Plains $CO_2$ Reduction (PCOR) Partnership

*Practical, Environmentally Sound $CO_2$ Sequestration*

# THE INFLUENCE OF TECTONICS ON THE POTENTIAL LEAKAGE OF $CO_2$ FROM DEEP GEOLOGICAL SEQUESTRATION UNITS IN THE WILLISTON BASIN

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## EXECUTIVE SUMMARY

Leakage of $CO_2$ out of a geological storage site is a major concern associated with sequestration of $CO_2$ in the subsurface as, clearly, any release to the atmosphere would limit the effectiveness of the sequestration effort. Thus, it is important to ensure that long term sequestration is not only feasible, but that the $CO_2$ remains in the geological units into which it is injected.

To better describe the situations in which $CO_2$ will be sequestrated, the term "geological sequestration unit (GSU)" is introduced in this report to acknowledge the legal and regulatory process that will be necessary to inject large volumes of $CO_2$ across areas consisting of numerous mineral ownership tracts. This term is not chosen to represent a physical geologic unit or formation, but rather to apply a concept applicable to the development of geological sequestration projects that is similar to the process by which petroleum fields become unitized. In modern oil field practice, prior to initiation of subsurface activities that will affect the fluid distribution and production within an area, mineral ownership tracts may be legally combined to form a larger working area. The process of combining individual tracts is referred to as "unitization" and the working area created by this process is referred to as a "unit." The result of unitization is the protection of correlative rights of all mineral owners within the designated area and coordinated injection and reservoir management practices that improve the efficiency of petroleum extraction. It is anticipated that a similar unitization process will need to be developed prior to large-scale injection of $CO_2$ for sequestration in geological formations. Potential sequestration units may be established in petroleum reservoirs, saline aquifers, and coalfields. Prior to injection of $CO_2$ into GSUs, it will be necessary to identify seals to trap and store the gas; it will also be necessary to understand potential pathways for leakage from those GSU's.

Possible primary pathways for escaping gases would be along zones of tectonic weakness which include regional faults, fractures, or lineaments. In order to predict

the position and orientation of regional tectonic trends, it is necessary to understand the tectonic nature of the geological province in which the sequestration unit is located.

The Williston Basin of central North America is considered to be tectonically stable, with a low frequency and magnitude of tectonic events. Relatively well-studied, the Williston Basin provides a good opportunity to examine the influence that large-scale, tectonically derived, but often subtle, features may have on the leakage of $CO_2$ from GSUs. The concepts described in this report may also be applicable to other midcontinental basins.

Subtle, but significant, tectonic features have been identified in the Williston Basin, including basement lineaments. Lineaments are zones of tectonic weakness that have been active through time and have exerted influence on the development of the structure and distribution of certain depositional facies. Most of the lineaments in the Williston Basin appear to be closed and are not likely to be points where leakage of sequestered $CO_2$ can occur. However, evidence suggests that at least one lineament may have associated open fractures and thereby provide pathways of leakage. It will be necessary to investigate further the possibility of open and leaking lineaments as part of the process for selecting effective regional GSUs.

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## BACKGROUND/INTRODUCTION

As one of seven Regional Carbon Sequestration Partnerships (RCSPs), the Plains $CO_2$ Reduction (PCOR) Partnership is working to identify cost-effective $CO_2$ sequestration systems for the PCOR region and, in future efforts, to facilitate and manage the demonstration and deployment of these technologies. In this phase of the project, the PCOR Partnership is characterizing technical issues, enhancing the public's understanding of $CO_2$ sequestration, identifying the most promising opportunities for sequestration in the region, and detailing an action plan for demonstration of regional $CO_2$ sequestration opportunities. Based on the information reviewed to date, it is generally accepted that some $CO_2$ leakage will occur from geological sinks. This report is concerned with identifying leakage potential associated with tectonically related features in the Williston Basin. This will be accomplished through a review of the origin and development of the basin.

The Williston Basin is a large, roughly circular depression on the North American Craton. It covers several hundred thousand square miles across parts of North Dakota, South Dakota, Montana, and the Canadian provinces of Manitoba and Saskatchewan. Relatively well studied, the Williston Basin is a good candidate to review and to develop a model to predict the influence that large-scale, tectonically derived, but often subtle, features may have on the leakage of $CO_2$ from geological sequestration units (GSUs). As the Williston Basin is similar to other midcontinental basins, the model will serve as a template for all of them. This report begins by briefly reviewing the conceptual models of $CO_2$ migration in the deep subsurface (deeper than 2000 ft), examines the current literature regarding the origin of the basement geology and the forces that were involved in forming the Williston Basin, and concludes with a discussion of the relationship that tectonics may have on leakage. Leakage is a key issue that must be addressed before large-scale sequestration in regional sequestration units can be initiated.

## CONCEPTUAL MODELS OF $CO_2$ MIGRATION

In order to evaluate the influence that tectonically derived structures can have on the leakage of $CO_2$ from a GSU, it is necessary to understand the basic concepts controlling $CO_2$ migration in the deep subsurface. It is important to note that much of the $CO_2$ injected will dissolve into formation water. In addition, the $CO_2$ will be in a supercritical state because of the temperatures and pressures found at depth. As a supercritical fluid, $CO_2$ will be dense and relatively inviscid. Nevertheless, $CO_2$ will be less dense than the surrounding formation fluids and, therefore, will tend to migrate upward if present as a free phase (undissolved). Upward-migrating $CO_2$ will be restricted by permeability and capillary barriers (Oldenburg et al., 2002). Because of upward buoyancy, the presence of low-permeability caprocks and hydrogeologic barriers in the geologic column, upward-migrating $CO_2$ will tend to spread out laterally against permeability and capillary barriers. In so doing, the length scales of the upward-migrating plume will increase, while the concentration of $CO_2$ will decrease exponentially. Actual $CO_2$ plumes will spread like a pancake under low-permeability layers, following the structure of those layers as it spreads. As the size of the plume increases, the probability of the $CO_2$ encountering a fast-flow path increases. The structural integrity of the GSU becomes a key consideration for predicting leakage and subsequent upward migration of the $CO_2$.

For example, consider the spreading of a buoyant $CO_2$ plume under a caprock that is cut by transmissive, or “open,” faults on a mile scale. As spreading expands the plume beyond 1 mile in lateral extent, transmissive features will be encountered and $CO_2$, with its low density (about 60%–80% of that of water) and viscosity (10–40 times less than that of water) would escape from the GSU into an overlying geological formation by buoyancy. Transmissive features can also provide fast-flow paths for formation fluids such as water or oil, thereby providing a mechanism for dissolved $CO_2$ to migrate from a GSU.

## TECTONIC SETTING AND HISTORY OF THE WILLISTON BASIN

Since tectonics control the development and movement of faults and other structural features that may result in a breach of caprock integrity, it is important to examine the tectonic history of the Williston Basin for a complete understanding of the possible avenues of leakage from potential GSUs. Zones of preexisting tectonic weakness are obvious places to investigate for leakage potential. This paper reviews the composition of the basement and location of the major tectonic trends and also discusses the importance of tectonic activity in the Williston Basin.

### Basement Terrane

The Precambrian basement under the Williston Basin can be divided into three ancient geological provinces (Green et al., 1985). Two of the provinces are Archean in age and represent cratons (protocontinents) (Figure 1). They are separated by oceanic sediments that are Proterozoic in age. Rocks of the Superior Craton underlie most of eastern North Dakota and South Dakota, as well as Manitoba, and consist primarily of granites and greenstones. The Wyoming Craton underlies eastern Montana, western Saskatchewan, western South Dakota, and southwestern North Dakota. It consists of quartz-rich rocks including gneisses. Both cratons are approximately the same age. Recently, Baird et al. (1996) have proposed the existence of a third cratonic block under western North Dakota. It is probable that, with further investigations, the understanding of the basement will continue to be modified.

Between the Superior and Wyoming Cratons are rocks of the Trans-Hudson Orogenic Belt (Figure 1). Sediments of the Trans-Hudson Orogenic Belt are relatively complex; they formed from oceanic sediments that were deposited as the result of an early rifting event between the two cratons. Later, a collision added island arc sediments. The major basement geological provinces can be identified on an aeromagnetic anomaly map (northeast illumination) of the region (Figure 2).

### Lineaments

The basement terrane, in turn, is dissected into blocks by a series of structural elements referred to as lineaments (Figure 3). Lineaments are zones of weakness which form in response to external tectonic stresses (Brown and Brown, 1987). They represent zones in which tectonic activity is more likely to occur. As such, they are sites for regional fracturing and faulting. Lineaments, therefore, have a higher probability of containing conduits along which subsurface fluid and gas flow will occur at higher-than-regional rates. They are also areas in which transformational flow may occur. Lineaments may be subtle, at best, often with little or no recognized surface or subsurface expression, and there may be no associated vertical throw. Active periodically through time, lineaments move in response to applied stress.

Lineaments may be very important in the Williston and other midcontinental basins. There is evidence to suggest that that they are responsible for basin development, formation of some structures, and even the geometry of depositional facies in overlying

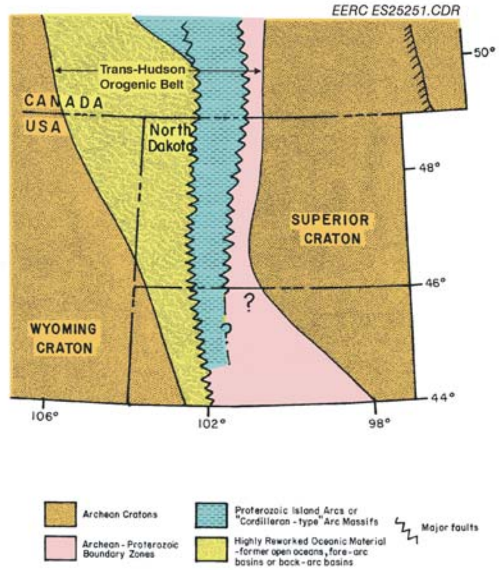


Figure 1. Basement geological provinces (Green et al., 1985).

sediments (Brown and Brown, 1987., Gerhard et al., 1982). Movement along two lineaments, the Weldon–Brockton lineament (also known as Brockton–Froid fault zone) and the Wyoming lineament zone (also known as Colorado–Wyoming shear zone) are considered to be responsible for initiating the development of the Williston Basin (Gerhard et al., 1982). Left lateral shearing motion along these lineaments is thought to have created enough tension to develop a sag in the crust (Figure 4). That sag continued to develop through time, differentiating into a basin.

As in other basins, the primary tectonic features in the Williston Basin are faulting and folding. In general, faults in the Williston Basin are difficult to recognize. Vertical throw is slight, especially when compared to other Rocky Mountain Basins. The presence of some faults in this basin is well documented. Clement (1987), Gerhard et al. (1987) and Chimney et al. (1992) showed the importance that faulting had in controlling the structural development of major anticlinal features (Figure 5). Growth along bounding or master faults can be demonstrated through time and appear to be the controlling mechanism for structural growth. It is possible that some of these faults formed as basement blocks moved in response to applied stresses and others formed in response to basin subsidence.

Faulting controlled by lineaments is also thought to be responsible for the development of some smaller structures in the basin. Individual basement blocks created by dissecting lineaments move in response to stresses applied along those same bounding features. It is the differential movement of these blocks that

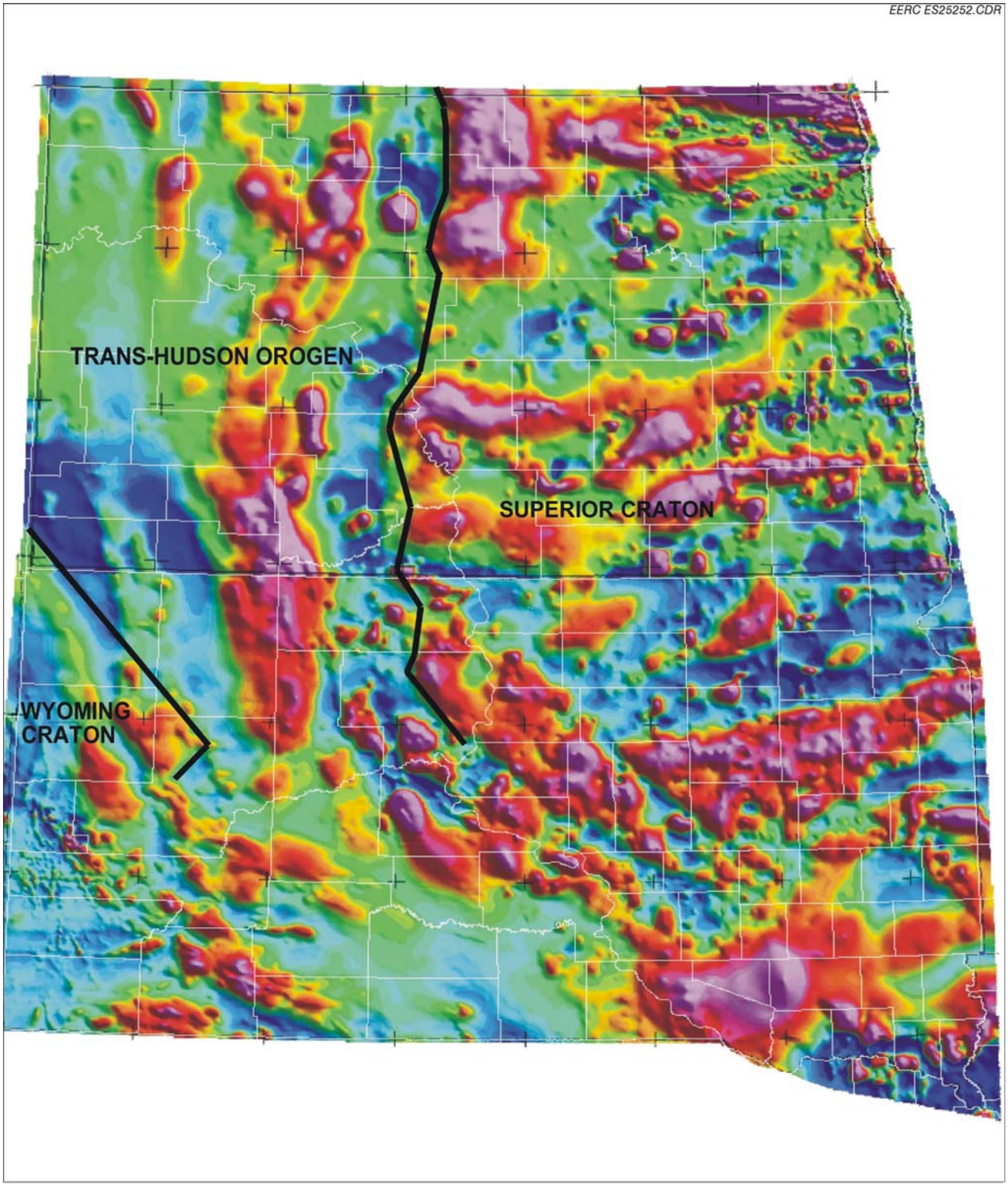


Figure 2. Aeromagnetic anomaly map of North Dakota and South Dakota with geological provinces noted (modified from Sweeney et al., 2003, aeromagnetic anomaly map).

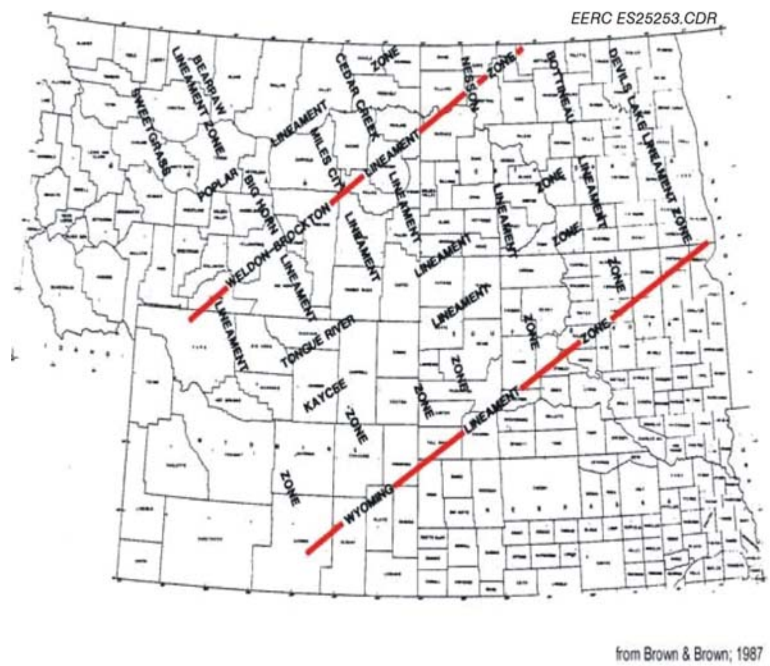


Figure 3. Major basement lineaments in the U.S. portion of the Williston Basin (modified from Brown and Brown, 1987).

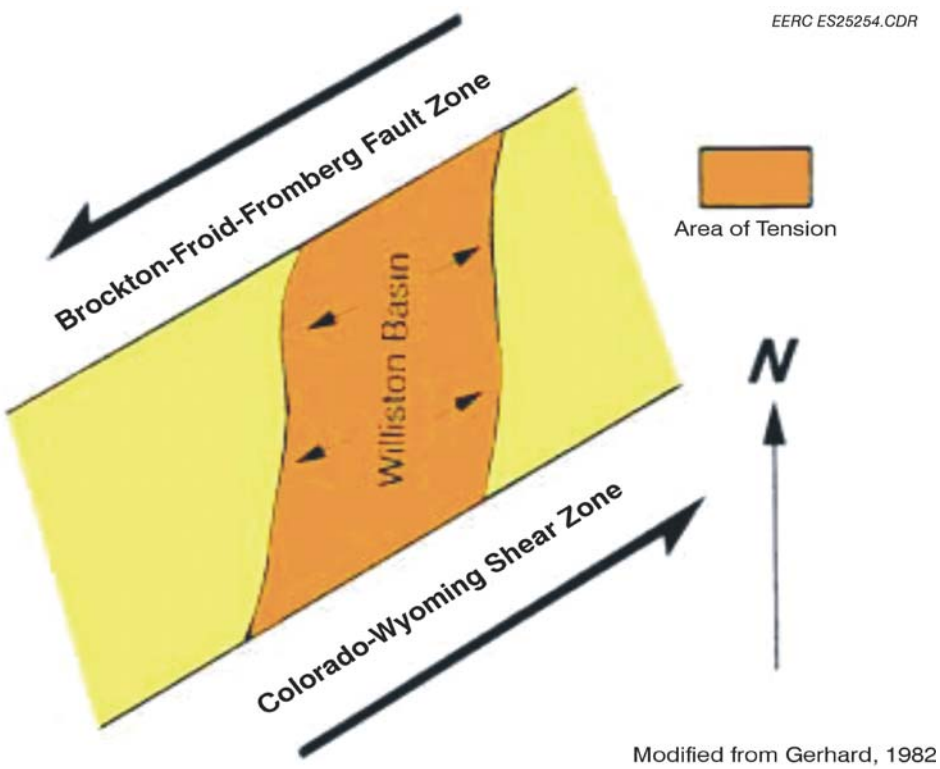


Figure 4. Structural model for the development of the Williston Basin (modified from Gerhard et al., 1982).

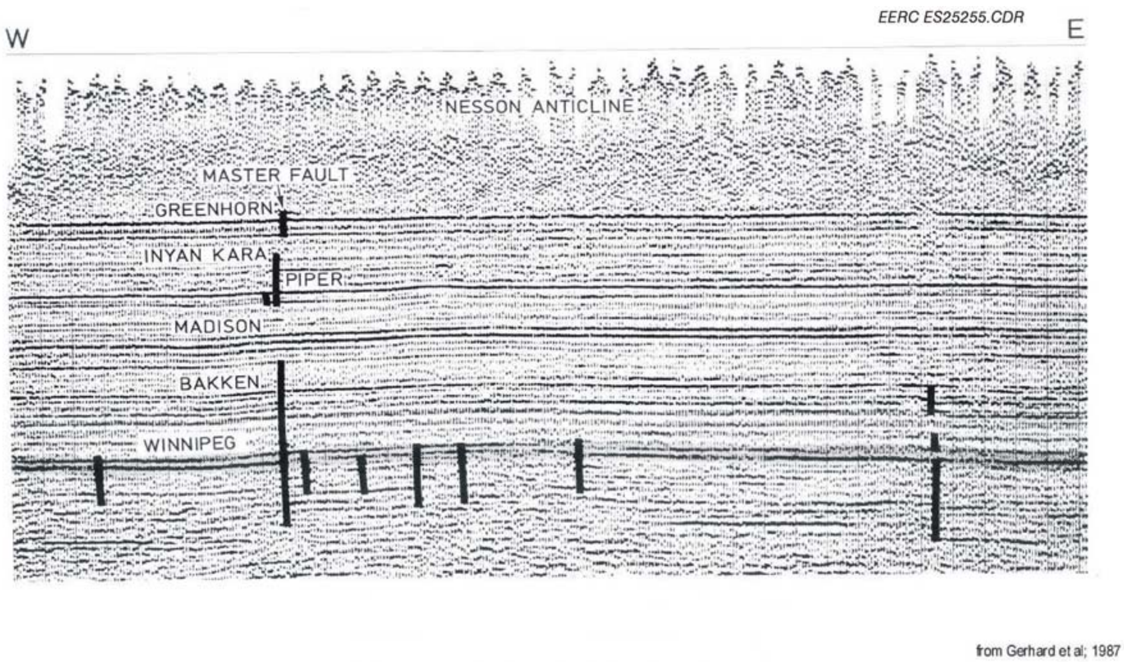


Figure 5. Transverse seismic section across the Nesson Anticline showing master, bounding, and secondary faults (Gerhard et al., 1987).

is believed to be responsible for the development of many of the small basement controlled structures in the Williston Basin (Figure 6).

Basement block movement along lineaments is also thought by some to control depositional facies. In a 1987 report prepared for the U.S. Geological Survey, Brown and Brown showed in a series of maps that depositional facies in the Mississippian Period were controlled, in part, by basement blocks (Figure 7).

Another possible relationship between lineaments and depositional facies can also be seen in the Mississippian Age shoreline, based on the geometry of anhydrite deposition (Figure 8). Basinal carbonates of the Mission Canyon Formation laterally pinch out into sabkha (shoreline) anhydrites. Detailed mapping of the zero-thickness edge of the anhydrites overlying the Mission Canyon Formation can be interpreted to show a distinct linearity that is controlled by the position of basement lineaments.

The Mission Canyon Formation has characteristics that suggest it may be a favorable candidate to become a GSU. Understanding the influence that lineaments exerted in the development of anhydrites and other evaporites (i.e., salts) can lead to better prediction of the location and areal extent of these low-permeability beds, which in turn can lead to more accurate modeling of potential leakage from sequestration units capped by evaporites.

**Current Status of Lineaments**

It is intuitively obvious that all or most lineaments in the Williston Basin are closed and have been for a significant amount of time. Evidence for this statement includes lack of earthquake activity—which is an indicator of tectonic

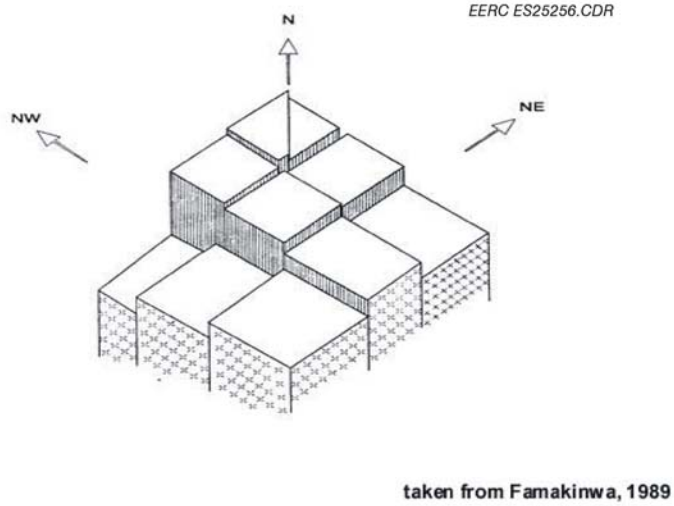


Figure 6. Structural controls on the development of basement-controlled structures (taken from Famakinwa, 1989).

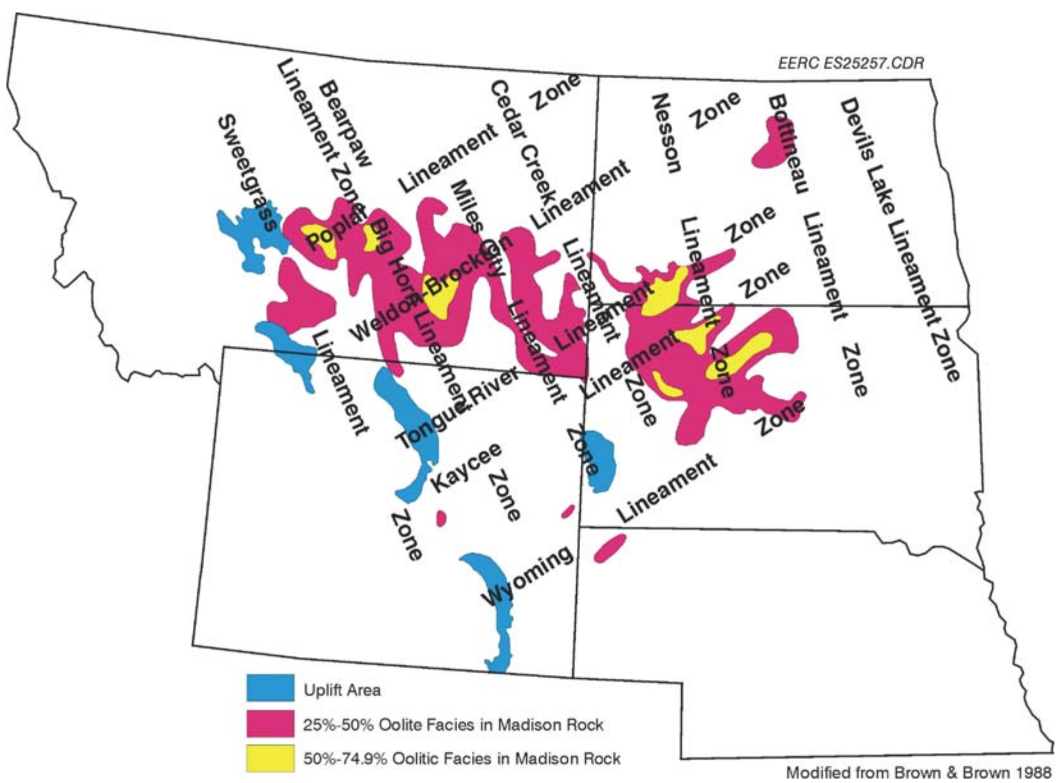


Figure 7. Lineament control of Mississippian (oolitic) depositional facies (modified from Brown and Brown, 1988).

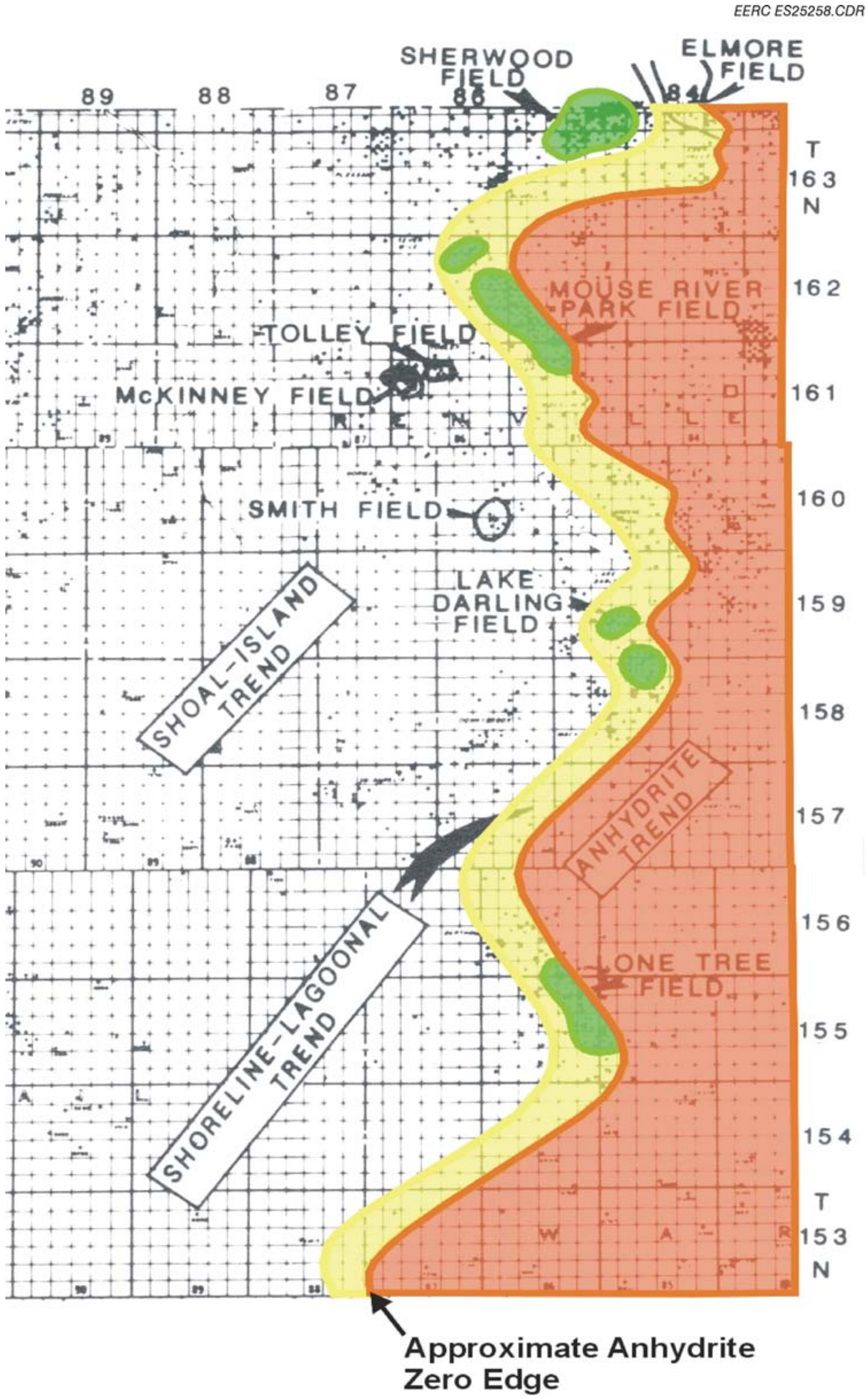


Figure 8. Approximate position of Mississippian Age Sherwood bed Anhydrite edge exhibiting linear geometry (Hendricks et al., 1987).

activity—in the Williston Basin. In fact, the Williston Basin is one of the least seismically active areas on the North American Craton, with North Dakota and Florida ranked least prone to earthquake activity in the continental United States. (USGS, 2004) (www.earthquake.usgs.gov/faq/hist.html#6 [accessed Sept. 2004]).

Furthermore, some of the reported seismic activity in the region may not be the result of basement tectonic activity, but rather the collapse of beds overlying areas that have active salt dissolution. The presence of trapped nitrogen gas in the Minnelusa Formation (Hoda, 1977; Rygh, 1990) and numerous oil fields (Figure 9) with associated gas can also be considered as evidence of at least locally closed lineaments.

There is also evidence that suggests the presence of open lineaments in the Williston Basin. A 30-meter digital elevation model (DEM) image of Montana using analytical hillshading clearly shows the position of the Brockton–Froid fault at the surface (Figure 10). The fault can also be ground-verified (Figure 11).

Recently, the PCOR Partnership became aware of a geochemical survey that was conducted in north-central North Dakota, which collected some potentially important data. The data collected were interpreted to outline the edge of a Mississippian Age anhydrite. The specific nature of the data is proprietary but suggests that leakage from depth may be possible along the edge of the anhydrite, which may be evidence of an open linear trend.

## DISCUSSION

Although the Williston Basin is considered to be tectonically inactive, lineaments appear to be a significant component of the basin and may have exerted influence over its structural and stratigraphic evolution. It is also apparent that lineaments have been active through time, controlling faulting, and the distribution of certain depositional lithofacies. It is, therefore, critical to determine, prior to widespread regional sequestration of $CO_2$, if lineaments are inactive and closed or if some may still be active and open. Further geochemical testing should be conducted to evaluate and expand the original survey in north-central North Dakota that may have identified an open lineament.

Sequestered $CO_2$ will reside in a dense, supercritical phase; some will be dissolved in the aqueous phase, and, in some cases, a small portion may react with minerals in the matrix of the target formation. Since the supercritical fluid will have a density and viscosity less than water, there is a strong tendency for it to flow to the top of the injection zone. If there were a vertical leakage path in the caprock within this area, $CO_2$, with its low density and viscosity, would escape by buoyancy.

A modeling study conducted by Pruess and Garcia (2002) included a simple estimate of the leakage that might be expected from a vertical fracture in the caprock of a brine formation and found it to be significant. The effective permeability of $CO_2$ in the vertical leakage path will increase as the saturation of $CO_2$ in the vertical channel increases. Given the migrational tendencies of supercritical $CO_2$, it is likely that a transmissive fault or vertical fracture in the caprock of a GSU will have a significant impact on the leakage of $CO_2$ in the injection zone. Thus a careful evaluation of caprock integrity and detection of possible faults or fractures are critical components to identifying potential sequestration units.

In the Williston Basin, lineaments appear to have a potential for leakage and should be thoroughly characterized as part of the due diligence necessary to safely and effectively sequester $CO_2$. Methods for evaluating caprock integrity have been

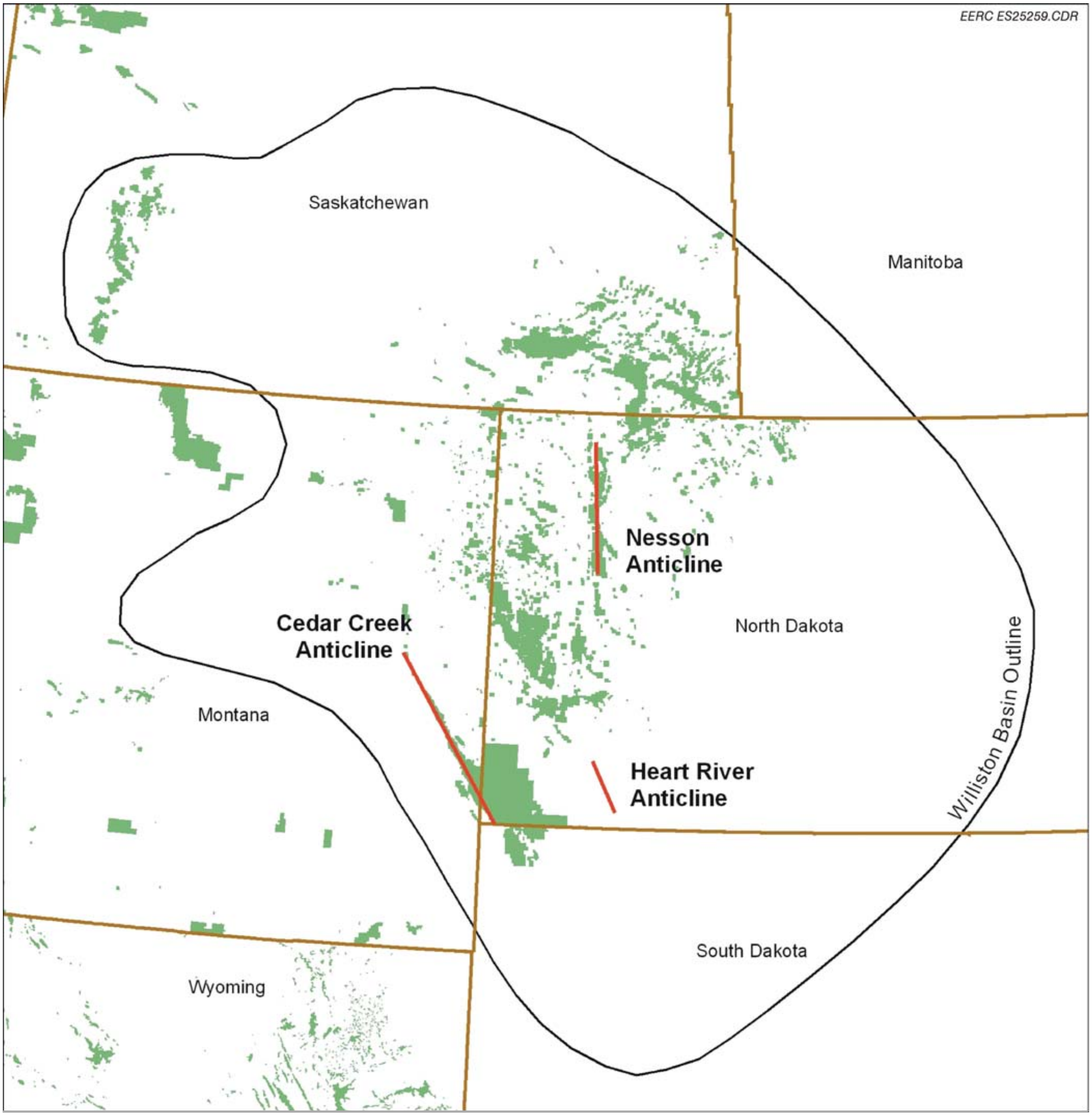


Figure 9. Location of oil and gas fields in the Williston Basin.

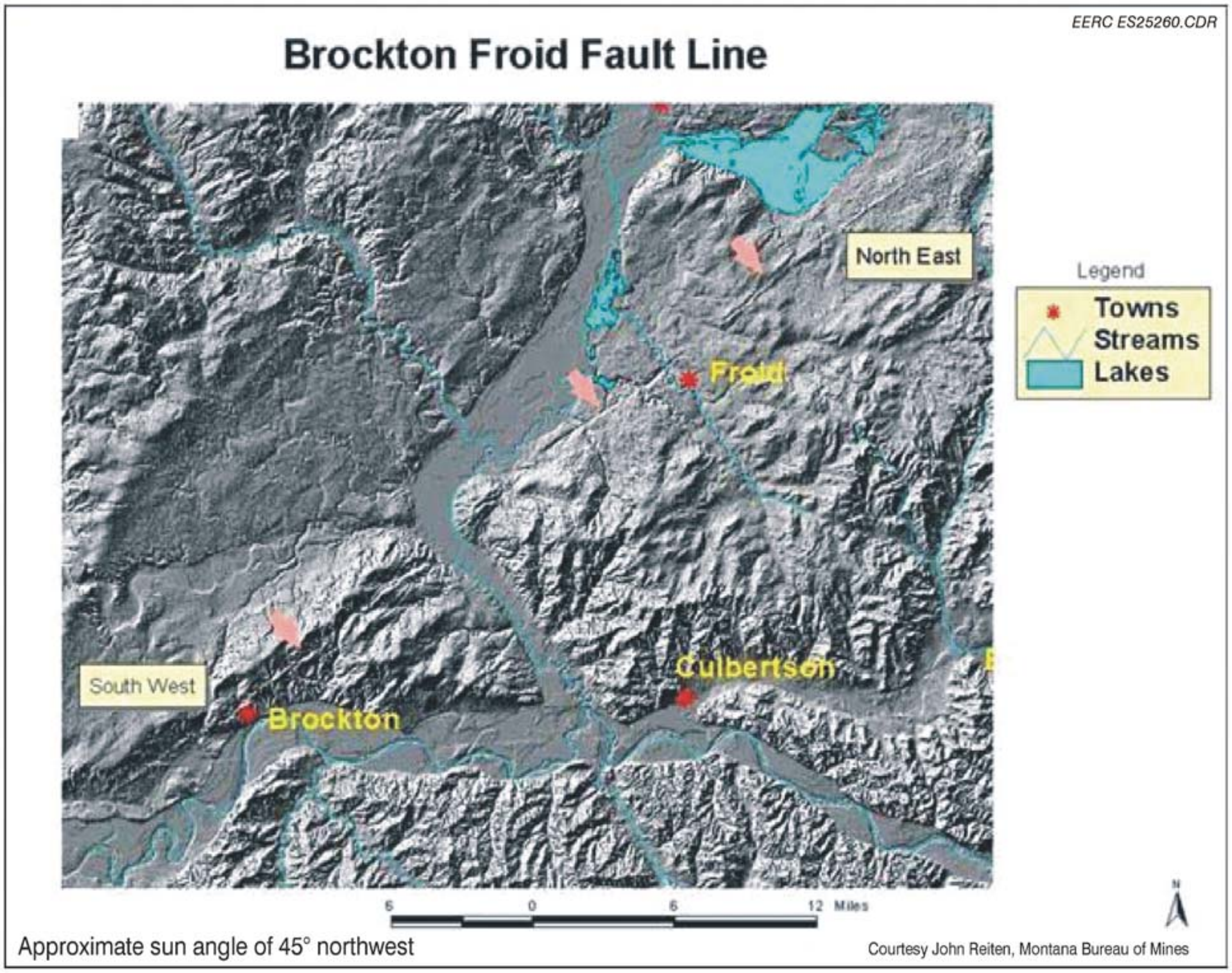


Figure 10. DEM image of the Brockton–Froid fault system associated with the Weldon–Brockton lineament (image courtesy of Jon Reiten, Montana Bureau of Mines and Geology).


Figure 11. Surface expression of the Brockton–Froid fault system associated with the Weldon–Brockton lineament (photo courtesy of Jon Reiten, Montana Bureau of Mines).

developed for natural gas storage applications and are likely to be applicable here. However, methods that provide basement geology characterization over very large areas are likely to be needed. Detailed geophysical techniques, including 3-D seismic, gravity and aeromagnetic surveys, satellite-based land surface imaging, and geochemical surveys are tools that may provide the necessary data.

It is important to keep the concept of a GSU leakage in perspective. While large-scale leakage obviously poses many problems, minor leakage of $CO_2$ into an overlying aquifer may not be a major environmental problem. In fact, in some cases, slow leakage of $CO_2$ followed by dissolution and possibly even mineralization of the $CO_2$ in overlying formations may be a desirable strategy for controlling reservoir pressures and limiting long-term impacts of $CO_2$ sequestration. Tsang et al. (2003) determined that the establishment of a “no migration” or “zero-leakage” requirement as a selection criterion for geologic sequestration units is not necessary. If minor leakage were anticipated or observed after the initiation of injection, the operation of the sequestration project would include the careful evaluation of the hydrogeologic setting and the use of model simulations to ensure that cumulative and instantaneous releases of $CO_2$ to the environment were within prescribed limits and would not compromise the sequestration effectiveness (Tsang et al., 2003).

It is also important to realize that any change in reservoir pressure introduced through the sequestration process has the potential to open closed conduits or fracture the GSU or caprock. Detailed engineering and petrophysical data will have to be collected on regionally prior to any sequestration. Careful monitoring of downhole conditions during the sequestration process will be needed.

## CONCLUSIONS

Understanding the tectonic history and setting of a geological province is a key component of predicting leakage of $CO_2$ from GSUs. In the Williston Basin, basement lineaments are significant tectonic features and their potential to act as migration pathways must be assessed. Most lineaments in the Williston Basin appear to be closed and are unlikely points where leakage of sequestered $CO_2$ may occur. However, evidence may suggest that some lineaments may provide pathways for leakage. It will be necessary to further investigate the possibility of leakage along lineaments before regional geological sequestration can take place.

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