

UNITED STATES DEPARTMENT OF THE INTERIOR  
GEOLOGICAL SURVEY

History of sulfidization of the Felder  
uranium deposit, south Texas

by

Richard L. Reynolds, Martin B. Goldhaber, Robert O. Rye,  
Neil S. Fishman, Kenneth R. Ludwig, and Richard I. Grauch

Open-File Report 80-1096

1980

## Contents

	<u>Page</u>
Abstract.....	1
Introduction... . . . .	2
Sample suite and laboratory procedures.....	4
Geochemistry.....	6
Uranium and molybdenum.....	6
Sulfur.....	7
Organic carbon.....	7
Other elements.....	7
Iron disulfide minerals and sulfur isotope systematics.....	8
Abundance and distribution of iron disulfide minerals.....	8
Generations of iron disulfide minerals.....	8
Sulfur isotopic compositions of iron disulfide minerals.....	13
Summary of petrographic observations and sulfur isotopic ratios..	14
Comparison of the Felder deposit with the Lamprecht deposit.....	14
Sources of sulfur for iron disulfide minerals.....	15
Pre-ore iron disulfide minerals.....	15
Ore-stage iron disulfide minerals.....	17
Post-ore iron disulfide minerals.....	17
Timing of resulfidization.....	18
Summary.....	20
Acknowledgments.....	22
References.....	23

## Illustrations

	<u>Page</u>
Figure 1. Map of Ray Point area showing location of Felder uranium deposit.....	3
2. Cross section of uranium deposit in pit 4B.....	5
3. Abundance of marcasite relative to FeS <sub>2</sub> minerals.....	9
4. Sulfur isotopic composition of samples, pit 4B.....	10
5. Schematic diagram showing textural relationships among the four generations of FeS <sub>2</sub> minerals.....	12
6. Plot of marcasite as a percentage of FeS <sub>2</sub> minerals, core 4, Lamprecht deposit.....	16
7. Plot of average $\delta^{34}\text{S}$ values and average marcasite abundance.....	19

## Table

Table 1. Summary of sulfidization history, Felder deposit.....	21
--	----

History of sulfidization of the Felder uranium deposit,  
south Texas

by Richard L. Reynolds, Martin B. Goldhaber, Robert O. Rye,  
Neil S. Fishman, Kenneth R. Ludwig, and Richard I. Grauch

Abstract

Studies of the mineralogy, sulfur isotope geochemistry, and U-Pb isotope geochronology of a roll-type orebody in the Felder deposit, south Texas, have indicated important constraints on the genesis of this deposit. Post-mineralization sulfidization of the host Oakville Sandstone (Miocene) resulted in precipitation of pyrite and marcasite in the altered tongue that differ in relative abundance and in isotopic composition from pyrite and marcasite elsewhere in the host rock. The altered tongue is characterized by a predominance of pyrite over marcasite and by heavy  $\delta^{34}\text{S}$  values (-5.2 and +20.6 permil), whereas reduced-barren and mineralized rock is characterized by abundant ore-stage marcasite and by light  $\delta^{34}\text{S}$  values (-29.9 to -47.7 permil). In reduced-barren and mineralized rock, two generations of pyrite are present: (1) pre-ore pyrite grains that are commonly enclosed by ore-stage marcasite, and (2) post-ore pyrite that is genetically equivalent to pyrite in the altered tongue. Resulfidization of the deposit by  $\text{H}_2\text{S}$ -bearing solutions introduced along one or more nearby faults is indicated by the similarity in isotopic compositions of pyrite in the altered tongue to that of sour gas in the underlying Edwards Limestone (Cretaceous). The time of this resulfidization is probably indicated by the unusually precise  $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{235}\text{U}/^{204}\text{Pb}$  isochron age of  $5.07 \pm 0.15$  m.y. The lack of significant scatter of the points on the isochron diagram must reflect the immobility of U and Pb over the last 5 m.y. due to the continued presence of  $\text{H}_2\text{S}$ . The 5-m.y. isochron age indicates that no significant roll-forming processes have occurred in the Felder deposit since this time.

## Introduction

The Felder uranium deposit is one of several deposits in the Ray Point district, Live Oak County, South Texas (fig. 1). In the Felder mine area, as in other mine areas near Ray Point, mineralization occurs in the basal fluvial sand of the Miocene Oakville Sandstone at the northeast margin of a major Oakville fluvial system that trends coastward across Live Oak County (Klohn and Pickens, 1970; Galloway and others, 1979). These deposits also share in common a close spatial relationship to faults. Mineralization is either aligned parallel to (Felder, Lamprecht, and Zamzow deposits) or intersected by (McLean and Hahn deposits) the Oakville fault, a down-to-the-coast normal fault. Such association suggests control by the faults on the origin and(or) preservation of the deposits.

In deposits intersected by faults, the ore occurs adjacent to and along fault zones; in other deposits, ore occurs in C-shaped rolls commonly bounded above by thin impermeable mudstone beds or lenses in the sandstone and below by mudstone of the Miocene Catahoula Tuff. In the roll-type deposits, uranium and molybdenum are concentrated at and near the concave margin of the roll and decrease in abundance downdip from the concave margin. Such a distribution pattern typically results from invasion of reduced ground by oxygenated solutions bearing hexavalent uranium migrating down a hydrologic gradient. Continued ingress of uranium-bearing solutions results in continuous solubilization behind (updip from) and reprecipitation of ore constituents ahead of (downdip from) the concave roll margin. This process leads to development of a tongue of oxidized rock (the altered tongue) that contains ferric oxide minerals and that is separated by a reduction-oxidation (redox) interface from the mineralized and reduced barren zone that contains iron disulfide ( $\text{FeS}_2$ ) minerals.

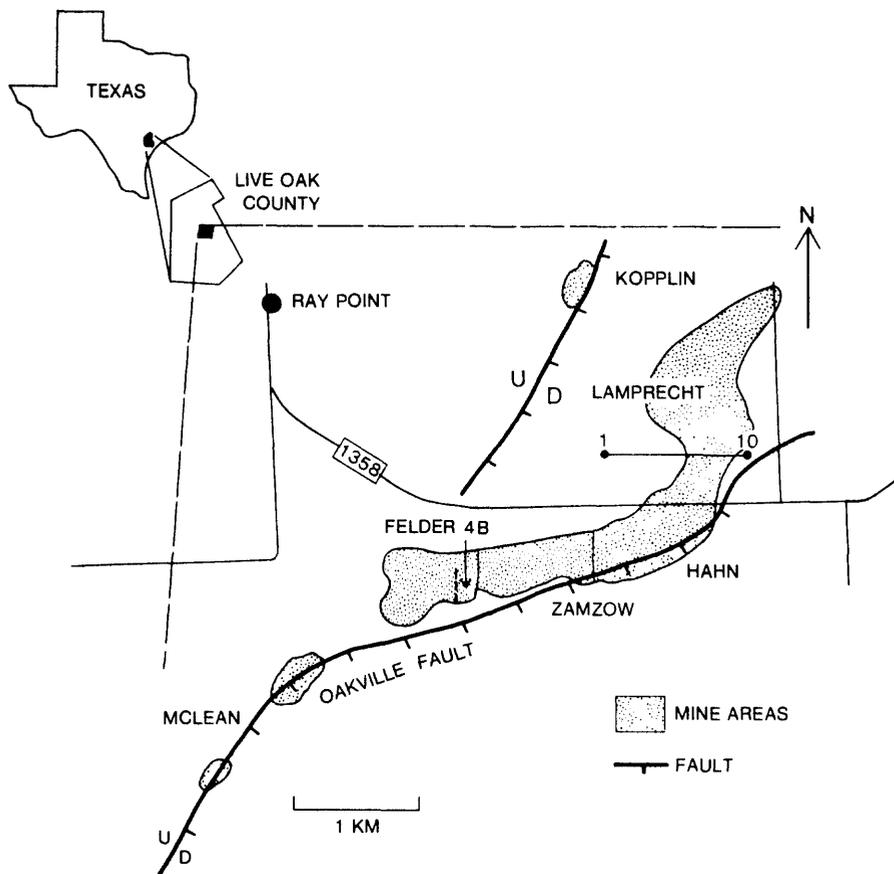


Figure 1.--Map of Ray Point area showing locations of the Felder uranium deposit, pit 4B, and other uranium mine areas discussed in the text. Core fence between cores 1 and 10 in the Lamprecht deposit is shown by line across the Lamprecht mine area. (Modified from Galloway and others, 1979.)

Post-mineralization sulfidization of the host beds involving precipitation  $\text{FeS}_2$  minerals in the altered tongue may obscure differences in mineralogy across the redox boundary that developed during ore formation. The Felder deposit and other roll-type deposits in the Ray Point area have been resulfidized so that  $\text{FeS}_2$ , not ferric oxide, minerals are abundant in the altered tongue.

In this paper, we outline the history of sulfidization of part of an ore roll in the Felder mine area based on studies of geochemistry and of the distribution, textural relationships, and sulfur isotopic composition of  $\text{FeS}_2$  minerals. We have previously conducted a similar study of the nearby Lamprecht deposit, which is also a resulfidized roll-type orebody (Goldhaber and others, 1979). Results of the Felder compared with those of the Lamprecht help to establish similarities and differences between the uranium deposits in the Ray Point area, and yield information on the evolution of these deposits, particularly on the role of the faults in controlling the position of the deposits.

#### Sample suite and laboratory procedures

Samples were collected from a partly excavated ore roll exposed in pit 4B in the southeast corner of the Felder mine area. The distribution of samples spanning 105 m horizontally across the deposit and up to 5 m vertically from the floor of the pit, and extent of exposure of the orebody at the time of sampling, are shown on figure 2. Drilling by Exxon prior to pit excavation indicated the presence of upper and lower mineralized limbs (only a small part of the latter were exposed at the time of our sampling) but revealed that the two limbs do not neatly converge.

Portions of each of the 64 samples were analyzed chemically for uranium using delayed neutron methods, and for major and minor elements by semi-

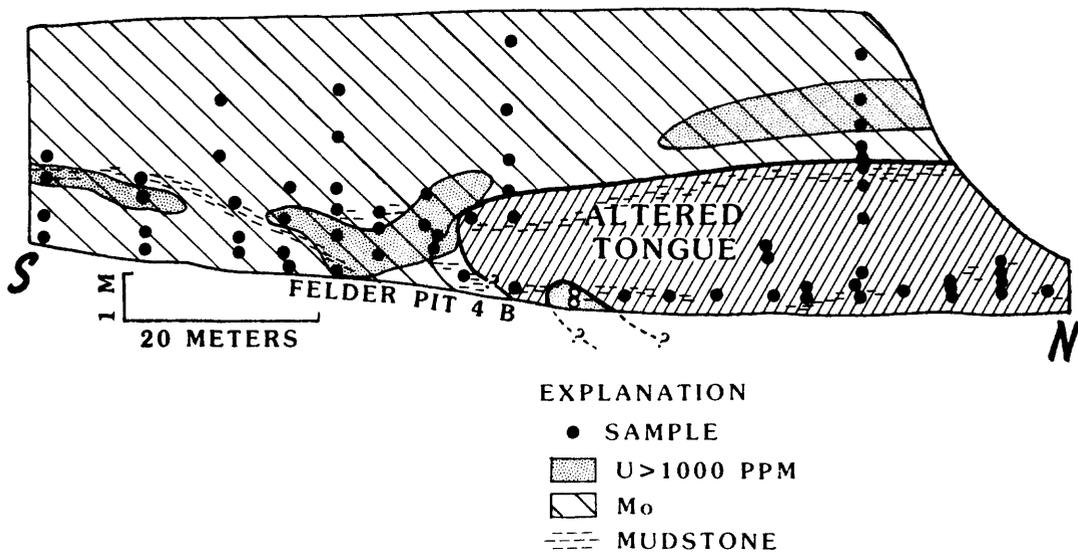


Figure 2.--Cross section of part of the ore roll exposed in the west wall of pit 4B. Large circles denote sample locations. Stippled pattern represents presence of uranium in amounts greater than 1000 ppm. Also shown are the zone of anomalously high concentrations of molybdenum (widely spaced slashes); the altered tongue (closely spaced slashes); and the paleo-redox boundary inferred from the presence and abundance of uranium and molybdenum, from relative abundances of marcasite (fig. 3) and from sulfur isotopic ratios (fig. 4.). Open circles denote two samples that may represent part of the lower mineralized limb.

quantitative emission spectroscopy. Most samples were analyzed for total sulfur and organic carbon using the LECO<sup>R</sup> induction furnace<sup>1</sup> technique. Other portions of 62 samples were treated with heavy liquids to obtain a heavy-mineral fraction. One aliquot of each heavy mineral separate was embedded in epoxy and polished for viewing under oil by reflected-light microscopy. Abundances of pyrite and marcasite were estimated by three independent observers; about 25 percent of these estimates were checked by semiquantitative X-ray diffraction analysis using relative peak heights. Another aliquot of 20 of the heavy mineral separates was prepared for stable isotope determination by treatment with hydrochloric and hydrofluoric acids to remove carbonates and silicates, respectively. The resulting FeS<sub>2</sub>-mineral concentrate was combusted in oxygen to yield SO<sub>2</sub> for isotopic analysis. Results are given as the permil deviation ( $\delta^{34}\text{S}$ ) of the isotopic ratio  $^{34}\text{S}/^{32}\text{S}$  from the ratios of a standard (Cañon Diablo troilite).

## Geochemistry

### Uranium and molybdenum

Uranium enrichment in pit 4B is sporadic yet broadly defines an upper limb of mineralization and a thin discontinuous band of mineralization extending southward (fig. 2). The broken pattern of uranium concentration is caused in part by unmineralized mudstone layers and lenses. The observed distribution of uranium in pit 4B is similar to that described by Klohn and Pickens (1970) for other parts of the Felder orebody.

---

<sup>1</sup>Any trade names or trademarks found in this publication are used for descriptive purposes only and do not constitute endorsement by the U.S. Geological Survey.

The zones of uranium and molybdenum enrichment closely correspond and together bound the altered tongue in which uranium and molybdenum occur in very low amounts or are undetectable, with the exception of two adjacent samples (fig. 2). These two samples contain higher amounts of uranium and molybdenum than are typical of other samples in the altered tongue and may represent remnants of ore or may be part of the lower ore limb. Accordingly, these samples are included in the suite of mineralized samples in the following discussion.

#### Sulfur

Sulfur occurs throughout the host rock in amounts ranging from 0.1 weight percent to nearly 9 weight percent. Sulfur is present, however, in much greater abundance in samples from reduced barren and mineralized ground (an average of 1.94 percent) than in samples from the altered tongue (an average of 0.28 percent).

#### Organic carbon

Organic carbon was detected in very low amounts (average 0.03 percent) in 53 of 62 samples. These results are similar to those given by Goldhaber and others (1979) for the Oakville host at the Lamprecht deposit. In addition, we did not observe plant debris in hand sample or in sections. Klohn and Pickens (1970) and Harshman (1974) reported an absence of carbonaceous matter and organic carbon in the Felder host beds.

#### Other elements

Distributions of other elements (Fe, V, Mg, Mn, Cr, N, Cu, Ca, Ba, Sr) show no pattern that can be confidently related to ore-forming processes. Differences in abundances of Fe, V, and Mg are related mainly to lithology: these elements occur in greater proportions in mudstone than in sandstone. Calcium abundance reflects the presence of bands and streaks of calcite cement which occur sporadically throughout the host beds.

## Iron disulfide minerals and sulfur isotope systematics

### Abundance and distribution of iron disulfide minerals

Iron disulfide minerals (pyrite and marcasite) occur throughout the deposit, but relative abundances of pyrite and marcasite in the altered tongue differs greatly from their relative abundances in reduced barren and mineralized ground (fig. 3). Similarly, bulk sulfur isotopic composition of samples from the altered interior contrast sharply with the isotopic composition of samples from elsewhere in the host beds (fig. 4). The reduced barren and mineralized zones are characterized by a dominance of marcasite over pyrite and by light  $\delta^{34}\text{S}$  (-28.8 to -47.4 permil), whereas the altered tongue is characterized by abundant pyrite and by heavy  $\delta^{34}\text{S}$  values (-5.2 to +20.6 permil).

In fact, all samples from reduced barren and mineralized ground contained at least (and commonly much more than) 50 percent marcasite. All but two samples from the altered tongue contained more than 50 percent pyrite.

Abundance of  $\text{FeS}_2$ , calculated in weight percent assuming that all S is incorporated into either pyrite or marcasite, reflects this distinction:  $\text{FeS}_2$  content is much higher in reduced barren and mineralized rock (an average of 3.68 percent) than in the altered tongue (an average of 0.52 percent).<sup>1</sup>

### Generations of iron disulfide minerals

Petrographic examination has led to the recognition of four generations of  $\text{FeS}_2$  minerals in the Felder host sands. The four generations from oldest to youngest are as follows: (1) a pre-ore generation composed dominantly of pyrite; (2) an ore-stage generation of marcasite; (3) a post-ore generation

---

<sup>1</sup>Some sulfur may be incorporated into barite ( $\text{BaSO}_4$ ) but in amounts insufficient to significantly alter calculated  $\text{FeS}_2$  content.

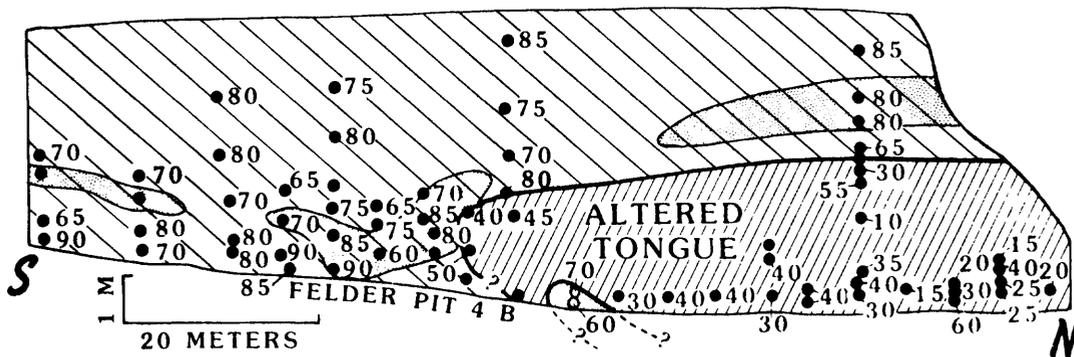


Figure 3.--Abundance of marcasite as a percentage of total iron disulfide minerals (pyrite plus marcasite) in samples from pit 4B.

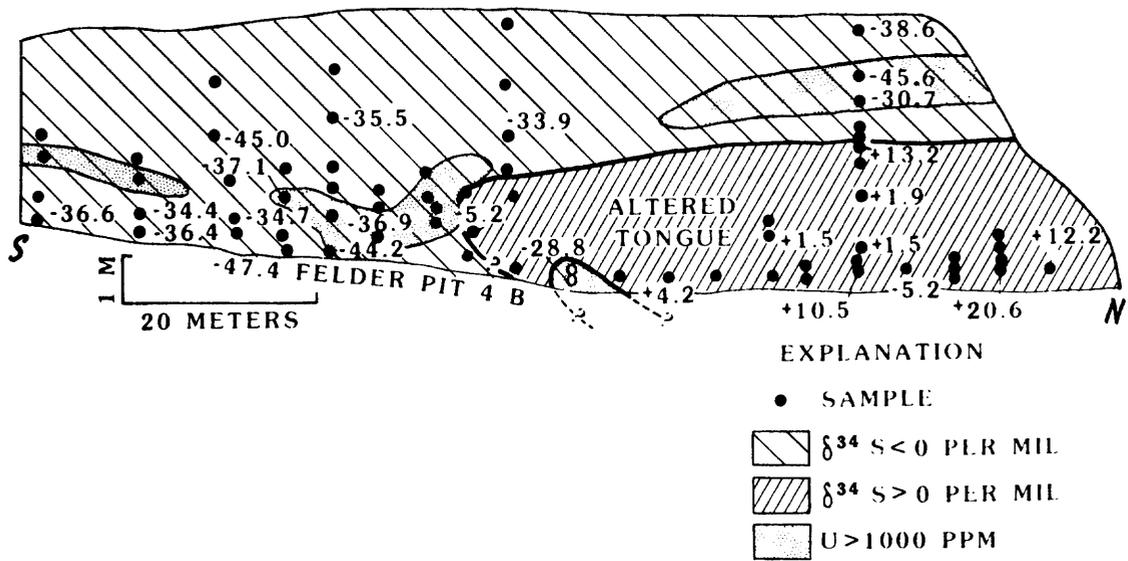


Figure 4.--Sulfur isotopic composition ( $\delta^{34}\text{S}$ ) of samples from pit 4B.

composed dominantly of pyrite; and (4) a later post-ore generation of marcasite. The four generations are shown schematically on figure 5. Brief descriptions of the four generations and textural evidence for their recognition are discussed below.

The most common identifiable pre-ore sulfide consists of clusters of euhedral to subhedral pyrite crystals (about 5 to 20  $\mu$ m across) which are found in reduced barren and mineralized ground and are absent in the altered tongue. Larger pyrite crystals, pyrite cement, and pyrite-marcasite as replacement of detrital iron-titanium (Fe-Ti) oxide minerals are also representative of the pre-ore sulfide. In reduced barren and mineralized rock a later generation of marcasite commonly occurs as rims on pre-ore pyrite and envelops clusters of pyrite crystals. Such textural relationships closely resemble those observed in other roll-type uranium deposits (Reynolds and Goldhaber, 1979a, b; Goldhaber and others, 1979). Preliminary examination of Felder ore samples (those from pit 4B and six others of U- and Mo- enriched samples from elsewhere in the deposit by electron microprobe indicates that deposition of marcasite spanned in part deposition of uranium and molybdenum; for the most part, however, uranium and molybdenum phases surround marcasite when found in close association. The significance of these observations is discussed in more detail below.

In addition to pre-ore and ore-stage sulfide, the reduced barren and mineralized zone contains a yet younger generation of FeS<sub>2</sub> that occurs primarily as pyrite rims on marcasite (which in turn may surround earlier pyrite). We interpret this outer zone of pyrite to be related to the post-ore sulfidization event and to be genetically equivalent to abundant pyrite in the altered tongue. In the altered tongue, the post-ore pyrite is present as cement of framework grains, as euhedral to subhedral pyrite crystals, and as

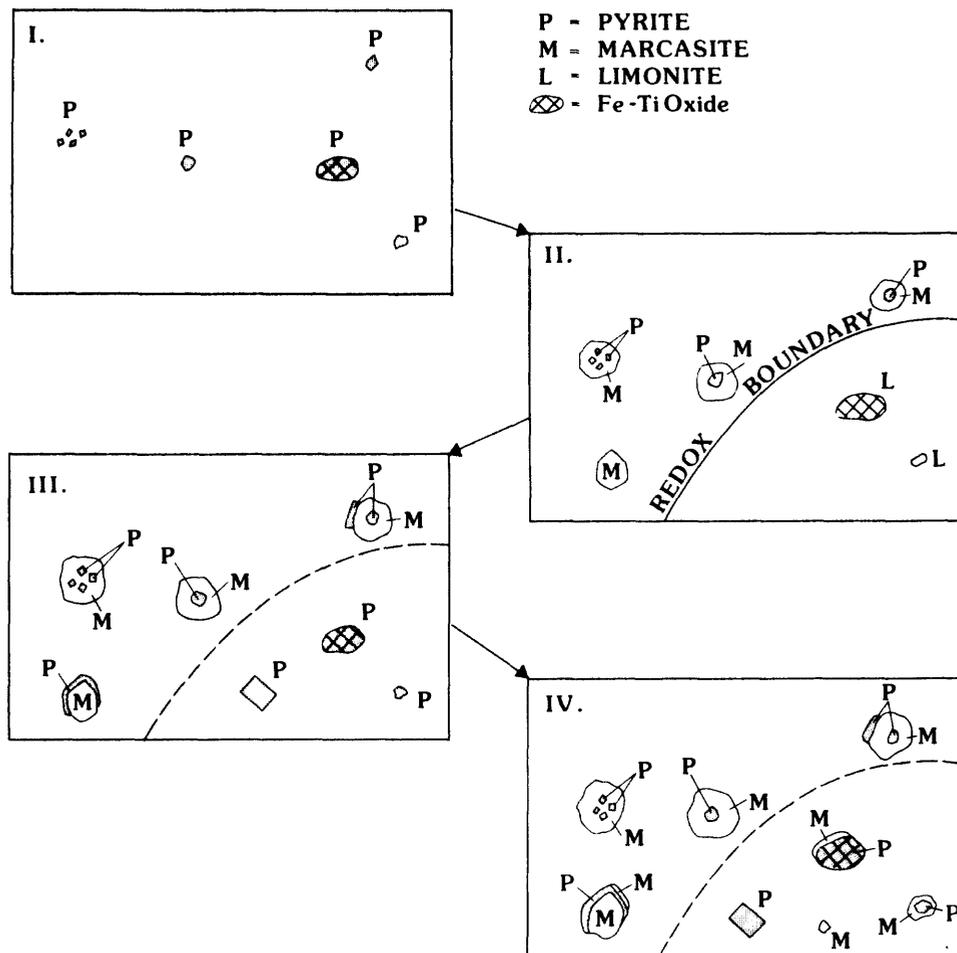


Figure 5.--Schematic diagram illustrating sulfidization stages and resulting textural relationships among the four generations of FeS<sub>2</sub> minerals. I, Initial sulfidization; II, mineralization; III, resulfidization involving pyrite precipitation; IV, resulfidization involving marcasite precipitation.

replacement of former Fe-Ti oxide grains. Pyrite also occurs around or within limonite grains, some of which were originally detrital Fe-Ti oxides. This association may have resulted from oxidation of sulfide (including sulfidized Fe-Ti oxide) to limonite during mineralization followed by replacement of limonite by post-ore pyrite.

The altered tongue contains a yet younger generation of sulfide that occurs dominantly as marcasite which forms thin rims on post-ore pyrite. This generation of marcasite is apparently present in reduced barren and mineralized ground where it occurs rarely around pyrite that rims earlier ore-stage marcasite. If present in other textural forms, it cannot be distinguished from abundant ore-stage marcasite.

#### Sulfur isotopic compositions of iron disulfide minerals

We have little data bearing on the sulfur isotopic composition of pre-ore FeS<sub>2</sub> but suspect that it is isotopically light. This tentative conclusion is based in part on light sulfur isotopic values (-24.4 to -34.2 permil) obtained from unmineralized mudstones that contain abundant pre-ore pyrite (about 80 percent of the FeS<sub>2</sub> in these samples) at the Lamprecht deposit. In addition, preliminary experimental data from samples of sandstone from the Felder and Lamprecht host beds involving removal of marcasite (most of which is isotopically light ore-stage marcasite) are consistent with a remaining sulfide component (most of which is, presumably, pre-ore FeS<sub>2</sub>) that is also isotopically light.

The dominance of ore-stage marcasite over pre-ore FeS<sub>2</sub> in samples from the reduced barren and mineralized zone and the light bulk sulfur isotopic composition of these samples indicates that the ore-stage marcasite is isotopically light (at least -29.9 to -47.7 permil).

Conversely, the dominance of post-ore pyrite in the altered tongue and the characteristically heavy bulk sulfur isotopic composition of samples in this zone indicates that the post-ore pyrite is isotopically heavy (for the most part greater than 0 permil). The later post-ore generation of dominantly marcasite in the altered tongue is probably isotopically light. Evidence for this is discussed at greater length below.

#### Summary of petrographic observations and sulfur isotopic ratios

Four different generations of FeS<sub>2</sub> minerals have been identified in the Felder host. The most commonly observed textural relationships among the FeS<sub>2</sub> minerals are ore-stage marcasite as rims on pre-ore pyrite in the reduced barren and mineralized zone and post-ore marcasite as rims on earlier post-ore pyrite in the altered tongue. Although grossly similar in textural appearance, and, therefore, potentially confusing, the different sulfide generations are present in vastly different absolute and relative abundances in the different geochemical zones. It is the volumetric dominance of two of the generations--isotopically light ore-stage marcasite in the reduced barren and mineralized zone and isotopically heavy post-ore pyrite in the altered tongue--that is responsible for the distinct divisions of relative abundances of pyrite and marcasite and of sulfur isotopic ratios in the different geochemical zones (figs. 3, 4).

#### Comparison of the Felder deposit to the Lamprecht deposit

Iron disulfide minerals of the Felder deposit are similar to those of the Lamprecht deposit in absolute and relative abundance of pyrite and marcasite, textural relationships between them, and their sulfur isotopic compositions. Isotopically heavy post-ore pyrite and isotopically light ore-stage marcasite dominate in the altered tongue and in reduced barren and mineralized zone of the Lamprecht deposit, respectively (Goldhaber and others, 1979). These

relationships are shown in detail for samples of core 4 which penetrated the altered tongue, upper and lower limb ore, and reduced barren ground beyond ore of the Lamprecht deposit (fig. 6). In the altered tongue of core 4, pyrite makes up about 85 percent of the FeS<sub>2</sub> minerals;  $\delta^{34}\text{S}$  values range from +9.9 to +26.1 permil. The marcasite in the altered tongue of the Lamprecht, as in the Felder, occurs primarily as thin rims around pyrite. Samples of sandstone from reduced barren and mineralized zones in core 4 contain dominantly isotopically light marcasite. The upper bounding mudstone, however, contains abundant isotopically light pre-ore pyrite.

#### Sources of sulfur for iron disulfide minerals

##### Pre-ore iron disulfide minerals

The source of sulfur for pre-ore FeS<sub>2</sub> minerals is not known with certainty. Pre-ore FeS<sub>2</sub> minerals in the Felder are similar in form and distribution to the isotopically light pre-ore FeS<sub>2</sub> of the Lamprecht deposit that we concluded was engendered by H<sub>2</sub>S and HS<sup>-</sup> from underlying hydrocarbon accumulations and introduced into the host beds along faults. If so, the sulfur isotopic composition of the fault-derived sulfide must also be light. Alternatively, pre-ore FeS<sub>2</sub> minerals in the Felder deposit (and the Lamprecht deposit) may have formed from sulfide-bearing solutions squeezed into the host sandstone from adjacent mudstone within the Oakville Sandstone and perhaps in the underlying Catahoula Tuff, as well. Bacterial control on isotopic fractionation yielding isotopically light sulfur is a possible mechanism for producing isotopically light pyrite. Such a mechanism for producing pre-ore pyrite in the Felder and Lamprecht deposits, however, is unsupported by the absence of observable carbonaceous debris, negligible to low amounts of organic carbon, and the paucity of framboidal pyrite in the Felder and Lamprecht host beds.

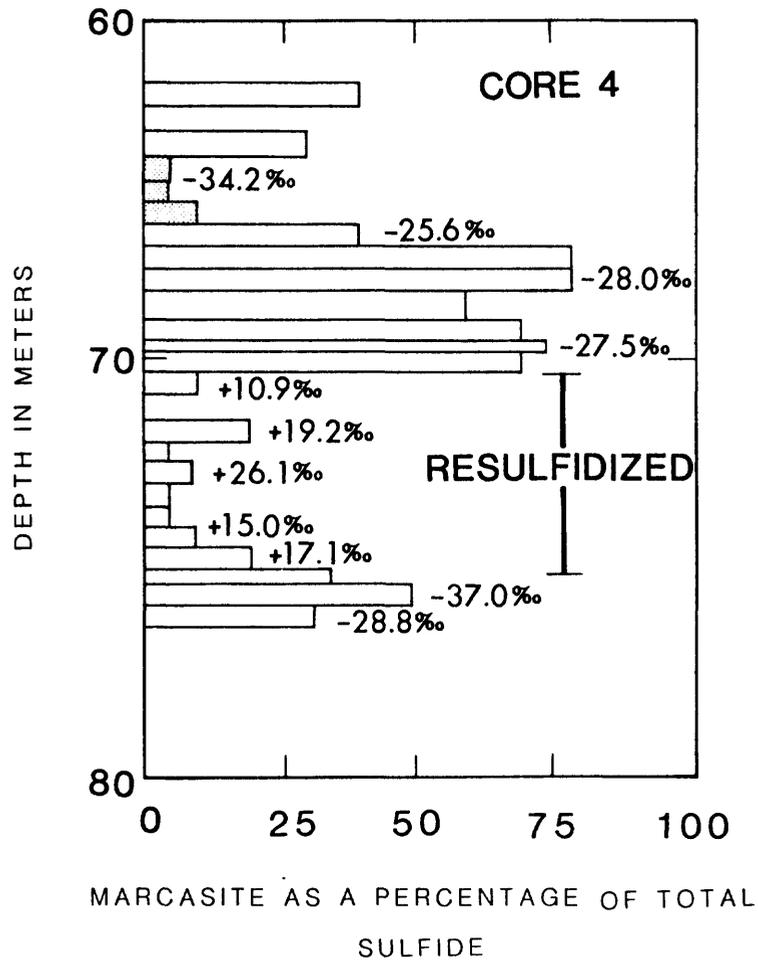


Figure 6.--Plot of the relative abundance of marcasite as a percentage of total iron disulfide mineral population (pyrite plus marcasite) against depth in core 4, Lamprecht deposit. The resulfidized zone is shown by the vertical bar. Note the depletion of marcasite relative to pyrite in the resulfidized interval. Also shown are  $\delta^{34}\text{S}$  values of the iron disulfide illustrating the marked difference between  $\text{FeS}_2$  minerals in resulfidized interval and those outside this zone. The shaded interval denotes mudstone (from Goldhaber and others, 1979).

### Ore-stage iron disulfide minerals

The distribution and textures of the abundant marcasite in the reduced barren and mineralized zone are consistent with formation from sulfur liberated by pyrite oxidation in the altered tongue and redistributed into reduced ground. Conditions of low pH resulting from pyrite oxidation and(or) the presence of elemental sulfur favored marcasite precipitation (see Goldhaber and Reynolds, 1979). Although some marcasite precipitation occurred with uranium precipitation, most marcasite appears to be surrounded by and, therefore, to predate molybdenum and uranium minerals. To account for this observation, we envision that marcasite formed from ore-related solutions sweeping ahead of the actual mineralizing front. This would require relatively easier transport of soluble intermediate sulfur species than of uranium and molybdenum complexes.

### Post-ore iron disulfide minerals

Sulfide from at least two different sources was involved in resulfidization of the Felder deposit: one, a source for isotopically heavy post-ore pyrite; the other, for isotopically light post-ore marcasite. We previously concluded (Goldhaber and others, 1979) that the source for isotopically heavy post-ore pyrite in the Lamprecht deposit was aqueous sulfide from the underlying Cretaceous Edwards Limestone that was introduced into the Oakville Sandstone along the Oakville fault. This conclusion was based on the close correspondence of the sulfur isotopic composition of the post-ore pyrite (an average of +16 permil) to that of H<sub>2</sub>S in the Edwards (ranging from about +12 to +15 permil). The heavy  $\delta^{34}\text{S}$  values of samples from the altered tongue of the Felder deposit (an average of +6 permil and as much as +20.6 permil) suggest that sulfide from the Edwards Limestone was likewise the source for at least some of the post-ore FeS<sub>2</sub> minerals in the Felder deposit.

The lighter average  $\delta^{34}$  of samples from the altered tongue of the Felder deposit contrasted with that of the Lamprecht deposit may indicate that the Felder samples contain a substantial proportion of isotopically light  $\text{FeS}_2$  minerals. The Felder samples also contain a significantly greater abundance of post-ore marcasite relative to their counterparts in the Lamprecht deposit (fig. 7). This relationship--more marcasite and lighter  $\delta^{34}\text{S}$  values in the Felder samples relative to those from the altered tongue of the Lamprecht deposit--suggests that the additional marcasite in the altered tongue of the Felder is isotopically light.

Analysis of present ground water in the Oakville Sandstone near the Oakville fault provides a clue to the origin of the isotopically light post-ore marcasite. Present ground water in the Felder mine area is reported to have a strong  $\text{H}_2\text{S}$  odor (Klohn and Pickens, 1970). Ground water in the nearby Lamprecht-Zamzow mine areas also contains dissolved sulfide; this sulfide is isotopically light (-35 to -60 permil) and so is not derived directly from the Edwards. The isotopically light post-ore marcasite in the altered tongue of the Felder, therefore, may be related closely to isotopically light aqueous sulfide in the present ground-water regime. Formations lying between the Oakville and Edwards, such as the Carrizo and Wilcox Formations contain sulfide (Galloway and others, 1979; F. Busche, oral commun., 1979) and may have provided sulfide to the modern ground water contained in the Oakville host beds.

#### Timing of resulfidization

Uranium-lead isotope systematics of ore samples from the Felder deposit, including four samples from pit 4B, yield a well-defined  $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{235}\text{U}/^{204}\text{Pb}$  isochron age of  $5.07 \pm 0.15$  m.y. (Ludwig and others, 1980). This isochron age reflects immobilization of uranium and lead over the past 5 m.y.,

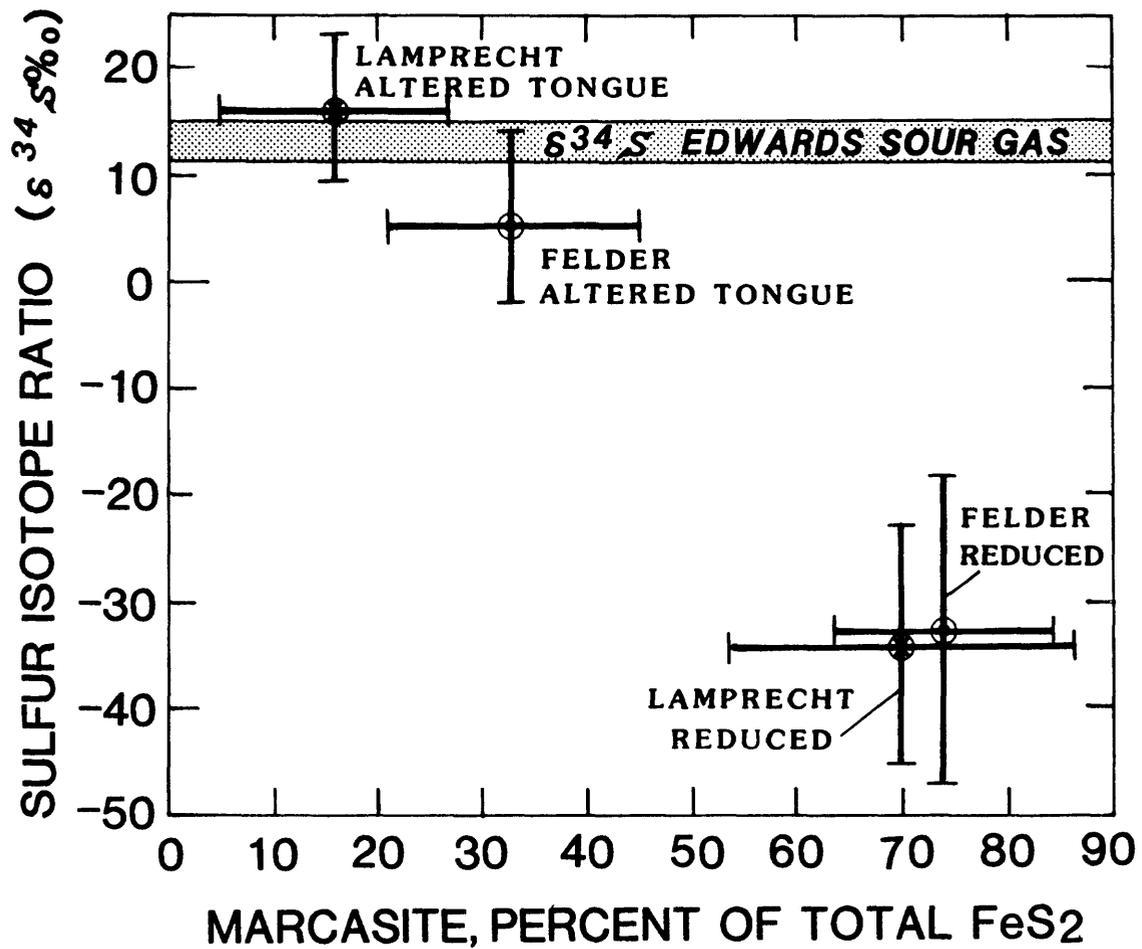


Figure 7.--Plot of average  $\delta^{34}\text{S}$  value against average marcassite content (as a percentage of the  $\text{Fe}_2$ -mineral population) for samples from the altered tongue and reduced barren and mineralized zone of the Felder (o) and Lamprecht (x) deposits. Length of bar is two standard deviations. Range of  $\delta^{34}\text{S}$  values of sour gas from the Edwards Limestone is shown by the stippled band.

and, therefore, indicates that roll-front development ended at about that time. We suggested previously that uranium and lead immobilization was caused by the presence of sulfide-saturated porewaters related to resulfidization processes (Ludwig and others, 1980).

#### Summary

Geochemical and petrographic studies help to decipher the history of sulfidization of the Felder uranium deposit (table 1) which in turn bears closely on the origin and preservation of the deposit.

The earliest recognizable sulfidization episode predated ore deposition and resulted in formation of dominantly pyrite, and to a lesser extent marcasite, throughout the Oakville host beds. The pre-ore  $\text{FeS}_2$  minerals are apparently isotopically light; the source of sulfur for pre-ore  $\text{FeS}_2$  minerals, however, has not been identified with certainty. Isotopically light sulfide from underlying hydrocarbon deposits and (or) biogenic sulfide produced in mudstones within and marginal to the host rock are possible sources for pre-ore  $\text{FeS}_2$ .

Isotopically light marcasite formed in reduced barren and mineralized ground during mineralization. Oxidation of pre-ore  $\text{FeS}_2$  by uranium-bearing solutions behind a migrating redox interface provided sulfur for, and resulted in conditions of low pH that favored, marcasite formation.

Following mineralization, isotopically heavy pyrite formed throughout the host rock. Isotopically heavy sulfide from the underlying Edwards Limestone was the likely source of sulfur for the post-ore pyrite. This episode of sulfidization began about 5 m.y. ago, based on an isochron age that reflects the end of roll-front development.

At some time since 5 m.y. ago, ground waters evolved to conditions that favored precipitation of isotopically light marcasite. The solutions that

Table 1.--Summary of sulfidization history,  
Felder deposit, south Texas

Stage	Dominant FeS <sub>2</sub> mineral	Sulfur isotopic composition	Timing
Pre-ore	Pyrite	<0 permil	Early post- depositional
Ore-stage	Marcasite	<0 permil	Pre- 5 m.y.
Post-ore	(a) Pyrite (b) Marcasite	>0 permil <0 permil	~5 m.y. to present

engendered the post-ore marcasite may be related to those now present in the Felder-Lamprecht mine areas, in which aqueous sulfide appears to be related to near-surface bacterial or inorganic processes (Goldhaber and others, 1979). The present Oakville ground water contains components of connate brines from sources below the Oakville Sandstone (Galloway and others, 1979) but has been modified by recharge of surface waters in part controlled by the Oakville fault (Goldhaber and others, 1979; Galloway and others, 1979).

The geochemistry and mineralogy of the Felder deposit, therefore, has been greatly influenced by communication of ground water in the Oakville Sandstone with extrinsically derived sulfide-bearing waters. Such communication has been permitted or enhanced by faults, particularly by the Oakville fault. The continuous or, at least, intermittent presence of sulfide-bearing waters over the past 5 m.y. is probably responsible for the preservation of the Felder deposit.

The Felder deposit is similar to the Lamprecht deposit in some fundamental respects, including the dominance of isotopically light marcasite over pyrite in the reduced barren and mineralized zone and of isotopically heavy pyrite over marcasite in the altered tongue. Such mineralized differences between the altered tongue and reduced zone may characterize other host rocks that have undergone post-mineralization sulfidization; recognition of these differences may aid exploration for uranium.

#### Acknowledgments

We thank the Exxon Corporation for access to the Felder property and A. L. Kidwell and W. R. Pickens III for their generous assistance in sampling, providing additional samples from the Felder orebody, and for many valuable discussions.

## References

- Galloway, W. E., Finley, R. J., and Henry, C. D., 1979, South Texas uranium province--geologic perspective: Austin, Texas University Bureau of Economic Geology, Guidebook 18, 81 p.
- Goldhaber, M. B., and Reynolds, R. L., 1979, Origin of marcasite and implications regarding the genesis of roll-type uranium deposits: U.S. Geological Survey Open-File Report 79-1696, 40 p.
- Goldhaber, M. B., Reynolds, R. L., and Rye, R. O., 1979, Formation and resulfidization of a south Texas roll-type uranium deposit: U.S. Geological Survey Open-File Report 79-1651, 41 p.
- Harshman, E. N., 1974, Distribution of elements in some roll-type uranium deposits, in Formation of uranium ore deposits: Vienna, International Atomic Energy Agency, Proceedings, 1974, p. 169-183.
- Klohn, M. L., and Pickens, W. R., 1970, Geology of the Felder uranium deposit, Live Oak County, Texas: Mining Engineers Society preprint no. 70-1-38, 19 p.
- Ludwig, K. R., Goldhaber, M. B., Reynolds, R. L., and Simmons, K. R., 1980, U-Pb isotope isochron age, and preliminary sulfur isotope systematics of the Felder uranium deposit, south Texas:
- Reynolds, R. L., and Goldhaber, M. B., 1979a, Marcasite in roll-type uranium deposits [abs.]: American Association of Petroleum Geologists Annual Meeting Program, p. 150-151.
- \_\_\_\_\_ 1979b, Iron disulfide minerals and the origin of roll-type uranium deposits: Geological Society of America Abstracts with Programs, v. 11, no. 7, p. 502.