

dominant ions (Spalding et al., 1984; Wyoming Fuel Company, 1983; FEN, 1987). Waters from the Chadron aquifer generally contain about 2 ppb (ug/l) uranium, but values as high as 2000 ppb (ug/l) have been reported (FEN, 1987). Spalding et al. (1984) have found Chadron waters to be reducing, at least in the vicinity of the uranium deposit.

The high TDS of the Chadron water is characteristic of water with a low velocity and long residence time in the aquifer. The high sodium content was produced by exchange of cations with the Pierre Shale, and the high sulfate content is the product of oxidation of pyrite contained in the sandstone or the Pierre Shale.

### Confining Beds

The Chadron aquifer is confined below by the Pierre Shale. The Pierre is at least 1200 ft (360 m) thick in the study area, and prohibits flow between the Chadron aquifer and aquifers below the Pierre. Cation exchange with the Pierre does, however, have a significant impact on water chemistry in the Chadron aquifer.

Claystones and siltstones of the Chadron and Brule formations form the upper confining beds for the Chadron aquifer. These units consist mostly of ash-rich sediments that have been altered to clay. Pump tests and laboratory tests of the confining units directly overlying the Chadron aquifer have shown these units to have very low hydraulic conductivity (Figure 6).

The Brule Formation consists mostly of fine-grained sediments, but contains some sand lenses and channels of limited extent. Waters from these sands average about 600 ppm (mg/l) TDS, with calcium, sodium, and bicarbonate as the dominant ions. They are high in silica and contain an average of 6.4 ppb (ug/l) uranium. Determination of the Eh of these waters indicates that they are oxidizing (Spalding et al., 1984). Recharge to the Brule sand is through the confining units in the valleys.

### High Plains Aquifer

The High Plains aquifer is a regional water-table aquifer contained within the sandy sediments of the Arikaree and Ogallala groups (Weeks and Gutentag, 1981). The potentiometric surface in the High Plains aquifer generally reflects the topography, with groundwater mounding at the topographic highs and discharge in the valleys. Flow is generally toward the east.

In the study area, the High Plains aquifer is contained within the sandstones of the Arikaree Group. The aquifer varies in thickness from 0 to 400

ft (0-120 m) and is underlain by the siltstones and claystones of the Brule Formation. Recharge to the aquifer is from the west (Hartville uplift) and south (Pine Ridge). Discharge is to springs along Pine Ridge and is the major source of water for surface streams in the area.

Chemical analyses of Arikaree waters in the Crawford area, by Spalding et al. (1984), show the waters to be oxidizing. Bicarbonate and calcium are the dominant ions present. The average concentration of TDS is 200-300 ppm (mg/l). The average uranium content of the Arikaree water is 5.2 ppb (ug/l) (Spalding et al., 1984). The chemistry of the Arikaree waters is characteristic of an immature groundwater with short travel time between the recharge and discharge area.

## HISTORY OF THE GROUNDWATER SYSTEM

The history of the groundwater system, within the study area, can be divided into four phases of development: 1) the establishment of the basic geometry and hydrologic characteristics of the Chadron aquifer by deposition of the Chadron sandstone during early Oligocene time, 2) a gradual change from water table to confined conditions in the Chadron aquifer due to the deposition and alteration of fine-grained volcaniclastic sediments in middle to late Oligocene time, 3) establishment of the High Plains aquifer as a water-table aquifer with deposition of sandy, fluvial and eolian sediments in late Oligocene to Miocene time, and 4) erosion of parts of the Cenozoic section during Pliocene time which caused a reversal of groundwater flow in part of the Chadron aquifer.

### Early Oligocene

With deposition of the Chadron sandstone by a braided-river system in early Oligocene time, a water-table aquifer was established in the coarse-grained sediments. During this time the water-table aquifer was in hydraulic connection with the river system and groundwater flow was parallel to flow in the river. Because the sands were deposited on the impermeable Pierre Shale, vertical flow was restricted to the channel sands and the Chadron aquifer was not in hydraulic connection with underlying aquifers.

The transmissivity of the Chadron aquifer was at its maximum during early Oligocene time because compaction and cementation had not yet occurred. The groundwater gradient was equal to the stream gradient because of the connection between the river and aquifer. This combination of high transmissivity and steep gradient produced high groundwater flux during this time.

The chemical composition of water in the Chadron aquifer in early Oligocene time was controlled by the lithology of the areas drained by the river system. The headwaters of the river system were in granites and sedimentary rocks of the Laramie Range. However, the river system drained and crossed large areas of Pierre Shale, which contributed sodium and sulfate to ground and surface waters.

### Middle to Late Oligocene

After deposition of the Chadron sandstone, sedimentation in the area was dominated by fine-grained, eolian volcanoclastic sediments. Prior to alteration to clay, the fine-grained volcanoclastic sediments of the Chadron and Brule formations were unconsolidated and permeable. Precipitation infiltrated through the newly deposited ash layers and was concentrated in the highly transmissive Chadron sandstone.

The Chadron aquifer was under water-table or semi-confined conditions during this time. Flow was dominantly to the east, in the direction of the paleoslope. Recharge through the ashy confining layers and flow in the Chadron aquifer led to alteration of the volcanic ash to clay. This resulted in the formation of a 10- to 40-ft (3- to 12-m) thick layer of red montmorillonite clay directly overlying the Chadron sandstone. This clay and several hundred feet of clay units higher in the section sealed off the Chadron aquifer, decreasing recharge and flow in the aquifer. Stanley and Bensen (1979) have stressed the importance of early diagenesis in the alteration of White River Group sandstones.

Because ash layers blanketed outcrops of older sediments, the chemical character of the groundwater may have changed through time. Water which infiltrated the ash-rich units was probably similar in character to waters contained in the Brule sands today, that is high in silica and uranium and low in sulfate.

### Late Oligocene to Miocene

With deposition of the Arikaree sands, a water-table aquifer developed which persists today. This water-table aquifer is underlain by several hundred feet of altered volcanoclastic material, which acts as the upper confining unit for the Chadron aquifer and the lower confining unit for the High Plains aquifer.

The development of thick confining layers limited recharge and discharge in the Chadron aquifer. Recharge and discharge occurred only through the confining units because these units completely covered the aquifer. This severely limited flow.

### Pliocene to Present

Since the beginning of Pliocene time erosion has outpaced deposition in the study area (Swinehart et al., 1985). This has led to removal of several hundred feet of sediment, including the entire Cenozoic sequence in the northern part of the area (Figure 3). North of Crawford, the Arikaree and Brule were removed, exposing the Chadron sandstone.

The effect of Pliocene erosion on the Chadron aquifer was to provide discharge points north of Crawford and rejuvenate the groundwater system updip of the outcrops. However, downdip of the outcrops, flow remained slow and remains so today. In the part of the aquifer south of Crawford, Pliocene erosion has caused a reversal of the direction of groundwater flow. This is due to the exposure of outcrops of the Chadron sandstone. Recharge in this area is through the confining units on the topographically high Pine Ridge, and discharge is to springs and alluvium to the east and possibly to the north of Crawford.

### OCCURRENCE OF URANIUM IN THE BASAL CHADRON AQUIFER

Uranium is concentrated in the Chadron Sandstone along the boundary between altered (oxidized) and unaltered (reduced) sediments. The unaltered sediments contain up to 10% pyrite and small amounts of organic matter (0.02-0.2%). Altered sediments contain no organic matter or pyrite, but do contain hematite and limonite as coatings on grains. Uranium is present in the matrix and as a coating on grains as coffinite and uraninite and occurs locally in concentrations as high as 3.0%.

Uranium mineralization occurs in crescent-shaped zones along the oxidation-reduction front. It is not distributed uniformly along the oxidation-reduction front, but is present only at specific sites along the boundary. Figure 8 shows the location of oxidation-reduction boundaries that have been identified during exploration drilling.

The main body of the Crow Butte uranium deposit is located along the margin of an oxidation tongue that moved through the Chadron aquifer. Because it is located along the margin of the oxidation tongue, the trend of the main body cannot be used to identify the groundwater flow direction at the time of mineralization. However, smaller roll-fronts, located within isolated sand bodies of the Chadron sandstone, have been identified by exploration drilling. The shape of these roll-fronts, as well as the shape of bends in the main trend, show that groundwater flow was from west to east at the time of mineralization (Figure 8).

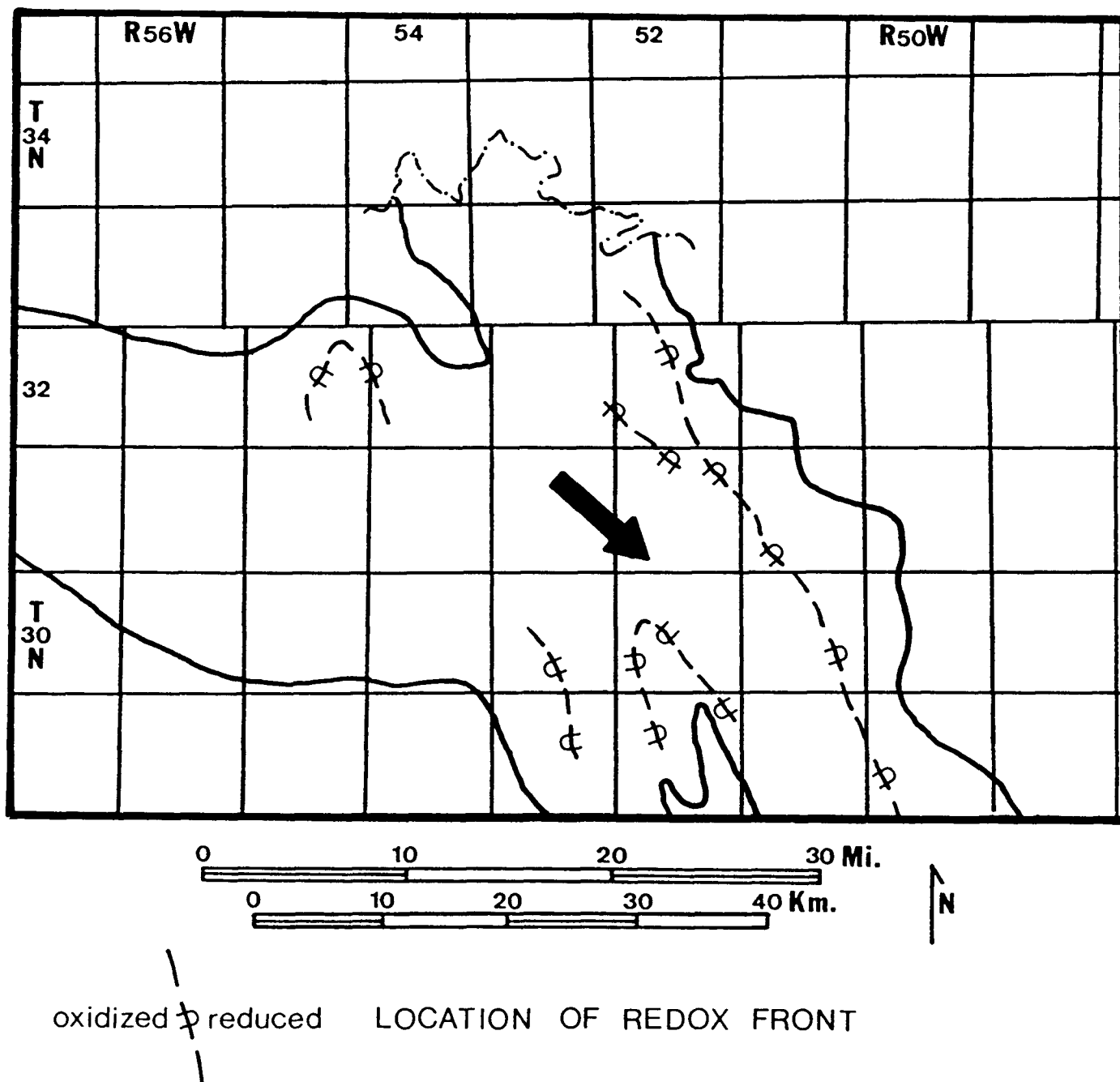


Figure 8 — Location of oxidation-reduction fronts detected during exploration drilling within the Chadron Sandstone, northwest Nebraska. Arrow shows the direction of groundwater flow at the time of mineralization, as indicated roll-front geometry.

### GENESIS OF CROW BUTTE URANIUM DEPOSIT

The Crow Butte uranium deposit is similar in character to Wyoming-type roll-front deposits in that the uranium occurs in Tertiary rocks at an oxidation-reduction boundary, with no hydrothermal uranium source in close proximity. Roll-front uranium deposits are viewed by most workers as having been deposited by

the precipitation of uranium from dilute solutions (Rackley, 1976; Nash et al, 1981; Galloway et al, 1978). Uranium is slightly soluble in its oxidized state  $U^{6+}$  and insoluble in its reduced state ( $U^{4+}$ ). It is deposited at the boundary of an evolving geochemical cell produced as uranium-rich oxidizing waters invade an aquifer that contains a reductant. In effect, uranium is deposited in a geochemical trap formed by a reducing aquifer.