets, respectively) emphasizes that much of the scatter in the graphs for Nabarlek and Koongarra is a function of the number of analyses and the scale at which the data are plotted. Actually, the Ca-P correlations at Nabarlek and Koongarra are visually more apparent in figures 11e and f than in 11e' and f', yet the only difference between the two sets of graphs is the scales on the axes.

A hypothesis we cannot fully evaluate is that the phosphorus metasomatic event that has affected both Ranger and Jabiluka, and possibly the other uranium deposits of the region, is the same event as the regional chloritization event(s) mentioned by Eupene (1980) and to which we alluded earlier. We have no samples of chloritized Kombolgie or Cahill Formation remote from ore and we know of no published analyses for rocks of this type. By "remote" we mean a distance at least an order of magnitude greater than the maximum dimension of any single deposit in the district--roughly 5 to 10 km. Ferguson and Winer (1980) include some analyses for Cahill Formation samples collected far from known ore, but none of these samples are described as chlorite bearing. Until data of this type are available, we can only speculate on the nature of the causal relationship, if any, between phosphorus metasomatism and uranium mineralization. We believe that a relationship must exist, but it may well be a circuitous one such as both uranium-bearing and then phosphorus-bearing fluids following the same disturbed, permeable zones of structural weakness.

Phosphorus-Uranium Associations in Other Uranium Deposits

Presuming that all four developed unconformity-vein uranium deposits in the ARUF have been subjected to a metasomatic event that has added phosphorus to the rocks, an obvious question is did this happen at other unconformity-vein deposits like those in the Athabasca Basin in Canada? If there is a genetic link between phosphorus metasomatism and this type of uranium deposit, instead of simply a fortuitous association, and if the Canadian and Australian deposits actually share some aspects of their genesis, then one might expect some Canadian deposits to also show some evidence of phosphorus enrichment.

Phosphorus-uranium associations with high phosphorus abundances are common at the base of the Proterozoic Thelon Formation in the Dubawnt - Baker Lake region of the Northwest Territories, Canada (L. W. Curtis, written communication, 1981) and these occurrences have been investigated to assess their importance as pathfinders for unconformity-vein uranium deposits (Miller, 1983). Uranium is also found in apatite-rich calcareous layers within one kilometer (stratigraphically) of the Rabbit Lake deposit in Saskatchewan (Hoeve and Sibbald, 1978) and phosphate prospects occur in the vicinity of the uranium deposits in the Rum Jungle Uranium Field, Australia (Crohn, 1968). However, both of these latter types of occurrences are thought to be of syngenetic or modified syngenetic origin (Tremblay, 1978, Pritchard and Cook, 1965). Frishman and others (1983) speculated on the differences between calcium-phosphorus relationships in Australian and Canadian unconformity-vein deposits and concluded that whole-rock Ca-P plots for fragmentary data from the Cluff Lake and Dawn Lake deposits were not similar to the graphs presented here.

Conclusions

On the basis of the relationships presented here, we are convinced that a substantial amount of phosphorus has been added to the volume of rock making up the Ranger orebodies. The same is probably true for Jabiluka and Nabarlek and possibly true for Koongarra. At Ranger, the effects of this metasomatic event cut across all lithologic and ore-grade boundaries and phosphorus and uranium abundances do not correlate for any rock type. Phosphorus metasomatism probably took place after the deposition of the Kombolgie Formation at both Ranger and Jabiluka and, at Ranger, apparently took place long after initial emplacement of uranium ore.

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