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# SECTION VI

# GEOLOGY REPORT

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## 4.0 ACTIVE AND INACTIVE GEOLOGIC PROCESSES

This section addresses active geologic processes in the vicinity of the facility. In discussing the "active" geologic processes, the "inactive" processes are discussed as well. Active geologic processes include flooding and submergence, faulting, seismicity, land surface subsidence, and the potential for surface erosion. Flooding is addressed by locating the facility out of a 100-year floodplain and submergence applies only to coastal zones. Faults, seismicity, land surface subsidence, and surface erosion are discussed in the following sections.

### 4.1 FAULTS

This section provides an analysis of faults in the vicinity of the facility at the regional and local scales. Various regulatory requirements for land disposal activities, as well as storage and processing of wastes, require delineation of all faults within the area of the facility, together with demonstrations for any such faults that:

(i) fault displacement has not occurred within Holocene time, or if fault displacement has occurred within Holocene time, that no such faults pass within 200 feet of the portion of the surface facility where treatment, storage, or disposal of wastes will be conducted;

(ii) it will not result in structural instability of the surface facility or provide for groundwater movement to the extent that there is endangerment to human health or the environment; and

(iii) disposal units will not be located near a capable fault that could cause a maximum credible earthquake larger than that which the unit could reasonably be expected to withstand.

The WCS site is situated over the north central portion of a prominent Paleozoic structural feature known as the Central Basin Platform. Significant faults are known in the deep subsurface as interpreted from petroleum exploration activities. The faults are expressed in Paleozoic rocks at depths of thousands of feet. The deep faults lose their expression as significant stratigraphic offsets after early Permian (Wolfcampian) time. All of the major faulting in the vicinity of the Central Basin Platform occurred in response to tectonic forces active before the global plate tectonic reorganization that created the North American continent. (Bally et al., 1989). The Paleozoic faults exhibit low natural microseismicity as a result of passive response to relatively low levels of tectonic stress in the trailing edge of the westward-drifting North American plate. The closest area of active regional tectonic stress and active faulting offsetting Quaternary or younger geologic deposits is the Rio Grande Rift that forms the eastern boundary of the Basin and Range Province. The Rio Grande Rift is over 200 miles west of the WCS area. There is no surface evidence of faulting within 3000 feet the WCS permitted area.

### 4.1.1 Regional Tectonic Setting and Faults

The WCS facility is located within the Permian Basin region of west Texas. The Permian Basin derives its name from the fact that it is underlain by extensive deposits of Permian sediments.

#### 4.1.1.1 *Tectonic Setting*

The WCS site is situated over the north-central portion of a prominent structural feature known as the Central Basin Platform (Figure 6.4-1). The Central Basin Platform is a deep-seated horst-like structure that extends northwest to southeast from southeastern New Mexico to eastern Pecos County, Texas. The Central Basin Platform is flanked by two prominent structural depressions known as the Delaware Basin to the southwest and the Midland Basin to the northeast, and by the Val Verde Basin to the south.

From the Cambrian to late Mississippian, west Texas and southeast New Mexico experienced only mild structural deformation that produced broad regional arches and shallow depressions (Wright, 1979). The Central Basin Platform served intermittently as a slightly positive feature during the early Paleozoic (Galley, 1958). During the Mississippian and Pennsylvanian, the Central Basin Platform uplifted using ancient lines of weakness (Hills, 1985), and the Delaware, Midland, and Val Verde Basins began to form as separate basins.

Late Mississippian tectonic events uplifted and folded the platform and were followed by more intense late Pennsylvanian and early Permian deformation that compressed and faulted the area (Hills, 1963). Highly deformed local structures formed ranges of mountains oriented generally parallel to the main axis of the platform (Wright, 1979).

This period of intense, late Paleozoic deformation was followed by a long period of gradual subsidence and erosion that stripped the Central Basin Platform and other structures to near base-level (Wright, 1979). The expanding sea gradually encroached over broad eroded surfaces and truncated edges of previously deposited sedimentary strata. New layers of arkose, sand, chert pebble conglomerate and shale deposits accumulated as erosional products along the edges and on the flanks of both regional and local structures. Throughout the remainder of the Permian, the Permian Basin slowly filled with several thousand feet of evaporites, carbonates, and shales (Figure 6.4-2).

From the end of the Permian until late Cretaceous, there was relatively little tectonic activity except for periods of slight regional uplifting and downwarping. During the early Triassic, the region was slowly uplifted and slightly eroded. These conditions continued until the late Triassic, when gentle downwarping formed a large land-locked basin in which terrigenous deposits of the Dockum Group accumulated in alluvial flood plains and as deltaic and lacustrine deposits (McGowen, et al., 1979). In Jurassic time, the area was again subject to erosion.

During Cretaceous time, a large part of the western interior of North America was submerged, and the west Texas/southeastern New Mexico region was part of a large continental shelf sea in which a thick sequence of Cretaceous rocks was deposited. The Cretaceous sequence of sediments comprised a basal clastic unit (the Trinity, Antlers or Paluxy sands) and overlying shallow marine carbonates.

Uplift and southward– and eastward-retreating Cretaceous seas were coincident with the Laramide Orogeny, which formed the Cordilleran Range west of the Permian Basin. The Laramide Orogeny uplifted the region to essentially its present position, supplying sediments for the late Tertiary Ogallala Formation. The major episode of Laramide folding and faulting occurred in the late Paleocene. There have been no major tectonic events jn North America since the Laramide Orogeny, except for a period of minor volcanism during the late Tertiary in northeastern New Mexico and in the Trans-Pecos area. Hills (1985) suggests that slight Tertiary movement along Precambrian lines of weakness may have opened joint channels which allowed the circulation of groundwater into Permian evaporite layers. The near-surface regional structural controls may be locally modified by differential subsidence related to groundwater dissolution of Permian salt deposits (Gustavson, 1980).

#### 4.1.1.2 *Faults*

Two types of faulting were associated with early Permian deformation. Most of the faults were long, high-angle reverse faults with several hundred feet of vertical displacement that often involved the Precambrian basement rocks (Hills, 1985). The traces of these faults are shown on the Precambrian structure map provided in Figure 6.4-3. The second type of faulting is found along the western margin of the Central Basin Platform where long strike-slip faults, with displacements of tens of miles, are found (Hills, 1985; Bebout and Meador, 1985) (Figure 6.4-4).

The large structural features of the Permian Basin are reflected only indirectly in the Mesozoic and Cenozoic rocks, as there has been virtually no tectonic movement within the basin since the Permian (Nicholson and Clebsch, 1961). The east-west and north-south regional cross-sections provided in Figures 6.4-5 and 6.4-6 illustrate this relationship. Figure 6.4-5 shows the draping of the Permian and Triassic sediments over the Central Basin Platform structure, located approximately 7000 feet beneath the present land surface. The faults that uplifted the platform do not appear to displace the younger Permian sediments. The northernmost fault on Figure 6.4-6, located at the Matador Uplift, terminates in lower Wolfcampian sediments.

A further comparison of the structure of the Devonian Woodford Formation to the structure of the younger Upper Guadalupe Whitehorse Group (Permian) (Figures 6.4-7 and 6.4-8) indicates that the faults in the Devonian section do not continue upward into the overlying Permian Guadalupe Whitehorse Group. The regional geologic and tectonic information does not indicate the presence of significant post-Permian faulting within the regional study area, although minor post-Permian faulting in the WCS area is discussed below. In addition, the local information does not indicate Holocene displacement of faults within 3000 feet of the proposed WCS landfill site. The site-specific structural setting is discussed below.

Two regional stratigraphic cross sections constructed in the vicinity of the WCS site using oil and gas well logs are shown as Plates 6.2-2 and 6.2-3. The locations of the cross sections are shown in Figure 6.2-1. These cross sections depict the major stratigraphic units that occur within about 2000 feet below ground surface in the vicinity of the site. The stratigraphic units depicted on Plates 6.2-2 and 6.2-3 include the upper OAG unit of a few tens of feet in thickness, the underlying Triassic red beds of the Dockum Group with a thickness of 1,000 to 1,500 feet, the underlying Permian Dewey Lake Formation red beds, and the Permian evaporites of the Rustler and Salado Formations. These cross sections do not indicate the presence of significant faulting in the upper 2,000 feet of sediments within 3 to 4 miles of the WCS site. The base of the underground source of drinking water (USDW) is the bottom of the Santa Rosa Formation at about 1,400 feet below ground surface in the vicinity of the WCS facility. The Santa Rosa Formation is the lowermost formation of the Triassic Dockum Group.

#### 4.1.1.3 *Post-Permian/Pre-Cretaceous Fault Investigation*

Faulting in a sandstone in the upper portion of the Triassic red beds of the RCRA landfill was anecdotally identified at a WCS project meeting February 11, 2004. Subsequently, photos taken in 1996 of an apparent southward-dipping reverse fault were located (Figure 6.4-9). Since regulatory criteria address the age of faults and the age of any geologic units affected or displaced by faulting, a geologic investigation of the fault was undertaken. The southeast wall of the RCRA landfill was extended about 200 feet to the southeast in May and June 2004, yielding about 60 feet of vertical geologic exposure along a length of about 400 feet. Two benches with subvertical walls were exposed.

The upper wall was approximately 25 feet high, extending about 6 feet into the Triassic red beds of the Dockum Group. The upper wall exposed caprock caliche developed on Cretaceous Antlers Formation sand and gravel, underlain by non-calichified Antlers sands and gravels, in turn underlain by the red bed clays of the Triassic Dockum Group. The upper 3 to 4 feet of the red beds have been altered from red to gray. Along the relatively sharp contact between the altered gray clay and unaltered red clay were numerous small faults with offsets ranging from a few inches to a few feet.

The lower wall was excavated an additional 30 to 35 feet into the red beds exposing a 10- to 15-foot thick sandstone layer in the upper part of the wall. The sandstone exhibited two opposing reverse faults with offsets of about 20 feet on the southward-dipping southern fault and about 3 feet on the northward-dipping northern fault (Figure 6.4-10). The southern reverse fault in the Triassic sandstone bed is the southeastern extension of the southward-dipping reverse fault in the 1996 photographs.

Geologic mapping

Geologic mapping of the upper and lower walls was completed by two field mapping teams, supervised by a senior coordinating geologist. Elevation baselines were surveyed onto both the upper and lower walls, and the walls were subdivided into five-foot square townships and ranges. Detailed geologic mapping was conducted on parts of the upper and lower walls using moveable five-foot square grids, subdivided into 25 one-foot square sections. The mapping focused on geologic contacts and distinguishable geologic features, including faults, joints, slickensides, bedding planes, partings, channels, alteration and weathering zones. The mapped geologic sections are provided in Figure 6.4-11.

The upper wall was mapped in considerably more detail than the lower wall in order to determine the youngest geologic units affected by faulting. The southern end of the upper wall, where the largest faults and offsets were observed, was mapped in the greatest detail. Parts of the upper wall were mapped by field sketching and photographic interpretation. The two faults in the lower wall were mapped in detail using the 5-foot grids, while the remainder of the lower wall was documented using photo mosaics.

Observations - Lower wall

The geologic materials exposed on the lower wall are part of the Triassic Dockum Group, specifically the Cooper Canyon Formation (Lehman, 1994b). The red beds are characteristically red and purple claystones, with interbedded discontinuous siltstone and sandstone units. As indicated above, a fine grained sandstone layer about 10 to 15 feet thick occurred in the upper third of the lower wall. The claystones were relatively plastic on excavation, drying within a week to a stiff, blocky structure.

The red beds exhibited nominally orthogonal, subvertical jointing with well-developed joints at about 0.5 to 1 foot spacing. Lower hemisphere stereonet projections of the poles to the subvertical joints show a maximum concentration at about 320° (north 40° west) with a secondary concentration at about 40° (north 40° east) (Figure 6.4-12). The subvertical joints are an expression of the orthogonal regional jointing system.

The concentration of subvertical joint directions at about 320° is partially due to bias induced by the orientation of the northeast-striking wall. If a similar length northwest-striking wall were available for measurement of subvertical joints, it is likely that the secondary concentration at about 40° would be more pronounced and the orthogonal pattern of the regional jointing system would be more obvious on the stereonet plot. There was only about 50 feet of northwest-striking wall exposed beneath the sandstone at the north end of the excavation, yielding a limited opportunity to eliminate the bias of the longer northeast-striking exposure of about 400 feet. The subvertical joints were often coated or partially coated with dark brown to purplish-black weathering products, likely manganese oxide. Slickensides on the subvertical joints were not observed.

Relatively large, continuous and 'wavy' lower-angle joints at about 30° to 60° from horizontal were also present, without an apparent well-developed spacing or repetition, as in the subvertical joints. The lower angle joints exhibited continuity over 10 to 15 feet of exposure on the lower wall, and slickensides were numerous and well developed on the wavy joints. The strike of the irregular, wavy joint planes show a maximum at about 300° (Figure 6.4-13), however the strikes of the irregular joint planes appear to be quite well distributed about the stereonet.

The sandstone exposed in the upper third of the lower wall was 10 to 15 feet in thickness. The sandstone exhibited two opposing reverse faults about 200 feet apart with apparent dips of the order of 30° to 40°. The southern reverse fault is the southeastern extension of the southward-dipping reverse fault in the 1996 photographs. The reverse fault in the southern end of the wall was south-dipping with a south-hanging-wall-up offset of about 20 feet. The reverse fault in the northern part of the wall was north-dipping with a north-hanging-wall-up offset of about 3 feet. The poles of the measured fault planes show a strike of the fault planes of about 277° to 280° (north 83° west to north 80° west) (Figure 6.4-14). Slickensides were measured on both the south and north fault planes, indicating dip slip with a compressional stress azimuth of about 15°

(north 15° east) (Figure 6.4-15). The sandstone was lower in the section on the northern third of the wall. The change in altitude may be related to possible fold development in the red beds in the vicinity of the reverse faults, or it may be depositionally-related in that the poorly developed bedding appeared to remain subhorizontal for much of the exposure.

Observations - Upper Wall

The geologic materials exposed on the upper wall include the upper 3 to 10 feet of Triassic red beds, overlain by Cretaceous Antlers Formation sands and gravels. The upper 10 to 15 feet of the Antlers Formation has been highly calichified and has developed into the characteristic caprock caliche of the Southern High Plains. The joint system in the red beds in the upper wall provided fewer subvertical joints to measure due to the limited exposure of only the upper few feet of the red beds over most of the upper wall. Of the comparatively limited number of measured subvertical joints, the strike maximum occurred at about 290° to 295° (Figure 6.4-16). The upper wall irregular, lower-angle, wavy joints with well-developed slickensides plotted similar to the lower wall irregular, low-angle, wavy joints, with a strike maximum at about 330° but also with a well distributed pole pattern throughout the stereonet (Figure 6.4-17).

There are numerous fault planes in the red beds on the upper wall. The faults in the red beds on the upper wall are very apparent, since the offsets occurred after the development of a grayish-colored altered layer approximately 3 to 4 feet thick at the top of the red beds. The sharp lower contact of the altered layer shows the offsets very well.

The faults in the red bed on the upper wall are virtually all reverse faults, with both south and north apparent dips on the fault planes. The offsets on the reverse faults range from inches to as much as several feet. The largest fault in the red beds on the upper wall, with an offset of about 4 feet, is in the southern third of the exposed wall. This fault is an upward continuation of the southern hanging-wall-up reverse fault in the sandstone on the lower wall, which shows an offset of about 20 feet. The fault appears to die out quickly in the vertical direction. The stress which caused the brittle failure and 20 feet of offset of the sandstone on the lower wall appears to be accommodated throughout the remainder of the red bed claystone/clay in the upper wall by a number of smaller faults and perhaps plastic deformation in the clays.

The faults in the red beds on the upper wall show a pattern of anastamozing slip surfaces, with many of the south- and north-dipping slip planes appearing to pair up and join into a primary slip plane with smaller dendritic slip surfaces splaying off the primary plane. The fault planes on the upper wall dip at about 30° to 40° to the northeast and southwest. Strikes of the fault planes on the upper wall show a maximum at about 284° (north 76° west) (Figure 6.4-18). Slickensides on the fault planes show dip-slip movement, with slickenside azimuths between about 340° and 30° (north 20° west and north 30° east) (Figure 6.4-19), consistent with the 15° apparent compressional stress azimuth of the faults on the lower wall.

During late Jurassic or early Cretaceous time, it appears that the upper part of the red beds was subjected to geochemically reducing conditions that altered the red bed clays from red to gray. The thickness of the altered layer is very uniform along the upper wall, which suggests that the alteration occurred while the top of the red beds were at some relatively uniform elevation, prior to faulting or folding. The reducing conditions and vertical downward advance of the alteration front suggest that the area may have been a submerged bog or shoreline with relatively stagnant, marshy conditions.

The alteration occurs to a very uniform depth marked by a sharp vertically delimited alteration front of about ¼ to ½ inch where the color of the red beds changes from gray to red. The sharp alteration front is most likely a diffusion front within the relatively impermeable clays. The uniform depth of penetration suggests matrix-dominated transport of a diffusion front, since the alteration front does not extend significantly further downward adjacent to the joints or fractures. The joints, though preferred fluid paths and perhaps marginally more transmissive than the unfractured matrix, apparently did not allow any significant additional downward penetration of alteration fluids. The joints were essentially non-transmissive to alteration fluids, likely due to the presence of swelling montmorillonite clays (Glass et al., 1973) and joint closure.

Liesegang banding between joints is very well developed within the altered layer. The liesegang banding parallels and mimics the joint surfaces in three dimensions. Alteration clearly occurred post-jointing, most likely as successive diffusion fronts moved inward from the joints from all directions under saturated conditions. The altered layer may have developed under successive, perhaps seasonal, wetting and drying conditions, with liesegang banding developing between joints as the joints swelled closed on passage of the wetting fronts.

At the top of the gray altered layer was a readily apparent parting that was present over approximately 80 to 90% of the exposed wall. The parting appears to be an erosional/depositional surface of either late Jurassic or early Cretaceous age based on the presence of some Cretaceous-aged gravels mixed into the upper portion of the zone above the parting. Above the parting are both reworked altered red beds (reworked and redeposited clays of the altered layer) as well as a second zone of alteration in the southern part of the wall where the reworked clays of the gray altered layer have apparently been further altered to a mixture of silt- to sand-sized crystalline carbonates and sulfates.

Above the reworked or reworked and altered clays are the Cretaceous-aged Antlers Formation sands and gravels. The lower part of the Antlers Formation contains numerous clasts and angular blocks of altered upper red beds or reworked altered red beds. The Antlers Formation exhibits a depositional pattern characteristic of braided streams, with a sequence of younger channels cross-cutting older channels and smaller channels a few tens of feet in width embedded within larger channel deposits. The Antlers Formation sands and gravels range from well-sorted fine to medium grained sands to poorly sorted sands and gravels with occasional cobble-sized particles. The lower few feet of the Antlers Formation is poorly to partially cemented sands and gravels apparently unaffected by the calichification process which is readily apparent in the upper parts of the section. Some of the finer sands higher in the section exposed on the upper wall appear well cemented, although the cementing may be due in part to the development of the caprock caliche.

The relationship between faulting in the Triassic red beds and the overlying Cretaceous Antlers Formation was carefully evaluated to determine if any displacement of the younger Cretaceous deposits had occurred. The Triassic red beds are separated from the overlying Cretaceous Antlers Formation sands and gravels by the distinct and mappable parting at the top of the gray altered layer of red beds. None of the observed fault planes or slip surfaces in the Triassic red beds in the extensively mapped section cross or offset the parting. In addition, the bedding in the Antlers Formation is continuous where observable and not calichified, and in particular, there are no Triassic/Cretaceous contact offsets or bedding offsets in the Cretaceous Antlers Formation above the area in the Triassic red beds where the largest displacements occur nor is there any apparent folding of the Antlers Formation in this area. Therefore, there are no indications that the Cretaceous-aged Antlers Formation was affected by the faulting in the Triassic red beds. There are clearly no geologic Formations present in the excavation younger than Triassic that are affected by faulting and there are no regulatory issues related to faulting at the WCS site. Additionally, there are no issues with respect to potential migration pathways resulting from the faulting at the WCS site. The uppermost faulting occurred completely within the Triassic red beds; which have great capacity for healing and closing fault planes and joints to fluid migration as indicated by the limited penetration of the alteration front in the red beds.

4.1.1.4 *Red Bed Ridge Development*

Faulting of any significance in the vicinity of the WCS site or the Central Basin Platform is generally considered to be Permian or earlier (Nicholson and Clebsch, 1961). Galley (1958, p.439-441) indicates that although "events associated with Laramide and several Tertiary orogenies have broken, destroyed, submerged, or obscured various segments of Paleozoic structures at the southwest edge of the Permian Basin", "Elsewhere the Paleozoic strata lie at almost the same attitudes they had attained at the end of Ochoa time, having been affected subsequently only by regional tilting and local folding or faulting of small vertical displacement." These statements indicate that the Central Basin Platform area has not been significantly disturbed by tectonic events since late Permian (Ochoa) time.

The post-Permian/pre-Cretaceous tilting, folding and faulting discussed in the previous section may have contributed to the development of the red bed ridge by creating a relatively local topographic high uplifted by the minor compressional faulting/folding of the red beds. The local geology discussed in Section 5.3 indicates that the first continuous red bed sandstone, which occurs at an approximate depth of about 225 feet below ground surface, has a south/southwestward dip of about 80 feet per mile. The south/southwestward dipping bedding may represent the southwestern limb of an anticline or monocline with the red bed ridge as the fold axis. The red bed ridge area may have been an inter-drainage topographic high since the compressional event.