New Mexico Geological Society

Downloaded from: http://nmgs.nmt.edu/publications/guidebooks/43

Isotopic ages of uranium deposits in the Todilto Limestone, Grants district, and their relationship to the ages of other Colorado Plateau deposits

William R. Berglof, 1992, pp. 351-358

in:

San Juan Basin IV, Lucas, S. G.; Kues, B. S.; Williamson, T. E.; Hunt, A. P.; [eds.], New Mexico Geological Society 43rd Annual Fall Field Conference Guidebook, 411 p.

This is one of many related papers that were included in the 1992 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. Non-members will have access to guidebook papers two years after publication. Members have access to all papers. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, *maps*, *stratigraphic charts*, and other selected content are available only in the printed guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

This page is intentionally left blank to maintain order of facing pages.

New Mexico Geological Society

Downloaded from: http://nmgs.nmt.edu/publications/guidebooks/43

Isotopic ages of uranium deposits in the Todilto Limestone, Grants district, and their relationship to the ages of other Colorado Plateau deposits

William R. Berglof, 1992, pp. 351-358

in:

San Juan Basin IV, Lucas, S. G.; Kues, B. S.; Williamson, T. E.; Hunt, A. P.; [eds.], New Mexico Geological Society 43rd Annual Fall Field Conference Guidebook, 411 p.

This is one of many related papers that were included in the 1992 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. Non-members will have access to guidebook papers two years after publication. Members have access to all papers. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, *maps*, *stratigraphic charts*, and other selected content are available only in the printed guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

This page is intentionally left blank to maintain order of facing pages.

ISOTOPIC AGES OF URANIUM DEPOSITS IN THE TODILTO LIMESTONE, GRANTS DISTRICT, AND THEIR RELATIONSHIP TO THE AGES OF OTHER COLORADO PLATEAU DEPOSITS

WILLIAM R. BERGLOF
University of Maryland, Asian Division, Unit 5060, Box 0100, APO AP 96328-0100

Abstract—Uranium-lead isotopic data suggest an age of 150–155 Ma for uraninite ores from the Todilto Limestone Member of the Wanakah Formation in the Grants uranium district. The deposits apparently began to form relatively soon after deposition of the host rock. The precise age of the Todilto is uncertain, and the interval between sedimentation and mineralization, possibly 10 Ma or more, cannot be determined from isotopic data alone. Some Todilto isotopic ages are concordant or nearly concordant; others are discordant, usually showing the pattern of normal discordance that is common in low-temperature uranium minerals. Discordance most likely resulted from loss of radiogenic lead and migration of intermediate daughters in the ^{238}U decay chain. Geologic and isotopic studies indicate that uranium deposits of several different ages are present throughout the Colorado Plateau, and that primary mineralization developed early in the history of the Chinle and Morrison Formations and the breccia pipes of the Grand Canyon. Some younger ores formed by redistribution of uranium from older deposits. Interpretations of Todilto isotopic data are consistent with these concepts. In the Grants region, ore in the Todilto may have existed before the much larger deposits in the Morrison Formation began to form, but age data supporting this conclusion are not definitive.

INTRODUCTION

Isotopic age studies of Colorado Plateau uranium deposits began during the early years of the "uranium boom." Despite the importance of reliable age data for concepts of ore genesis, initial results were not conclusive, owing in part to the discordant U-Pb ages obtained from most samples. However, it was suggested that several deposits in the Chinle and Morrison Formations are Late Cretaceous to early Tertiary in age, similar to the vein-type deposits of the Colorado Front Range. Subsequent studies have yielded quite different conclusions, and indicate that mineralization throughout the Plateau occurred at various times, commonly soon after deposition of the host rocks.

This article includes isotopic age data from uranium deposits in the Todilto Limestone Member of the Wanakah Formation in the Grants, New Mexico, uranium district. The data were part of an unpublished dissertation (Berglof, 1970). Isotopic data from other Plateau deposits were also obtained and are reviewed. Several of the age determinations were reported previously (Davidson and Kerr, 1966, 1968; Nash and Kerr, 1966; Nash, 1968; Gornitz and Kerr, 1970), but not all of the related data have been published. The objectives of this article are therefore to report previously unpublished age data, especially from the Todilto, and to interpret the data in the light of numerous recent studies in the Colorado Plateau and other areas.

PREVIOUS STUDIES

Concepts of the genesis and age of sandstone-type uranium deposits have evolved significantly over the past 40 years (Adams, 1991). Stieff et al. (1953) reported the first isotopic ages for Colorado Plateau deposits, and concluded that deposits in different host rocks are similar in age (Late Cretaceous or younger), comparable to deposits in the Colorado Front Range.

U-Pb age studies often report "apparent" ages, which are analytical results only, and may not clearly indicate the most likely age of a sample. Discordant apparent ages are common in the Plateau, and generally exhibit a "normal" pattern in which ages based on three isotope ratios differ in the following sequence: ^{207}Pb/^{238}U age $<$ ^{207}Pb/^{235}U age $<<$ ^{207}Pb/^{206}Pb age. When concordant ages are obtained (i.e., the three apparent ages agree), they are usually assumed to be close to the true age. There has been disagreement on the causes of discordance and thus on which of the apparent ages most nearly approaches the true age. Stieff et al. (1953) and Stieff and Stern (1956) proposed that old radiogenic lead was incorporated in Colorado Plateau uranium minerals when they were deposited, which would cause the apparent ages to be both normally discordant and also greater than the true age.

Subsequent studies reached varying conclusions. Eckelmann and Kulp (1957) agreed that Colorado Plateau and Front Range ores formed at about the same time, and that the Plateau ores are much younger than their host rocks. Miller and Kulp (1958) concluded that Plateau ores could have formed either in the past five Ma or during Laramide time. One problem in their study was that apparent ages of around 200 Ma from Chinle deposits seemed to be much greater than the age of the Chinle itself, then estimated to be about 150 Ma.

Miller and Kulp (1963) proposed another interpretation, suggesting that concordant ages, especially those comparable to the age of the host rock, are approximately correct, and that discordance results from loss of radiogenic lead with preferential loss of ^{206}Pb related to migration of radioactive daughters in the ^{238}U decay chain. Under this interpretation, the ^{207}Pb/^{235}U ratio provides a minimum age. Their suggestion was best documented for ores in the Chinle Formation in the Lisbon Valley district, where they obtained essentially concordant age sequences with ^{207}Pb/^{235}U ages about equal to the age of the Chinle, which they now estimated to be close to 200 Ma. Their data was less definitive for other districts. The conclusions of Stieff et al. (1953) thus remained influential, appearing "to have influenced many plateau geologists more than all other geologic evidence combined" (Moench and Schlee, 1967, p. 105), while Mauger (1967, p. 96) concluded that "classical field criteria remain as the best methods of age determination for these deposits."

Since 1978, K. R. Ludwig and several colleagues have reported detailed studies of uranium deposits, utilizing numerous isotopic analyses, for the Colorado Plateau and other areas. They have provided reliable age estimates for many deposits as well as explanations of the complex open-system behavior that produced the discordant ages exhibited by most analyzed samples. These studies will be referred to specifically later in this article.

GEOLOGY OF TODILTO URANIUM DEPOSITS

Economically important uranium deposits in the Grants region were first discovered in the Todilto, which has accounted for about 2% of the total uranium production in New Mexico (Chenoweth, 1985; McLemore and Chenoweth, 1989). Fig. 1 shows the principal area of Todilto deposits near Grants.

Uraninite is common in primary Todilto deposits, along with coffinite, fluorite, barite, hematite, and vanadium minerals such as paramontroseite and häggite. Where the deposits have been oxidized, they contain tyuyamunite, metatyuyamunite, uranophane and other secondary minerals.

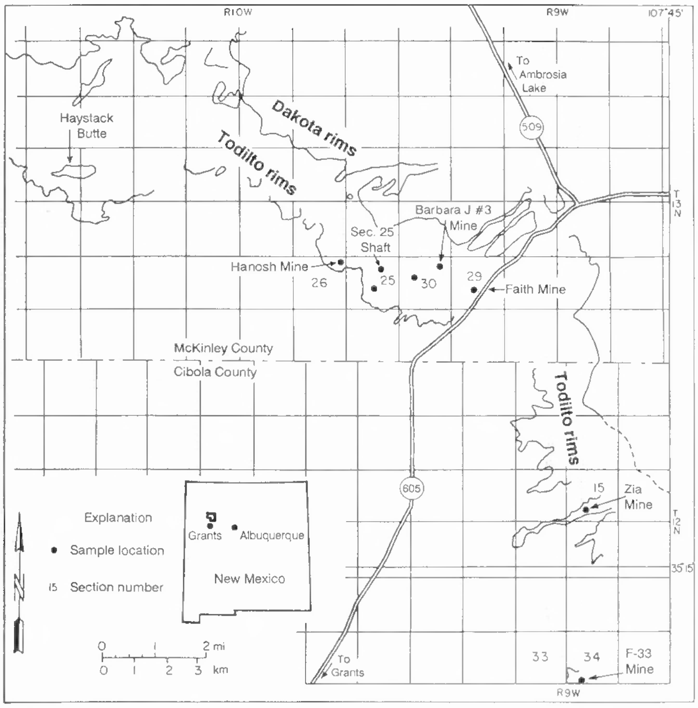

FIGURE 1. Index map showing the principal area of uranium deposits in the Todilto Limestone Member of the Wanakah Formation near Grants, New Mexico (modified from Chenoweth, 1985), with sample locations.

Mineable orebodies in the Todilto are generally localized along folds that are predominantly intraformational, ranging widely in size and geometry. The importance of these folds was recognized in early studies of the deposits, and different explanations of their origin have been advanced. Their age is critical for concepts of ore genesis, as the deposits can be no older than the folds which localize them. Some geologists have concluded that they formed by soft-sediment deformation during or shortly after deposition (Rawson, 1980; Green, 1982; Armstrong, 1991). Others have proposed that at least some of the folds formed or were modified in conjunction with tectonic activity (Gabelman, 1956, 1970; Hilpert and Moench, 1960; Gabelman and Boyer, 1988).

Most geological studies of Todilto deposits have concluded that they are epigenetic (i.e., not strictly syngenetic) based on the discontinuous nature of the deposits and the intraformational folds that typically localize them, and on crosscutting relationships. When examined in detail, primary ore often cuts across bedding, and occasionally occurs along fractures. Sample C-5, analyzed in this study, is from a fracture-controlled orebody in the Section 25 shaft (sec. 25, T13N, R10W). This orebody was localized by subvertical fractures up to one meter in vertical extent, with one to three main fractures distributed within a zone about one meter across and more than 30 m long. Primary ore occasionally extends below the Todilto into the Entrada Sandstone, and may include abundant uraninite. Sample C-4 is from one such deposit at the Zia mine in Section 15, T12N, R9W. Primary ore may also extend into overlying strata of the Beclabito Member of the Wanakah Formation.

Further descriptions of Todilto deposits are available in numerous studies, including Gabelman (1956, 1970), Hilpert and Moench (1960), Granger (1963a), McLaughlin (1963), Moench and Schlee (1967), Kelley et al. (1968), Hilpert (1969), Rawson (1980), Green (1982), McLemore (1983), Gabelman and Boyer (1988), and McLemore and Chenoweth (1989).

ANALYTICAL PROCEDURES

Details of the analytical procedures used in this study are from Berglof (1970), from which the isotopic data are taken. Lead and uranium concentrations, and lead isotopic composition, were determined by mass spectrometry using isotope dilution techniques. To correct for initial or common lead (lead included in the minerals when they formed and not produced by radioactive decay), the isotope ^{208}Pb was used as an index. This procedure is appropriate when the analyzed materials contain little thorium, from which ^{208}Pb forms by radioactive decay. The initial lead composition used was that of Miller and Kulp (1963), with the following ratios: ^{206}Pb/^{204}Pb = 18.6; ^{207}Pb/^{204}Pb = 15.8; ^{208}Pb/^{204}Pb = 39.1. Especially for most Todilto samples, the initial lead content is so low that the choice of its composition has little effect on the calculated ages.

Apparent ages were calculated using the decay constants recommended by the IUGS (Steiger and Jäger, 1977). Ages that were previously published have been recalculated. As a result, some are slightly different from those included in Davidson and Kerr (1966, 1968), Nash and Kerr (1966), Nash (1968), Gornitz and Kerr (1970), and McLemore (1983). The ages reported in these earlier publications were calculated using the tables of Stieff et al. (1959) which are based on different decay constants.

The samples for isotopic study were small chips taken from the highest grade portion of a hand sample, providing a total of about 5–8 milligrams of uranium. This procedure is now known to be not necessarily optimal; small-scale, open-system behavior affecting U/Pb ages is common and can occur on scales greater than the size of these samples. Larger whole-rock samples may more nearly approximate a closed system (Ludwig et al., 1981, 1987). All analyzed samples were uraninite, except for an ore-grade sample (C-9) consisting of uraninite disseminated in limestone and coffinite from the Jackpile and Woodrow deposits (samples C-12 and C-20).

RESULTS

Analytical data and apparent ages for Todilto ores and others discussed in this study are in Table 1. The apparent ages are analytical results based on the measured isotope ratios. Isotopic age data for the Todilto from Miller and Kulp (1963) are included in this table. It should be noted that the F-33 mine data are described in their paper as being from the "Section 33" mine. Unfortunately, there is a Section 33 mine in the Ambrosia Lake district, creating the impression that the analyzed samples were from that mine. For many years sample K-194b appeared to provide the only available U-Pb age for Ambrosia Lake, and was therefore mentioned in several studies (Melvin, 1976; Lee and Brookins, 1978; Brookins, 1980; Squyres, 1980; Ludwig et al., 1984).

Miller and Kulp used the expression "Ambrosia Lake," but did not include ages from the Morrison Formation. They showed the ^{207}Pb/^{235}U age for the Section 33 sample on a histogram (p. 622) as being from the Todilto. Bassett et al. (1963) similarly referred to the F-33 mine as the Section 33 mine, and mentioned the age of 78 Ma for this deposit (^{206}Pb/^{238}U age) determined by Miller and Kulp. Ludwig et al. (1984) reported isotopic data for many Ambrosia Lake samples, and thus this misunderstanding is no longer of concern.

Todilto deposits

Isotopic data for the Todilto are in Table 1, and sample descriptions in Table 2. Samples C-2, C-2b, C-3, C-5 and C-7 yield concordant or nearly concordant apparent ages. The highest ^{207}Pb/^{235}U apparent ages are about the same as the ages for the concordant samples, while the ^{206}Pb/^{235}U ages are mostly lower. This pattern is not consistent with the presence of old radiogenic lead, for reasons summarized by Miller and Kulp (1963), Ludwig (1978) and Ludwig et al. (1984). It is best explained by open-system behavior involving migration of radiogenic Pb and intermediate radioactive daughters in the ^{238}U decay chain, as has been cited for numerous deposits in the western United States (Miller and Kulp, 1963; Ludwig, 1978, 1979; Ludwig et al., 1981, 1984) and in Europe (e.g., Turpin and Leroy, 1987; Holliger et al., 1989; Respaut et al., 1991). Concordant ages are usually assumed to approximate true ages. However, because of the inherent errors associated with the determination of Pb-U isotope ratios, significant loss of lead could occur before discordance would be analytically resolvable. Multiply replicated concordant ages are therefore desirable before they can be accepted with reasonable confidence; it must also be possible to explain the likely causes of discordant age relationships in related samples.

TABLE 1. U and Pb concentrations, isotope ratios and apparent ages. Isotope ratios include radiogenic Pb only. Assigned errors are an estimate of analytical accuracy at the 95% confidence level. Data for K-179 and K-194 are from Miller (1960) and Miller and Kulp (1963).

Sample Number	Mine	U (%)	Pb (%)	Common Pb (ppm)	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	^{206}Pb/^{238}U age (Ma)	^{207}Pb/^{235}U age (Ma)	^{207}Pb/^{206}Pb age (Ma)
Todilto and Entrada, Grants district										
C-1	Barbara J #2	45.0	0.76	11.1	0.0183	0.140	0.0556	117 ± 2	133 ± 5	435 ± 55
C-2	Barbara J #3	50.6	1.10	0.77	0.0238	0.161	0.0492	152 ± 3	152 ± 4	156 ± 35
C-2b	Barbara J #3	51.B	1.07	0.21	0.0230	0.155	0.0490	147 ± 3	146 ± 4	148 ± 35
C-3	Section 25	44.2	0.91	0.91	0.0228	0.157	0.0499	145 ± 3	148 ± 4	190 ± 35
C-3b	Section 25 (leach #1)						0.0483			115 ± 35
C-3c	Section 25 (leach #2)						0.0470			50 ± 35
C-5	Section 25 shaft	35.1	0.72	0.65	0.0227	0.157	0.0502	145 ± 3	148 ± 4	204 ± 35
C-4	Zia (in Entrada)	16.5	0.30	0.42	0.0203	0.143	0.0513	130 ± 3	136 ± 4	254 ± 35
C-6	F-33	51.0	0.95	0.95	0.0204	0.154	0.0548	130 ± 3	145 ± 4	404 ± 45
C-7	Hanosh	34.9	0.72	0.43	0.0226	0.160	0.0513	144 ± 3	151 ± 4	254 ± 35
C-8	Faith	33.3	0.54	0.49	0.0176	0.161	0.0662	112 ± 2	152 ± 4	810 ± 55
C-8b	Faith	32.2	0.51	0.10	0.0172	0.161	0.0682	110 ± 2	152 ± 3	870 ± 55
C-9	Barbara J #2	0.79	0.012	<0.01	0.0163	0.173	0.0771	104 ± 2	162 ± 5	1120 ± 50
K-179b	Haystack Butte	13.0	0.47	4.4	0.0400	0.184	0.0334	253 ± 5	171 ± 5	-840
K-179c	Haystack Butte						0.0487			130 ± 20
K-194a	F-33						0.0574			510 ± 35
K-194b	F-33				0.0121	0.109	0.0663	78 ± 5	105 ± 6	810 ± 30
Morrison Formation, Laguna district										
C-12	Jackpile	20.0	0.23	2.8	0.0126	0.0953	0.0550	81 ± 2	93 ± 3	412 ± 35
C-20	Woodrow	54.3	0.68	13.0	0.0136	0.0917	0.0490	87 ± 2	89 ± 3	148 ± 35
Chinle Formation, Lisbon Valley and Kane Creek, Utah										
C-13	Texwood	73.0	1.28	1.8	0.0189	0.140	0.0539	121 ± 3	133 ± 4	367 ± 35
C-16	North Alice	66.1	1.84	19.8	0.0306	0.213	0.0506	194 ± 4	196 ± 4	220 ± 35
C-17	South Almar	70.9	1.87	35.5	0.0286	0.212	0.0539	182 ± 4	195 ± 5	367 ± 35
C-11	Climax Schl. Sec. 32	30.4	0.98	146	0.0308	0.218	0.0513	196 ± 5	200 ± 5	254 ± 35
C-19	Climax Schl. Sec. 32	67.4	1.74	48.4	0.0277	0.195	0.0511	176 ± 4	181 ± 5	245 ± 35
Kane Creek, Utah										
C-14	Honey Bee No. 1	55.3	0.56	85	0.00964	0.0671	0.0506	62 ± 3	66 ± 3	220 ± 35
Grand Canyon district, Arizona										
C-21	Orphan	55.6	1.09	45.9	0.0208	0.147	0.0514	133 ± 3	139 ± 4	259 ± 35

Migration of radiogenic lead and ^{238}U daughters results in the presence of less radiogenic lead in a sample than there would be if it had evolved in a closed system, lowering the apparent U-Pb ages. The ^{238}U daughters ^{226}Ra and ^{222}Rn have longer half-lives than the corresponding isotopes for these elements in the ^{235}U chain, and are thus more likely to migrate from the site of their formation before decaying to ^{206}Pb. This decreases the ^{206}Pb/^{238}U age compared to the ^{207}Pb/^{235}U age, and raises the ^{207}Pb/^{206}Pb age. The ^{207}Pb/^{235}U ratio is least disturbed, and should provide a minimum age of formation.

Based on these arguments, it is likely that the U-Pb ages for the Barbara J #3 samples are close to the true age. Two analyses of samples from the same specimen differ by a few Ma, although both are concordant. The U-Pb ages of 152 Ma for sample C-2 are the same as the highest ^{207}Pb/^{235}U age for the remaining samples (except for sample C-9, a low-grade sample). The ^{207}Pb/^{235}U age should be a minimum, but it seems unlikely that the actual age of the samples is much higher than 155 Ma, based on the concordant analyses. It is concluded that the best estimate of the true age of the uraninite samples is in the range of 150–155 Ma. Sample C-5, from a fracture-controlled orebody, is similar in apparent ages to the other essentially concordant samples, and thus is unusual only in its form of occurrence. Sample K-194b of Miller and Kulp (1963) is interpreted as showing the most pronounced effects of Pb and ^{238}U daughter migration among the normally discordant Todilto ages.

Fig. 2 is a concordia plot of the Todilto and Entrada U-Pb ages. The scatter below concordia is consistent with variable loss of radiogenic Pb and radioactive daughters of ^{238}U; the data points approach concordia (and the two concordant ages) with increasing ^{206}Pb/^{238}U apparent age.

Sample C-4 is from the Zia mine, where uraninite occurred in the upper part of the Entrada Sandstone. The apparent ages are in the same range as those for the Todilto, and thus the uraninite does not appear

TABLE 2. Locations and descriptions of Todilto and Entrada samples.

Sample number	Mine and location	Description
C-1	Barbara J #2 Sec. 30, T13N, R9W	Uraninite from fractured and recrystallized limestone, with paramontroseite, calcite, and traces of secondary minerals.
C-2	Barbara J #3 Sec. 30, T13N, R9W	Uraninite with submetallic luster replacing fine-grained limestone, with minor hematite and barite. No visible secondary minerals.
C-2b	Barbara J #3 Sec. 30, T13N, R9W	Second chip from sample C-2.
C-3	Section 25 Sec. 25, T13N, R10W	Massive uraninite replacing limestone. No visible secondary minerals. From open pit.
C-5	Section 25 shaft Sec. 25, T13N, R10W	Uraninite replacing brecciated limestone in fracture zone, with hematite and coarse calcite. No visible secondary minerals.
C-4	Zia Sec. 15, T12N, R9W	Uraninite coating sand grains in Entrada Sandstone, immediately below Todilto, with pyrite and calcite. From open pit.
C-6	F-33 Sec. 33/34, T12N, R9W	Uraninite replacing partially recrystallized limestone, with traces of secondary minerals.
C-7	Hanosh Sec. 26, T13N, R10W	Uraninite replacing fine-grained thin-bedded folded and brecciated limestone, with coarse calcite and traces of secondary minerals.
C-8	Faith Sec. 29, T13N, R9W	Uraninite replacing deformed silty limestone along bedding, with hematite and calcite.
C-8b	Faith Sec. 29, T13N, R9W	Second chip from sample C-8.
C-9	Barbara J #2 Sec. 30, T13N, R9W	Minor uraninite disseminated along bedding planes in fine-grained silty limestone.

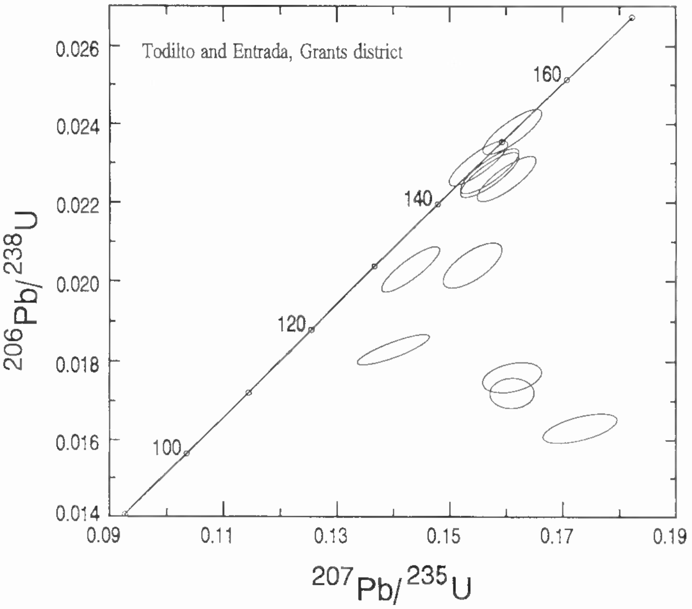

FIGURE 2. Concordia plot of Todilto and Entrada age data. The line (concordia) is the locus of concordant ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ages.

to have been derived from the overlying Todilto by recent redistribution of uranium, as suggested by Kelley et al. (1968). As reviewed later, redistributed ore is important in the Ambrosia Lake district. Relatively recent redistribution of uranium also occurred in Todilto deposits (McLemore and Chenoweth, 1989), but little age data is available for the yellow U^{6+} minerals that typically formed. Brookins (1981b) obtained U-Pb apparent ages of 3–7 Ma for uranophane from the Flat Top mine in the Todilto (sec. 30, T13N, R9W).

Interpretation of discordant age data

One type of evidence supporting the migration of ^{238}U daughters is the existence of anomalously low ^{207}Pb/^{206}Pb ratios. Decay of modern uranium in a closed system produces a ^{207}Pb/^{206}Pb ratio of 0.046. Lower ratios, if observed in analyzed samples, yield negative or "future" ^{207}Pb/^{206}Pb ages. Stieff and Stern (1956) argued against ^{222}Rn migration as a cause of discordance because of the lack of known abnormal concentrations of ^{206}Pb. Since then many such occurrences have in fact been noted on the basis of their ^{207}Pb/^{206}Pb ratios.

Cobb and Kulp (1961) observed ^{207}Pb/^{206}Pb ratios of 0.030, 0.035 and 0.040 in black shale from Sweden, attributing them to excess ^{206}Pb originating in nearby uranium-rich kolm lenses. In three samples of pitchblende and secondary black uranium oxide from the Limouzat, France deposit, Durand (1963) obtained ^{207}Pb/^{206}Pb ratios ranging from 0.0437 to 0.0216, equivalent to ages of about −130 to −2300 Ma. Ludwig (1978) reported the remarkably low ratio of 0.012, with a −5850 Ma age, from the Shirley Basin, Wyoming, together with other less extreme low ratios. Subsequently, negative ages have been observed in such geologically diverse locations as the Gas Hills and Crooks Gap, Wyoming; the Midnite mine, near Spokane, Washington; and the Jabiluka and Ranger deposits, Australia (Ludwig, 1979; Ludwig et al., 1981, 1987). These results reflect mobility of ^{206}Pb or ^{238}U daughters such as ^{222}Rn. The ^{206}Pb may be incorporated by various materials, including pyrite.

For the Todilto, Miller and Kulp (1963) reported a ^{207}Pb/^{206}Pb ratio of 0.0334 for sample K-179b, from Haystack Butte, equivalent to a −840 Ma age. Uranium deposits at Haystack Butte were oxidized and contained abundant secondary minerals. Since sample K-179b was a microsample obtained by drilling a polished section, it is likely that it included excess ^{206}Pb resulting from small-scale migration of Pb or a ^{238}U daughter; the latter can occur on a scale of 10 cm (Ludwig et al., 1981). A macrosample, K-179c, from the same area yielded a ^{207}Pb/^{206}Pb ratio of 0.0487, for an apparent age of 130 Ma. The larger sample size may have minimized the effects of open-system behavior. The U-Pb ages for sample K-179b are anomalously high, suggesting the presence of excess radiogenic lead, especially ^{206}Pb. High U-Pb ages can result from loss of uranium, but this should not affect the ^{207}Pb/^{206}Pb ratio, and thus some process involving the Pb isotopes is required.

Extremely high ^{207}Pb/^{206}Pb apparent ages (much greater than the host-rock age) also imply extensive migration of ^{238}U daughters. Samples C-8, C-8b and C-9 have ages of 810, 870 and 1120 Ma, respectively; the age for sample K-194b of Miller and Kulp (1963) is 810 Ma. These are deficient in ^{206}Pb as compared to the concordant and nearly concordant samples. Because the ages for sample C-8 were strongly discordant, a second sample from the same specimen (C-8b) was analyzed, with similar results.

Miller and Kulp (1963) obtained high ^{207}Pb/^{206}Pb ages from Cameron, Arizona, where the deposits occurred at shallow depth and were probably extensively altered. Similarly high and widely varying ratios have been observed at numerous other locations (Ludwig, 1978, 1979; Ludwig et al., 1981, 1987), many of which also yield the negative ages discussed previously. The presence of anomalously low and high ^{207}Pb/^{206}Pb ratios in the same deposits provides especially good evidence of complex open-system behavior.

Leaching experiments also document the potential for loss of ^{206}Pb. Experiments were performed on samples C-3b and C-3c, which were new portions of sample C-3. In one experiment, a 260 mg uraninite fragment was leached of soluble lead in warm 0.5N HCl for several hours. In a second, 210 mg of crushed uraninite were leached for 1½ hours in cold 0.5N HCl. The isotopic composition of the lead removed in solution in each experiment was determined by mass spectrometry, yielding radiogenic ^{207}Pb/^{206}Pb ratios of 0.0483 and 0.0470, respectively, equivalent to ages of 115 Ma and 50 Ma. The results show that ^{206}Pb is preferentially soluble under laboratory conditions in these uraninite samples, and presumably would also be in nature. Many similar experiments have been reported. For example, Ludwig (1978, 1979) reported a wide variety of experiments showing differential solubility of Pb isotopes.

Discordant Todilto ages correlate fairly well with the appearance and source of the samples (see Table 2). Sample C-2, which yields a concordant age, is from one of the deepest mines in the district, has an especially massive appearance, and shows no associated secondary minerals. It ranks highest in suitability for isotopic dating according to the sample-rating criteria of Ludwig (1979). Samples C-3 and C-5 contain no visible secondary minerals, but are from an open pit and a shallow underground mine. Samples C-1, C-6 and C-7 include traces of secondary minerals. Sample C-4 is a uraninite-bearing sandstone from an open pit mine. Sample C-6, and sample K-194b of Miller and Kulp, are from the F-33 deposit, an underground mine that contained secondary minerals in solution channels. The Haystack Butte ores were extensively oxidized. There is no obvious correlation for samples C-8 and C-8b. Sample C-9 contained much less U and Pb than the other samples, and should have been more easily affected by open-system behavior. The small size of analyzed samples may have increased the probability that discordant ages would be observed. Taken as a group, the samples illustrate the difficulty of selecting material that has experienced minimal open-system behavior.

Age of the Todilto Limestone Member

Stratigraphic relationships and nomenclature for the Todilto and other Jurassic rocks have been revised, and the Todilto is now considered to be part of the Wanakah Formation (Condon and Peterson, 1986; Condon and Huffman, 1988). Imlay (1952) correlated the Todilto with the Upper Jurassic Oxfordian Stage. However, recent fossil evidence indicates that it is Callovian or possibly older (Schaeffer and Patterson, 1984; Lucas et al., 1985; Lucas and Kietzke, 1986). The age of the Callovian-Oxfordian boundary, which also marks the division between the Middle and Upper Jurassic, is therefore of interest as the Todilto should be slightly older. Unfortunately, it has been difficult to establish accurate dates within the Jurassic, owing to the scarcity of reliable isotopic ages

(Kent and Gradstein, 1985; Fischer and Gygi, 1989), which is especially true for pre-Oxfordian stages (Westermann, 1984).

Fischer and Gygi (1989) suggest ages of 146–149 Ma for glauconite from an ammonite-bearing Oxfordian succession in Switzerland, implying an age close to 150 Ma for the Callovian-Oxfordian boundary (not stated in their paper). They review the controversy over the use of glauconite in measuring geologic time, which contributes to the problems with the Jurassic. Other recent estimates of the age of the Callovian-Oxfordian boundary are 152 Ma (Haq et al., 1987; Snelling, 1987; Cowie and Bassett, 1989), 154 Ma (Odin and Odin, 1990), 157 Ma (Harland et al., 1990), 161 Ma (Pessagno and Blome, 1990), 162 Ma (Westermann, 1984), and 163 Ma (Palmer, 1983; Kent and Gradstein, 1985).

It therefore does not seem possible to select a reliable age for the Callovian-Oxfordian boundary from among the many different recent estimates. If the age of the Todilto ores is 150–155 Ma, they could have formed virtually syngenetically, or more than 10 Ma after sedimentation, depending on which Callovian-Oxfordian date is chosen. The origin of Todilto deposits, and the source of their uranium, is beyond the scope of this article. However, as pointed out by Lucas (1986), mineralization 10 Ma or more after deposition would present problems for the hypothesis of sabkha origin (Rawson, 1980), in which ore formation soon after sedimentation is favored.

Relationships between Todilto and Morrison deposits

The Todilto in the Grants district is not far below the Morrison Formation, which contains enormous uranium deposits. Because of the proximity of the deposits in different host rocks it is possible that there is some relationship between them (Lucas, 1986), but no compelling evidence of a connection has been reported. Moench and Schlee (1967) and Hilpert (1969) concluded, mostly on geological evidence, that ores in the Todilto formed before Morrison deposition. Granger (1968) tentatively dismissed the possibility that Morrison ores are related to deposits in other rocks.

As discussed above and in the following section, the ages of the Todilto and Morrison are not precisely known. Considering the available data, primary ore in each unit could be virtually syngenetic, or could have formed several Ma or more after sedimentation, depending on the estimated age of the host formation. If the 130 Ma minimum age for Ambrosia Lake ore is close to its true age, these deposits should have formed well after those in the Todilto. However, this is a minimum, and recent estimates of the age of the Jurassic-Cretaceous boundary (which may be within the Morrison) range up to 145.6 Ma, which is not much less than the suggested age of Todilto ores. The combined age data for the deposits and the host rocks are therefore not definitive.

Deposits in the Morrison Formation

Grants uranium region

For many years the Grants region in northwestern New Mexico produced more uranium than any other district in the world, mostly from deposits in the Morrison Formation at Ambrosia Lake and Laguna (McLemore and Chenoweth, 1989). Isotopic data for coffinite from the Jackpile and Woodrow deposits near Laguna are reported here; the ages were published previously (Nash and Kerr, 1966; Nash, 1968). They do not provide a definitive estimate of the age of the deposits, although the ^{207}Pb/^{235}U data suggest a minimum age of deposition.

Granger et al. (1961) established the concept that both primary and redistributed ores are present at Ambrosia Lake. Subsequent studies have reiterated this concept, and many have concluded, mostly on geological criteria, that primary ore formed soon after deposition of the Morrison (e.g., Moench and Schlee, 1967; Granger, 1968; Squyres, 1972, 1980; Adams et al., 1978; Turner-Peterson, 1985; Turner-Peterson et al., 1986).

In a detailed study of the Ambrosia Lake and Smith Lake districts, Ludwig et al. (1984) concluded that the primary ores have a minimum age of about 130 Ma. Rb-Sr ages of clays and chlorite suggest a minimum age of 139 Ma for both the ores and the host rock (Lee and Brookins, 1978, 1980; Brookins, 1980). Granger (1963b) earlier proposed a minimum age of 100 Ma based on total U-Pb ratios, and anticipated that isotopic ages would be discordant owing to the apparent migration of ^{226}Ra. Redistributed ore formed in the late Tertiary, or more recently, as indicated by U-Pb and fission-track dating (Ludwig et al., 1984; Rosenberg and Hooper, 1982); deposits in the Church Rock area are as young as Pleistocene (Ludwig et al., 1982). Uranophane from an Ambrosia Lake locality yields U-Pb ages of about 8 Ma (Brookins, 1981a).

As is true for the Todilto, it is difficult to estimate the age of the Morrison. The Jurassic-Cretaceous boundary in New Mexico may be within the Morrison (Lucas, 1989), and thus the age of that boundary is of interest. Recent suggestions range from 131 Ma (Haq et al., 1987) to 145.6 Ma (Harland et al., 1990); Palmer et al. (1983), Westermann (1984), Kent and Gradstein (1985), Snelling (1987), Cowie and Bassett (1989), and Odin and Odin (1990) provided intermediate estimates. Based on the minimum ages derived from U-Pb and Rb-Sr dating, and depending on which estimate of the age of this boundary is chosen, primary ore at Ambrosia Lake could be virtually syngenetic or could have formed several million years or more after Morrison deposition.

Other Colorado Plateau deposits in the Morrison

Deposits in the Morrison Formation in other Plateau districts may vary in age. Northrop and Goldhaber (1990) suggested that ores in the Henry basin, Utah, approach the age of the host beds. One of the deposits has an estimated minimum age of 115 Ma, and may be slightly younger than the primary ore at Ambrosia Lake (Wanty et al., 1990; K. R. Ludwig, personal comm. 1992). Geologic relationships support early Tertiary mineralization in the Uravan mineral belt (Shawe et al., 1991), but isotopic data from this district suggest minimum ages of >100 Ma (K. R. Ludwig, personal comm. 1992). Sanford (1982) points out that some apparent ages from the Morrison are similar to ones obtained from the Chinle (such as sample C-13, this study), and suggests a possible relationship. However, as discussed in the following section, these mostly discordant younger Chinle ages may reflect open-system behavior.

Deposits at Lisbon Valley and Kane Creek, Utah

Five isotopic ages from deposits in the Chinle Formation near Moab, Utah, are reported here, most of which have not previously been published. Three are from the Lisbon Valley district; two are from the Climax School Section #32 deposit, a stratabound deposit in the Chinle at Kane Creek, Utah. Miller and Kulp (1963) included seven ages from Lisbon Valley, with a similar range as those reported here. Ages for samples C-11 and C-16 are nearly concordant, with ^{207}Pb/^{235}U ages around 200 Ma, approaching the age of the Chinle. Under the interpretation suggested for Todilto ores, the essentially concordant ages should approximate the true age of the samples, whereas lower discordant U-Pb values reflect loss of lead and migration of ^{238}U daughters. However, Shawe et al. (1991) suggest that Chinle ores yielding lower U-Pb dates may indeed be younger. Morrison and Parry (1988) indicated that deposits associated with a collapse structure at Temple Mountain, Utah, may be as young as 13 Ma, based on K-Ar dating of alunite in altered zones.

Stieff et al. (1953) reported U-Pb ages for uraninite from the Shinarump Conglomerate that were much less than the age of the Chinle. However, Stieff (1958) referred to unpublished U-Pb ages of 149–206 Ma for Lisbon Valley ores, similar to those reported here, suggesting that the earliest studies might have yielded different conclusions if more samples had been available.

An age of 200 Ma for Lisbon Valley deposits is also tentatively suggested by two concordant ages reported by Cunningham and Ludwig (1980). These results were obtained from an unlikely source—samples resembling Lisbon Valley ores that were apparently discarded on a distant mine dump.

At Kane Creek, vein-type uranium deposits occur along faults cutting the Cutler Formation (Davidson and Kerr, 1968). Sample C-14, from one of these deposits, and a sample analyzed by Miller and Kulp (1963), yield much younger U-Pb ages than the nearby stratabound ores. The geologically different stratabound and vein-type deposits may therefore also be different in age, as the limited isotopic data suggest. Reynolds et al. (1985) believed that small uranium deposits in the Cutler Formation at Lisbon Valley formed by Cretaceous or Tertiary redistribution of uranium from the Chinle into the Cutler. It is possible that similar redistribution occurred at Kane Creek, but no compelling evidence supporting this concept has been noted (Davidson and Kerr, 1966).

Grand Canyon breccia pipe deposits

Many mineralized breccia pipes are known in the Grand Canyon region (Wenrich, 1985). Isotopic data from one sample from the Orphan deposit is reported here. Little can be concluded from this analysis, although the ^{207}Pb/^{235}U age of 139 Ma may provide a minimum age. Recent studies by Ludwig and Simmons (1988, 1991) indicate that many pipes were mineralized at around 200 Ma, and that the ores are thus similar in age to the stratabound deposits in the Lisbon Valley district. Some deposits may be as old as 260 Ma.

Study of the breccia pipe ores strongly supports the concept that open-system processes can affect uranium ores, as was stressed for the Todilto deposits. Ludwig and Simmons (1991) pointed out that the breccia pipe data show evidence for nearly all possible violations of the ideal conditions for U-Pb dating. Nevertheless, they have obtained estimates of the age of several deposits through the analysis of literally hundreds of total samples.

SUMMARY AND CONCLUSIONS

Primary uranium ore in the Todilto Limestone Member of the Wanakah Formation in the Grants uranium region has an estimated age of 150–155 Ma and apparently began to form relatively soon after deposition of the host rocks. Because of uncertainty in the isotopic ages and in the age of the Todilto, the interval between sedimentation and mineralization cannot be specified from isotopic data alone. Primary ore deposition could have been virtually syngenetic, or 10 Ma or more later, still relatively soon after sedimentation. The latter possibility would create problems for concepts of ore genesis that suggest penesyngenetic mineralization.

There were several periods of uranium mineralization in the Colorado Plateau. Similar to the Todilto, the oldest deposits in the Chinle and Morrison Formations, and the breccia pipes of the Grand Canyon, formed relatively early in the history of their host rocks. Some deposits in the Chinle and Morrison that yield significantly younger U-Pb apparent ages may have formed during later periods of primary mineralization. Others formed by redistribution of uranium from older deposits.

Because Plateau ores vary widely in age, nearby deposits in host rocks of different age may have formed at different times. For example, uraninite ores in the Todilto may have existed before the much larger nearby deposits in the Morrison Formation began to form, although the available age data for these deposits and their host rocks are not definitive.

Apparent U-Pb ages obtained from Todilto and other Colorado Plateau samples, and from many other low-temperature uranium deposits throughout the world, are usually discordant. At this time, after hundreds of isotopic analyses have been reported, it seems clear that complex open-system behavior, even in massive high-grade ores, is much more common than was anticipated when isotopic studies of these deposits began. The method used in this study of analyzing small high-grade samples is not necessarily optimal; open-system behavior can occur on scales larger than these samples, and their size may have contributed to the observed discordant ages. The predominant causes of the common pattern of normal discordance appear to be loss of radiogenic lead and migration of radioactive daughters from the ^{238}U decay chain. Under this interpretation, the ^{207}Pb/^{235}U ratio should provide a minimum age. When discordant data from a sufficient number of samples are available it may be possible to obtain reliable age estimates. Data from one or two samples are usually insufficient to yield useful conclusions.

ACKNOWLEDGMENTS

The writer is grateful for the assistance of Kenneth R. Ludwig and Virginia T. McLemore, who critically reviewed the manuscript and provided many valuable comments and suggestions. Kenneth R. Ludwig prepared the concordia plot (Fig. 2) of Pb-U ratios for Todilto and Entrada samples.

REFERENCES

Adams, S. S., 1991, Evolution of genetic concepts for principal types of sandstone uranium deposits in the United States; *in* Hutchinson, R. W. and Grauch, R. I., eds., Historical perspectives of genetic concepts and case histories of famous discoveries: Economic Geology Monograph 8, p. 225–248.

Adams, S. S., Curtis, H. S., Hafen, P. L. and Salek-Nejad, H., 1978, Interpretation of postdepositional processes related to the formation and destruction of the Jackpile-Paguate uranium deposit, northwest New Mexico: Economic Geology, v. 73, p. 1635–1654.

Armstrong, A. K., 1991, Jurassic Todilto Limestone—facies, diagenesis and mineralogy, Grants district, McKinley and Cibola Counties, New Mexico: New Mexico Geology, v. 13, p. 61.

Bassett, W. A., Kerr, P. F., Schaeffer, O. A. and Stoenner, R. W., 1963, Potassium-argon ages of volcanic rocks near Grants, New Mexico: Geological Society of America Bulletin, v. 74, p. 221–226.

Berglof, W. R., 1970, Absolute age relationships in selected Colorado Plateau uranium ores [Ph.D. dissertation]: New York, Columbia University, 149 p.

Brookins, D. G., 1980, Geochronologic studies in the Grants mineral belt; *in* Rautman, C. A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources, Memoir 38, p. 52–58.

Brookins, D. G., 1981a, Primary uranophane from the Ambrosia Lake uranium district, Grants mineral belt, USA: Mineralium Deposita, v. 16, p. 3–5.

Brookins, D. G., 1981b, U-Pb ages for U(VI) hydrosilicates, Grants, New Mexico: Isochron West, no. 32, p. 25.

Chenoweth, W. L., 1985, Historical review of uranium production from the Todilto Limestone, Cibola and McKinley Counties, New Mexico: New Mexico Geology, v. 7, p. 80–83.

Cobb, J. C. and Kulp, J. L., 1961, Isotopic geochemistry of uranium and lead in the Swedish kolm and its associated shale: Geochimica et Cosmochimica Acta, v. 24, p. 226–249.

Condon, S. M. and Huffman, A. C., 1988, Revisions in nomenclature of the Middle Jurassic Wanakah Formation, northwestern New Mexico and northeastern Arizona: U.S. Geological Survey, Bulletin 1633-A, 12 p.

Condon, S. M. and Peterson, F., 1986, Stratigraphy of Middle and Upper Jurassic rocks of the San Juan Basin: historical perspective, current ideas, and remaining problems; *in* Turner-Peterson, C. E., Santos, E. S. and Fishman, N. S., eds., A basin analysis case study: the Morrison Formation, Grants uranium region New Mexico: American Association of Petroleum Geologists, Studies in Geology no. 22, p. 7–26.

Cowie, J. W. and Bassett, M. G., compilers, 1989, International Union of Geological Sciences 1989 global stratigraphic chart: Episodes, v. 12, no. 2, supplement.

Cunningham, C. G. and Ludwig, K. R., 1980, Sagacious scientific sleuthing solves salting saga: Economic Geology, v. 75, p. 1109–1111.

Davidson, D. M. Jr. and Kerr, P. F., 1966, Uranium deposits at Kane Creek, Utah: American Institute of Mining Engineers Transactions, v. 235, p. 127–132.

Davidson, D. M. Jr. and Kerr, P. F., 1968, Uranium-bearing veins in Plateau Strata, Kane Creek, Utah: Geological Society of America Bulletin, v. 79, p. 1503–1526.

Durand, G. L., 1963, Contribution à l'étude de la mine d'uranium de Limouzat (Massif des Bois-Noirs): Bulletin de la Société française de Minéralogie et de Cristallographie, v. 86, p. 394–404.

Eckelmann, W. R. and Kulp, J. L., 1957, Uranium-lead method of age determination. Part II: North American localities: Geological Society of America Bulletin, v. 68, p. 1117–1140.

Fischer, H. and Gygi, R., 1989, Numerical and biochronological time scales correlated at the ammonite subzone level; K-Ar, Rb-Sr ages, and Sr, Nd, and Pb sea-water isotopes in an Oxfordian (Late Jurassic) succession of northern Switzerland: Geological Society of America Bulletin, v. 101, p. 1584–1597.

Gabelman, J. W., 1956, Uranium deposits in limestone: U.S. Geological Survey, Professional Paper 300, p. 387–404.

Gabelman, J. W., 1970, The Flat Top uranium mine, Grants, New Mexico: U.S. Atomic Energy Commission, RME 4112, 81 p.

Gabelman, J. W. and Boyer, W. H., 1988, Uranium deposits in Todilto Limestone, New Mexico: The Barbara "J" No. 1 mine: Ore Geology Reviews, v. 3, p. 241–276.

Gornitz, V. and Kerr, P. F., 1970, Uranium mineralization and alteration, Orphan Mine, Grand Canyon, Arizona: Economic Geology, v. 65, p. 751–768.

Granger, H. C., 1963a, Mineralogy; *in* Kelley, V. C., compiler, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources, Memoir 15, p. 21–37.

Granger, H. C., 1963b, Radium migration and its effect on the apparent age of uranium deposits at Ambrosia Lake, New Mexico: U.S. Geological Survey, Professional Paper 475-B, p. B60–B63.

Granger, H. C., 1968, Localization and control of uranium deposits in the southern San Juan Basin mineral belt, New Mexico—an hypothesis: U.S. Geological Survey, Professional Paper 600B, p. B60–B70.

Granger, H. C., Santos, E. S., Dean, B. G. and Moore, F. B., 1961, Sandstone-type uranium deposits at Ambrosia Lake, New Mexico—an interim report: Economic Geology, v. 56, p. 1179–1210.

Green, M. W., 1982, Origin of intraformational folds in the Jurassic Todilto Limestone, Ambrosia Lake uranium mining district, McKinley and Valencia Counties, New Mexico: U.S. Geological Survey, Open-file Report 82-69, 29 p.

Haq, B. U., Hardenbol, J. and Vail, P. R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1167.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G. and Smith, D. G., 1990, A geologic time scale 1989: Cambridge, Cambridge University Press, 263 p.

Hilpert, L. S., 1969, Uranium resources of northwestern New Mexico: U.S. Geological Survey, Professional Paper 603, 166 p.

Hilpert, L. S. and Moench, R. H., 1960, Uranium deposits of the southern part of the San Juan Basin, New Mexico: Economic Geology, v. 55, p. 429–464.

Holliger, P., Pagel, M. and Pironon, J., 1989, A model for ^{238}U radioactive daughter loss from sediment-hosted pitchblende deposits and the Late Permian–Early Triassic depositional U-Pb age of the Müllenbach uranium ore (Baden-Württemberg, F.R.G.): Chemical Geology (Isotope Geoscience Section), v. 80, p. 45–53.

Imlay, R. W., 1952, Correlation of the Jurassic formations of North America, exclusive of Canada: Geological Society of America Bulletin, v. 63, p. 953–992.

Kelley, V. C., Kittel, D. F. and Melancon, P. E., 1968, Uranium deposits of the Grants region; *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–1967: New York, American Institute of Mining, Metallurgical and Petroleum Engineers, v. 1, p. 747–769.

Kent, D. V. and Gradstein, F. M., 1985, A Cretaceous and Jurassic geochronology: Geological Society of America Bulletin, v. 96, p. 1419–1427.

Lee, M. J. and Brookins, D. G., 1978, Rubidium-strontium minimum ages of sedimentation, uranium mineralization, and provenance, Morrison Formation (Upper Jurassic), Grants mineral belt, New Mexico: American Association of Petroleum Geologists Bulletin, v. 62, p. 1673–1683.

Lee, M. J. and Brookins, D. G., 1980, Rubidium-strontium minimum ages of sedimentation, uranium mineralization, and provenance, Morrison Formation (Upper Jurassic), Grants mineral belt, New Mexico: Reply: American Association of Petroleum Geologists Bulletin, v. 64, p. 1719.

Lucas, S. G., 1986, Fossil fishes and age of uranium mineralization in the Middle Jurassic Todilto Formation of northern New Mexico: New Mexico Geology, v. 8, p. 67.

Lucas, S. G., 1989, Jurassic-Cretaceous boundary in west-central New Mexico: New Mexico Geological Society, Guidebook 40, p. 6–7.

Lucas, S. G. and Kietzke, K. K., 1986, Stratigraphy and petroleum potential of the Jurassic Todilto Formation in northeastern New Mexico; *in* Ahlen, J. L. and Hanson, M. E., eds., Southwest Section of AAPG Transactions and Guidebook of 1986 Convention: New Mexico Bureau of Mines and Mineral Resources, p. 121–127.

Lucas, S. G, Kietzke, K. K. and Hunt, A. P., 1985, The Jurassic System in east-central New Mexico: New Mexico Geological Society, Guidebook 36, p. 214–242.

Ludwig, K. R., 1978, Uranium-daughter migration and U/Pb isotope apparent ages of uranium ores, Shirley Basin, Wyoming: Economic Geology, v. 73, p. 29–49.

Ludwig, K. R., 1979, Age of uranium mineralization in the Gas Hills and Crooks Gap districts, Wyoming, as indicated by U-Pb isotope apparent ages: Economic Geology, v. 74, p. 1654–1668.

Ludwig, K. R., Grauch, R. I., Nutt, C. J., Nash, J. T., Frishman, D. and Simmons, K. R., 1987, Age of uranium mineralization at the Jabiluka and Ranger deposits, Northern Territory, Australia: new U-Pb evidence: Economic Geology, v. 82, p. 857–874.

Ludwig, K. R., Nash, J. T. and Naeser, C. W., 1981, U-Pb isotope systematics and age of uranium mineralization, Midnite mine, Washington: Economic Geology, v. 76, p. 89–110.

Ludwig, K. R., Rubin, B., Fishman, N. S. and Reynolds, R. L., 1982, U-Pb ages of uranium ores in the Churchrock uranium district, New Mexico: Economic Geology, v. 77, p. 1942–1945.

Ludwig, K. R. and Simmons, K. R., 1988, Progress in U/Pb isotope studies of collapse-breccia pipes in the Grand Canyon region, northern Arizona: Geological Society of America, Abstracts with Programs, v. 20, p. A139.

Ludwig, K. R. and Simmons, K. R., 1991, U-Pb dating of uranium ores in collapse-breccia pipes, Grand Canyon region; *in* Pagel, M. and Leroy, J. L., eds., Source, transport and deposition of metals: Rotterdam, Balkema, p. 405–408.

Ludwig, K. R., Simmons, K. R. and Webster, J. D., 1984, U-Pb isotope systematics and apparent ages of uranium ores, Ambrosia Lake and Smith Lake districts, Grants Mineral Belt, New Mexico: Economic Geology, v. 79, p. 322–337.

Mauger, R. L., 1967, A summary of isotopic ages of Colorado Plateau, Utah, mineral deposits; *in* Hintze, L. F., ed., Uranium districts of southeastern Utah: Utah Geological Society Guidebook 21, p. 91–98.

McLaughlin, E. D. Jr., 1963, Uranium deposits in the Todilto Limestone of the Grants district; *in* Kelley, V. C., compiler, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources, Memoir 15, p. 136–149.

McLemore, V. T., 1983, Uranium and thorium occurrences in New Mexico—distribution, geology, production, and resources, with selected bibliography: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 183, 1541 p.

McLemore, V. T. and Chenoweth, W. L., 1989, Uranium resources in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Resource Map 18, 36 p.

Melvin, J. W., 1976, Systematic distribution of large uranium deposits in the Grants uranium region, New Mexico; *in* Woodward, L. A. and Northrop, S. A., eds., Tectonics and mineral resources of southwestern North America: New Mexico Geological Society, Special Publication 6, p. 144–150.

Miller, D. S., 1960, The isotopic geochemistry of uranium, lead and sulfur in the Colorado Plateau uranium ores [Ph.D. dissertation]: New York, Columbia University, 143 p.

Miller, D. S. and Kulp, J. L., 1958, Isotopic study of some Colorado Plateau uranium ores: Economic Geology, v. 53, p. 937–948.

Miller, D. S. and Kulp, J. L., 1963, Isotopic evidence on the origin of the Colorado Plateau uranium ores: Geological Society of America Bulletin, v. 74, p. 609–629.

Moench, R. H. and Schlee, J. S., 1967, Geology and uranium deposits of the Laguna district, New Mexico: U.S. Geological Survey, Professional Paper 519, 117 p.

Morrison, S. J. and Parry, W. T., 1988, Age and formation conditions of alteration associated with a collapse structure, Temple Mountain uranium district, Utah: Geological Society of America Bulletin, v. 100, p. 1069–1077.

Nash, J. T., 1968, Uranium deposits in the Jackpile sandstone, New Mexico: Economic Geology, v. 63, p. 737–750.

Nash, J. T. and Kerr, P. F., 1966, Geologic limitations on the age of uranium deposits in the Jackpile sandstone, New Mexico: Economic Geology, v. 61, p. 1283–1287.

Northrop, H. R. and Goldhaber, M. B., eds., 1990, Genesis of tabular-type vanadium-uranium deposits of the Henry basin, Utah: Economic Geology, v. 85, p. 215–269.

Odin, G. S. and Odin, C., 1990, Échelle numérique des temps géologiques: Géochronique, no. 35, p. 12–21.

Palmer, A. R. et al., 1983, The Decade of North American Geology 1983 geologic time scale: Geology, v. 11, p. 503–504.

Pessagno, E. A. and Blome, C. D., 1990, Implications of new Jurassic stratigraphic, geochronometric, and paleolatitudinal data from the western Klamath terrane (Smith River and Rogue Valley subterranes): Geology, v. 18, p. 665–668.

Rawson, R. R., 1980, Uranium in Todilto Limestone (Jurassic) of New Mexico—example of a sabkha-like deposit; *in* Rautman, C. A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources, Memoir 38, p. 304–312.

Respaut, J. P., Cathelineau, M. and Lancelot, J. R., 1991, Multistage evolution of the Pierres-Plantées uranium ore deposit (Margeride, France): evidence from mineralogy and U-Pb systematics: European Journal of Mineralogy, v. 3, p. 85–103.

Reynolds, R. L., Hudson, M. R., Fishman, N. S. and Campbell, J. A., 1985, Paleomagnetic and petrologic evidence bearing on the age and origin of uranium deposits in the Permian Cutler Formation, Lisbon Valley Utah: Geological Society of America Bulletin, v. 96, p. 719–730.

Rosenberg, P. E. and Hooper, R. L., 1982, Fission-track dating of sandstone-type uranium deposits: Geology, v. 10, p. 481–485.

Sanford, R. F., 1982, Preliminary model of regional Mesozoic groundwater flow and uranium deposition in the Colorado Plateau: Geology, v. 10, p. 348–352.

Schaeffer, B. and Patterson, C., 1984, Jurassic fishes from the western United States, with comments on Jurassic fish distribution: American Museum Novitates, no. 2796, 86 p.

Shawe, D. R., Nash, J. T. and Chenoweth, W. L., 1991, Uranium and vanadium deposits; *in* Gluskoter, H. J., Rice, D. D. and Taylor, R. B., eds., Economic Geology, U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. P-2, p. 103–124.

Snelling, N. J., 1987, Measurement of geological time and the geological time scale: Modern Geology, v. 11, p. 365–374.

Squyres, J. B., 1972, Uranium deposits of the Grants region, New Mexico: Wyoming Geological Association Earth Science Bulletin, v. 5, p. 3–12.

Squyres, J. B., 1980, Origin and significance of organic matter in uranium deposits of Morrison Formation, San Juan Basin, New Mexico; *in* Rautman, C. A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources, Memoir 38, p. 86–97.

Steiger, R. H. and Jäger, E., 1977, Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.

Stieff, L. R., 1958, Geochronology, U.S. Atomic Energy Commission, TEI-740, p. 299–302.

Stieff, L. R. and Stern, T. W., 1956, Interpretation of the discordant age sequence of uranium ores: U.S. Geological Survey, Professional Paper 300, p. 549–555.

Stieff, L. R., Stern, T. W. and Milkey, R. G., 1953, A preliminary determination of the age of some uranium ores of the Colorado Plateau by the lead-uranium method: U.S. Geological Survey, Circular 271, 19 p.

Stieff, L. R., Stern, T. W., Oshiro, S. and Senftle, F. E., 1959, Tables for the calculation of lead isotope ages: U.S. Geological Survey, Professional Paper 334-A, 40 p.

Turner-Peterson, C. E., 1985, Lacustrine-humate model for primary uranium ore deposits, Grants uranium region, New Mexico: American Association of Petroleum Geologists Bulletin, v. 69, p. 1999–2020.

Turner-Peterson, C. E., Santos, E. S. and Fishman, N. S., eds., 1986, A basin analysis case study: the Morrison Formation, Grants uranium region New Mexico: American Association of Petroleum Geologists, Studies in Geology no. 22, 391 p.

Turpin, L. and Leroy, J. L., 1987, Isotopic investigation of the Piégut uranium deposit (Marche, northwest Massif Central, France): U series disequilibrium and geochronology: Economic Geology, v. 82, p. 752–756.

Wanty, R. B., Goldhaber, M. B. and Northrop, H. R., 1990, Geochemistry of vanadium in an epigenetic, sandstone-hosted vanadium-uranium deposit, Henry basin, Utah: Economic Geology, v. 85, p. 270–284.

Wenrich, K. J., 1985, Mineralization of breccia pipes in northern Arizona: Economic Geology, v. 80, p. 1722–1735.

Westermann, G., 1984, Gauging the duration of stages: a new approach for the Jurassic: Episodes, v. 7, no. 2, p. 26–28.