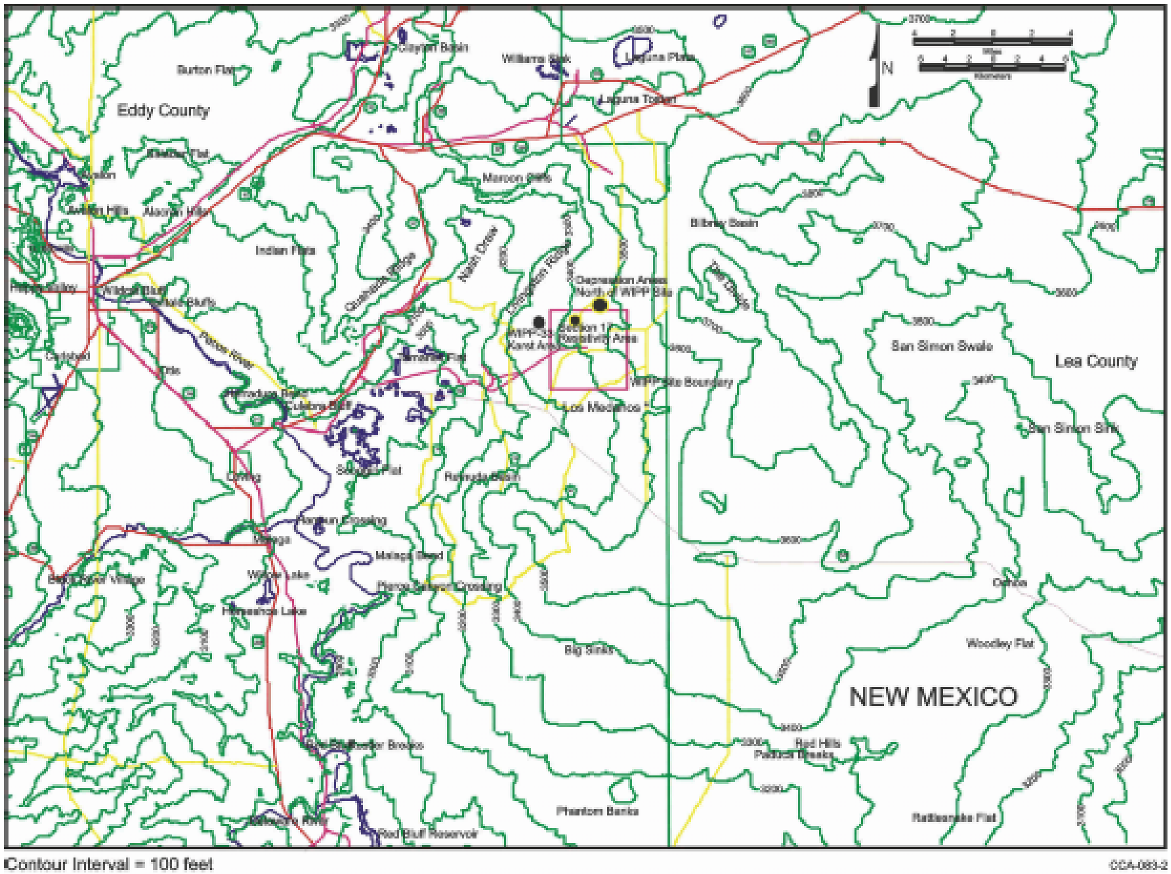

~~**Figure 2-18. Topographic Map of the Area Around the WIPP Site**~~

Livingston Ridge is the most prominent physiographic feature near the site. It is a west-facing escarpment that has about 23 m (75 ft) of topographic relief and marks the eastern edge of Nash Draw, the drainage course nearest to the site (see Figure 2-~~18~~*23*). Nash Draw is a shallow 8-km-wide (5-mi-wide) basin, 61 to 91 m (200 to 300 ft) deep and open to the southwest. It was caused, at least in part, by subsurface dissolution and the accompanying subsidence of overlying sediments. Livingston Ridge is the approximate boundary between terrain that has undergone erosion and/or solution collapse to the west and terrain that has been little affected to the east.

About 24 km (15 mi) east of the site is the southeast-trending San Simon Swale, a depression caused, at least in part, by subsurface dissolution. Between San Simon Swale and the site is a broad, low mesa named the Divide. Lying about 9.7 km (6 mi) east of the site and about 30 m (100 ft) above the surrounding terrain, it is a boundary between southwest drainage toward Nash Draw and southeast drainage toward San Simon Swale. The Divide is capped by the Ogallala and the overlying caliche, upon which have formed small, elongated depressions similar to those in the adjacent High Plains section to the east.

Surface drainage is intermittent; the nearest perennial stream is the Pecos River, 19 km (12 mi) southwest of the WIPP site boundary. The site's location near a natural divide protects it from flooding and serious erosion caused by heavy runoff. Should the climate become more humid, any perennial streams should follow the present basins, and Nash Draw and San Simon Swale would be the most eroded, leaving the area of the Divide relatively intact.

2.1.5 Tectonic Setting and Site Structural Features

The DOE has screened out, on the basis of either probability or consequence or both, all tectonic, magmatic, and structural related processes. The screening discussions can be found in Appendix ***PA, Attachment*** SCR. The information needed for this screening is included here and covers regional tectonic processes such as subsidence and uplift and basin tilting, magmatic processes such as igneous intrusion and events such as volcanism, and structural processes such as faulting and loading and unloading of the rocks because of long-term sedimentation or erosion. Discussions of structural events, such as earthquakes, are considered to the extent that they may create new faults or activate old faults. The seismicity of the area is considered in Section 2.6 for the purposes of determining seismic design parameters for the facility.

2.1.5.1 Tectonics

The processes and features included in this section are those more traditionally considered part of tectonics, processes that develop the broad-scale features of the earth. Salt dissolution is a different process that can develop some features resembling those of tectonics.

Most broad-scale structural elements of the area around the WIPP developed during the Late Paleozoic (***CCA*** Appendix GCR, ***pp.*** 3-58 to 3-77). There is little historical or geological evidence of significant tectonic activity in the vicinity, and the level of stress in the region is low. The entire region tilted slightly during the Tertiary, and activity related to Basin and Range tectonics formed major structures southwest of the area. Seismic activity is specifically addressed in a separate section.

Broad subsidence began in the area as early as the Ordovician, developing a sag called the Tobosa Basin. By Late Pennsylvanian to Early Permian time, the Central Basin Platform developed (Figure 2-~~19~~***24***), separating the Tobosa Basin into two parts: the Delaware Basin to the west and the Midland Basin to the east. The Permian Basin refers to the collective set of depositional basins in the area during the Permian Period. Southwest of the Delaware Basin, the Diablo Platform began developing either in the Late Pennsylvanian or Early Permian. The Marathon Uplift and Ouachita tectonic belt limited the southern extent of the Delaware Basin.

According to Brokaw et al. (1972, ***p.*** 30), pre-Ochoan sedimentary rocks in the Delaware Basin show evidence of gentle downwarping during deposition, while Ochoan and younger rocks do not. A relatively uniform eastward tilt, generally from about 14 to 19 m/***per*** km (75 to 100 ft/mi), has been superimposed on the sedimentary sequence.[1] ~~P.B.~~ King (1948, ***pp.*** 108 and 121) generally attributes the uplift of the Guadalupe and Delaware mountains along the west side of the Delaware Basin to the later Cenozoic, though he also notes that some faults along the west margin of the Guadalupe Mountains have displaced Quaternary gravels.

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[1] Local dip of the Salado has been determined by mapping in the WIPP underground excavations. This dip is modeled as one degree to the south, as discussed in Section 6.4.2.1.

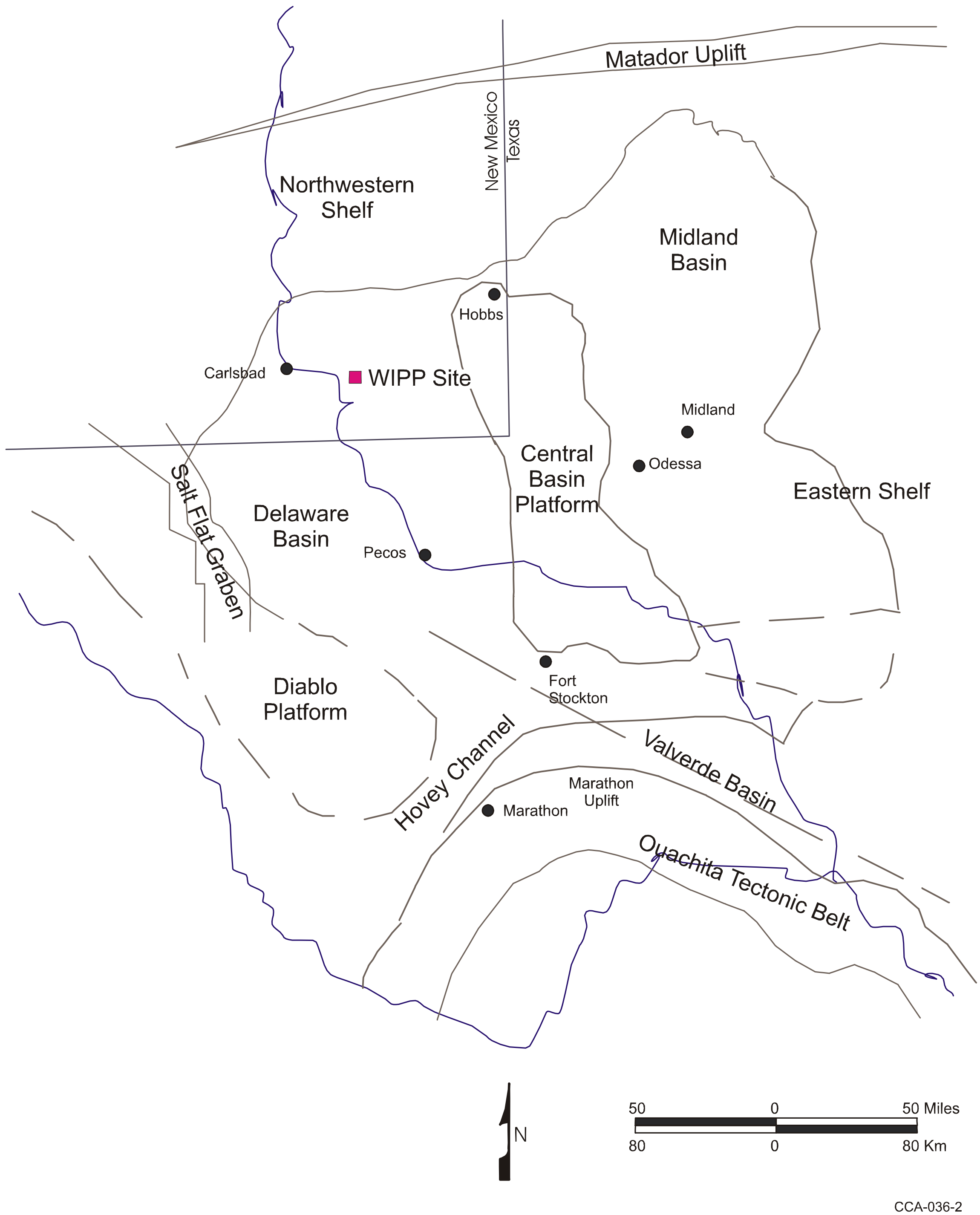


Figure 2-~~19~~*24*. Structural Provinces of the Permian Basin Region

~~P.B.~~ King (1948, ***p.*** 144) also infers the uplift from the Pliocene-age deposits of the Llano Estacado. Subsequent studies of the Ogallala of the Llano Estacado show that it varies in age from Miocene (about 12 million years before present) to Pliocene (Hawley 1993). This is the most likely range for uplift of the Guadalupe Mountains and broad tilting to the east of the Delaware Basin sequence.

Analysis of the present regional stress field indicates that the Delaware Basin lies within the Southern Great Plains stress province. This province is a transition zone between the extensional stress regime to the west and the region of compressive stress to the east. An interpretation by Zoback and Zoback (1991, ***p.*** 350) of the available data indicates that the level of stress in the Southern Great Plains stress province is low. Changes to the tectonic setting, such as the development of subduction zones and a consequent change in the driving forces, would take much longer than 10,000 years to occur.

To the west of the Southern Great Plains province is the Basin and Range province, or Cordilleran Extension province, where according to Zoback and Zoback (1991, ***pp.*** 348 **-** 351)*,* normal faulting is the characteristic style of deformation. The eastern boundary of the Basin and Range province is marked by the Rio Grande Rift. Sanford et al. (1991, ***p.*** 230) note that, as a geological structure, the ***r***ift extends beyond the relatively narrow geomorphological feature seen at the surface, with a magnetic anomaly at least 500 km (300 mi) wide. On this basis, the Rio Grande Rift can be regarded as a system of axial grabens along a major north-south trending structural uplift (a continuation of the Southern Rocky Mountains). The magnetic anomaly extends beneath the Southern Great Plains stress province, and regional-scale uplift of about 1,000 m (3,300 ft) over the past 10 million years also extends into eastern New Mexico.

To the east of the Southern Great Plains province is the large Mid-Plate province that encompasses central and eastern regions of the conterminous United States and the Atlantic basin west of the Mid-Atlantic Ridge. The Mid-Plate province is characterized by low levels of paleo- and historic seismicity. Where Quaternary faulting has occurred, it is generally strike-slip and appears to be associated with the reactivation of older structural elements.

Zoback et al. (1991) report no stress measurements from the Delaware Basin. The stress field in the Southern Great Plains stress province has been defined from borehole measurements in west Texas and from volcanic lineaments in northern New Mexico. These measurements were interpreted by Zoback and Zoback (1991, ***p.*** 353) to indicate that the least principal horizontal stress is oriented north-northeast and south-southwest and that most of the province is characterized by an extensional stress regime.

There is an abrupt change between the orientation of the least principal horizontal stress in the Southern Great Plains and the west-northwest orientation of the least principal horizontal stress characteristic of the Rio Grande Rift. In addition to the geological indications of a transition zone as described above, Zoback and Zoback (1980, ***p.*** 6134) point out that there is also evidence for a sharp boundary between these two provinces. This is reinforced by the change in crustal thickness from about 40 km (24 mi) beneath the Colorado Plateau to about 50 km (30 mi) or more beneath the Southern Great Plains east of the Rio Grande Rift. The base of the crust within the Rio Grande Rift is poorly defined but is shallower than that of the Colorado Plateau (Thompson and Zoback 1979, ***p.*** 152). There is also markedly lower heat flow in the Southern

Great Plains (typically < 60 mWm^{-2}) reported by Blackwell et al. (1991, ***p.*** 428) compared with that in the Rio Grande Rift (typically > 80 mWm^{-2}) reported by Reiter et al. (1991, ***p.*** 463).

On the eastern boundary of the Southern Great Plains province, there is only a small rotation in the direction of the least principal horizontal stress. There is, however, a change from an extensional, normal faulting regime to a compressive, strike-slip faulting regime in the Mid-Plate province. According to Zoback and Zoback (1980, ***p.*** 6134), the available data indicate that this change is not abrupt and that the Southern Great Plains province can be viewed as a marginal part of the Mid-Plate province.

2.1.5.2 Loading and Unloading

Loading and unloading during the geological history since deposition is considered an influence on the hydrology of the Permian units because of its possible effect on the development of fractures.

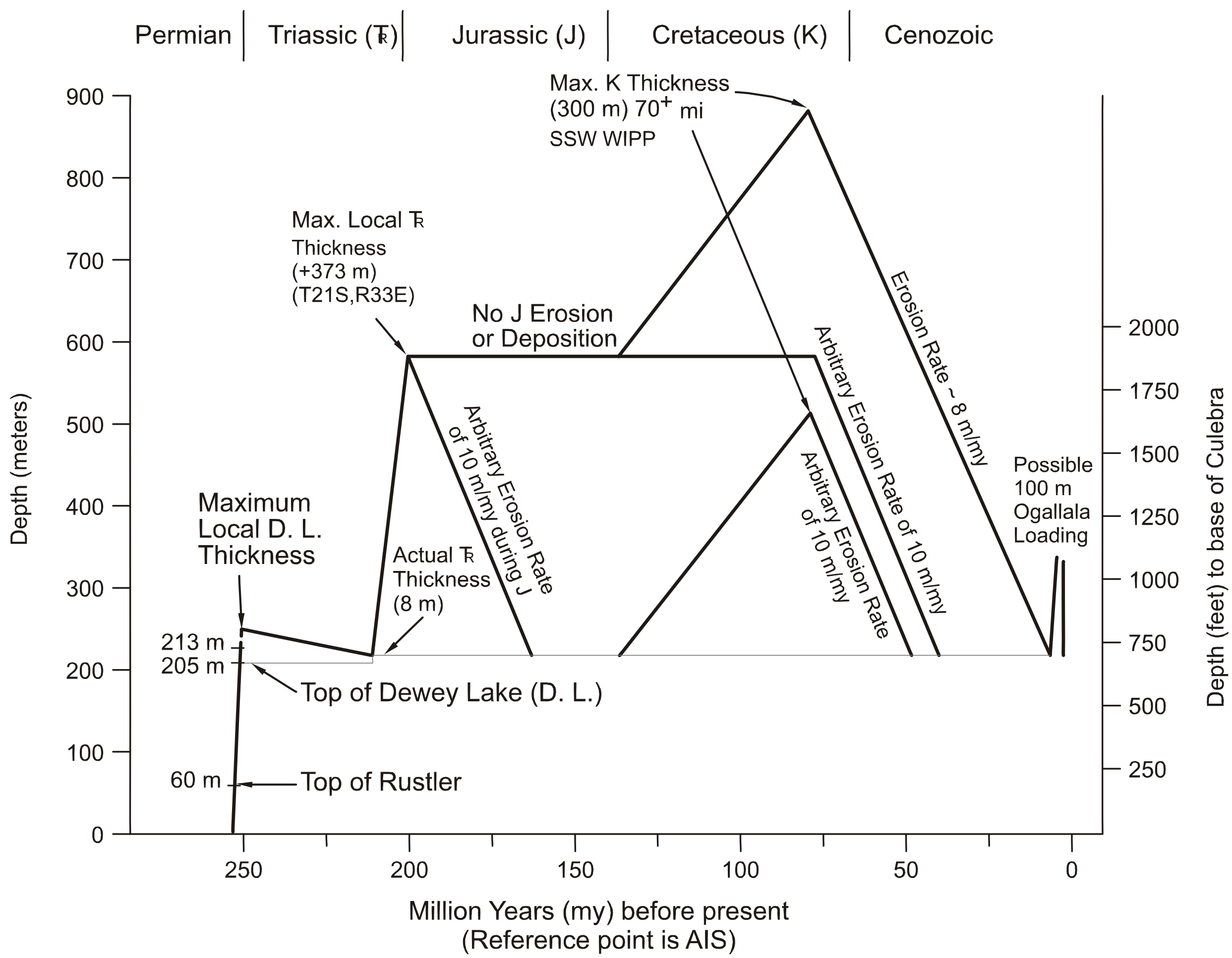
The sedimentary loading, depth of total burial, and erosion events combine in a complex history reconstructed here from regional geological trends and local data. The history is presented in Figure 2-~~20~~***25*** with several alternatives, depending on the inferences that are drawn, ranging from minimal to upper-bound estimates (Powers and Holt 1995, Section 5.3). Borns (1987) also made a generalized estimate of loading that is similar. The estimates are made with a reference point and depth to the Culebra at the AIS.

Given the maximum local thickness of the Dewey Lake, the maximum load at the end of the Permian was no more than approximately 240 m (787 ft). Given the present depth to the Culebra from the top of the Dewey Lake in the AIS, approximately 35 m (115 ft) of Dewey Lake might have been eroded during the Early Triassic before additional sediments were deposited. The Triassic thickness at the AIS is approximately 8 m (26 ft). Northeast of the WIPP site (T21S, R33E), Triassic rocks (Dockum Group) have a maximum local thickness of approximately 373 m (1,233 ft). This thickness is a reasonable estimate of the maximum thickness also attained at the WIPP site prior to the Jurassic Period. At the end of the Triassic, the total thickness at the WIPP site may have then attained approximately 586 m (1,863 ft) in two similar loading stages of a few million years each, over a period of approximately 50 million years.

The Jurassic outcrops nearest to the WIPP site are in the Malone Mountains of west Texas. There is no evidence that Jurassic rocks were deposited at or in the vicinity of the WIPP site.

As a consequence, the Jurassic is considered a time of erosion or nondeposition at the site, though erosion is most likely.

Widespread erosion during the Jurassic obviously cannot be broadly inferred for the area or there would not be thick Triassic rocks still preserved. Triassic rocks of this thickness are preserved nearby, indicating either pre-Jurassic tilting or that erosion did not occur until later (but still after tilting to preserve the Triassic rocks near the WIPP site). It is also possible that the immediate site area had little Triassic deposition or erosion, but very limited Triassic deposition (that is, 8 m [26 ft]) at the WIPP site seems unlikely.



Note: The estimates are made with a reference point and depth to the base of the Culebra at the AIS. Source: Powers and Holt 1995, Figure 34.

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Figure 2-~~20~~*25*. Loading and Unloading History Estimated to the Base of the Culebra

Lang (1947) reported fossils from Lower Cretaceous rocks in the Black River Valley southwest of the WIPP site. Bachman (1980, ***p.*** 28) also reported similar patches of probable Cretaceous rocks near Carlsbad and south of White's City. From these reports, it is likely that some Cretaceous rocks were deposited at the WIPP site. Approximately 110 km (70 mi) south-southwest of the WIPP site, significant Cretaceous outcrops of both Early and Late Cretaceous age have a total maximum thickness of approximately 300 m (1,000 ft). Southeast of the WIPP, the nearest Cretaceous outcrops are thinner and represent only the Lower Cretaceous. Based on outcrops, a maximum thickness of 300 m (1,000 ft) of Cretaceous rocks could be estimated for the WIPP site. Compared to the estimate of Triassic rock thickness, it is less likely that Cretaceous rocks were this thick at the site. The uppermost lines of Figure 2-~~20~~***25*** summarize the assumptions of maximum thickness of these units.

A more likely alternative is that virtually no Cretaceous rocks were deposited, followed by erosion of remaining Triassic rocks during the Late Cretaceous to the Late Cenozoic. Such erosion may also have taken place over an even longer period, beginning with the Jurassic Period. Ewing (1993) favors Early Cretaceous uplift and erosion for the Trans-Pecos Texas area, but ~~he~~ does not analyze later uplift and erosional patterns.

In the general vicinity of the WIPP site, there are outcrops of Cenozoic rock from the Late Miocene (Gatuña and Ogallala Formations). There is little reason to infer any significant Early Cenozoic sediment accumulation at the WIPP site. Erosion is the main process inferred to have occurred during this period and an average erosion rate of approximately 10 m (33 ft) per million years is sufficient during the Cenozoic to erode the maximum inferred Triassic and Cretaceous thickness prior to Gatuña and Ogallala deposition. Significant thicknesses of Cretaceous rocks may not have been deposited, however, and average erosion rates could have been lower.

Maximum-known Gatuña thickness in the area around the WIPP is approximately 100 m (330 ft); at the WIPP site, the Gatuña is very thin to absent. Ogallala deposits are known from the Divide east of the WIPP site, as well as from the High Plains further east and north. On the High Plains northeast of the WIPP, the upper Ogallala surface slopes to the southeast at a rate of approximately 4 m/km (20 feet per mile). A straight projection of the 1,250-m (4,100-ft) contour line from this High Plains surface intersects the site area, which is at an elevation slightly above 1,036 m (3,400 ft). This difference in elevation of 213 m (700 ft) represents one estimate, probably near an upper bound, of possible unloading subsequent to deposition of the Ogallala Formation.

Alternatively, the loading and unloading of the Ogallala could have been closer to 100 m (330 ft). In any case, it would have occurred as a short-lived pulse over a few million years at most.

While the above inferences about greater unit thicknesses and probable occurrence are permissible, a realistic assessment suggests a more modest loading and unloading history (Powers and Holt 1995). It is likely that the Dewey Lake accumulated to near local maximum thickness of approximately 240 m (787 ft) before being slightly eroded prior to the deposition of Triassic rocks. It also is most probable that the Triassic rocks accumulated at the site to near local maximum thickness. In two similar cycles of rapid loading, the Culebra was buried to a depth of approximately 650 m (2,132 ft) by the end of the Triassic.

It also seems unlikely that a significant thickness of Cretaceous rock accumulated at the WIPP site. Erosion probably began during the Jurassic, slowed or stopped during the Early Cretaceous as the area was nearer or at base level, and then accelerated during the Cenozoic, especially in response to uplift as Basin and Range tectonics encroached on the area and the basin was tilted more. Erosional beveling of Dewey Lake and Santa Rosa suggest considerable erosion since tilting in the mid-Cenozoic. Erosion rates for this shorter period could have been relatively high, resulting in the greatest stress relief on the Culebra and surrounding units. Some filling occurred during the Late Cenozoic as the uplifted areas to the west formed an apron of Ogallala sediment across much of the area, but it is not clear how much Gatuña or Ogallala sediment was deposited in the site area. From general reconstruction of Gatuña history in the area (Powers and Holt 1993, ***p.*** 281), the DOE infers that Gatuña or Ogallala deposits likely were not much thicker at the WIPP site than they are now. The loading and unloading spike (Figure 2-~~20~~***25*****)** representing Ogallala thickness probably did not occur. Cutting and headward erosion by the Pecos River has created local relief and unloading by erosion.

At the WIPP site, this history is ***a*** little complicated by dissolution, though locally (for example, Nash Draw) the effects of erosion and dissolution are more significant. The underlying evaporites have responded to foundering of anhydrite in less dense halite beds. These have caused local uplift of the Culebra (as at ERDA 6) but little change in the overburden at the WIPP. Areas east of the WIPP site are likely to have histories similar to that of the site. West of the site, the final unloading is more complicated by dissolution and additional erosion leading to exposure of the Culebra along stretches of the Pecos River Valley.

2.1.5.3 Faulting

Fault zones are well known along the Central Basin Platform, east of WIPP, from extensive drilling for oil and gas, as reported by Hills (1984). Holt and Powers performed~~ a more recent~~ ***an*** analysis in 1988 (***CCA*** Appendix FAC, ***p.*** 4-14) of geophysical logs from oil and gas wells to examine the regional geology for the Rustler. This analysis showed that faults along the margin of the Central Basin Platform displaced Rustler rocks of at least Late Permian age. The overlying Dewey Lake shows marked thinning along the same trend, according to Schiel (1988, Figure 21), but the structure contours of the top of the Dewey Lake are not clearly offset. Schiel ***(1988)*** concluded that the fault was probably reactivated during the Dewey Lake's deposition, but movement ceased at least by the time the Santa Rosa was deposited. No surface displacement or fault has been reported along this trend.

Muehlberger et al. (1978) ~~have ~~mapped Quaternary fault scarps along the Salt Basin graben west of both the Guadalupe and Delaware mountains. These are the nearest known Quaternary faults of tectonic origin to the WIPP. Kelley ~~in ~~***(***1971***)*** inferred the Carlsbad and Barrera faults along the eastern escarpment of the Guadalupe Mountains based mainly on vegetative lineaments. Hayes and Bachman ***(1979)*** reexamined the field evidence for these faults in 1979 and concluded that they were nonexistent. Figure 2-~~21~~***26*** illustrates major regional structures, including faults.

On a national basis, Howard et al. (1971, sheets 1 and 2) assessed the location and potential for activity of young faults. For the region around the WIPP site, Howard et al. (1971, sheet 1) located faults along the western escarpment of the Delaware and Guadalupe mountain trend. These faults were judged to be Late Quaternary (approximately the last 500,000 years) or older.

In summary, there are no known Quaternary or Holocene faults of tectonic origin that offset rocks at the surface nearer to the site than the western escarpment of the Guadalupe Mountains. A significant part of the tilt of basin rocks is attributed to a mid-Miocene to Pliocene uplift trend along the Guadalupe-Sacramento Mountains that is inferred on the basis of High Plains sediments of the Ogallala.

2.1.5.4 Igneous Activity

Within the Delaware Basin, only one feature of igneous origin is known to have formed since the Precambrian. An igneous lamprophyre dike or series of dikes occurs along a linear trace about 120 km (75 mi) long from the Yeso Hills south of White's City to the northeast of the WIPP site

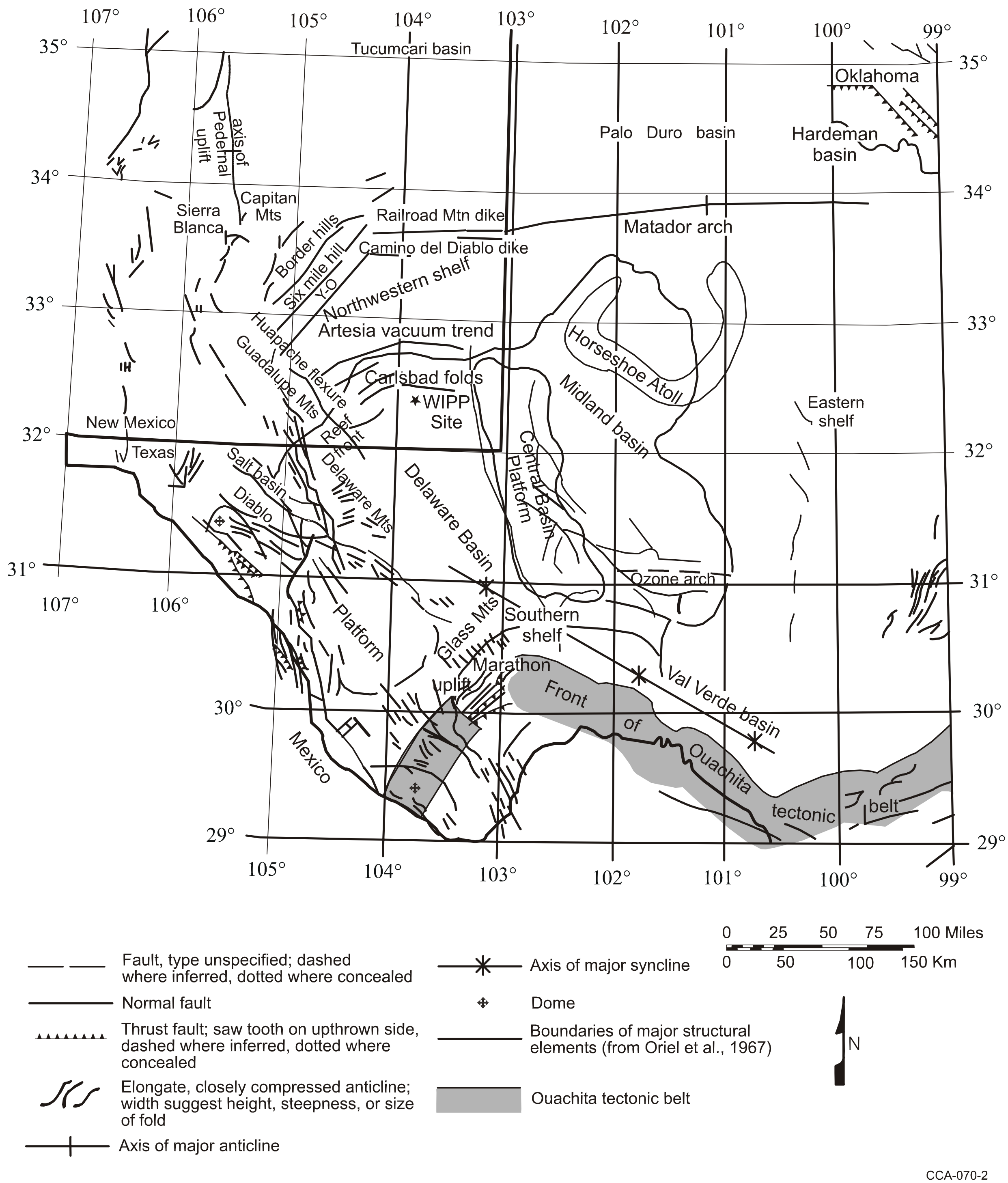


Figure 2-~~21~~*26*. Regional Structures

(Elliot Geophysical Company 1976). At its closest, the dike trend passes about 13 km (8 mi) northwest of the WIPP site center, as shown in Figure 2-~~22~~***27***. Evidence for the extent of the dike includes outcroppings at Yeso Hills, subsurface intercepts in boreholes and mines, and airborne magnetic responses.

An early radiometric determination for the dike by Urry (1936) yielded an age of 30 ± 1.5 million years. ~~More recent~~ ~~w~~***W***ork on dike samples by Calzia and Hiss (1978) is consistent with earl**ier** work, indicating an age of 34.8 ± 0.8 million years.[2] Work by Brookins (1980) on polyhalite samples in contact with the dike indicated an age of about 21.4 million years. Volcanic ashes found in the Gatuña (Section 2.1.3.8) were airborne from distant sources and do not represent volcanic activity at the WIPP site.

2.1.6 Nontectonic Processes and Features

Nontectonic processes and features, which include evaporite deformation and dissolution of strata, are known to be active in the Delaware Basin. These processes are of interest because they represent mechanisms that are potentially disruptive to the repository in the long term. Both processes have been investigated extensively. The conclusions from these investigations are summarized in this section.

Halite in evaporite sequences is relatively plastic, which can lead to the process of deformation; it is also highly soluble, which can lead to the process of dissolution. Both processes (deformation and dissolution) can produce structural features similar to those produced by tectonic processes. The features developed by dissolution and deformation can be distinguished from similar-looking tectonic features where the underlying units do not reflect the same feature as do the evaporites. As an example, the evaporite deformation commonly does not affect the underlying Bell Canyon. Beds underlying areas of dissolved salt are not affected, but overlying units to the surface may be affected. The deformation in the Castile and Salado also tends to die out in overlying units, and the Rustler or the Dewey Lake may show little, if any, effects from deformed evaporites.

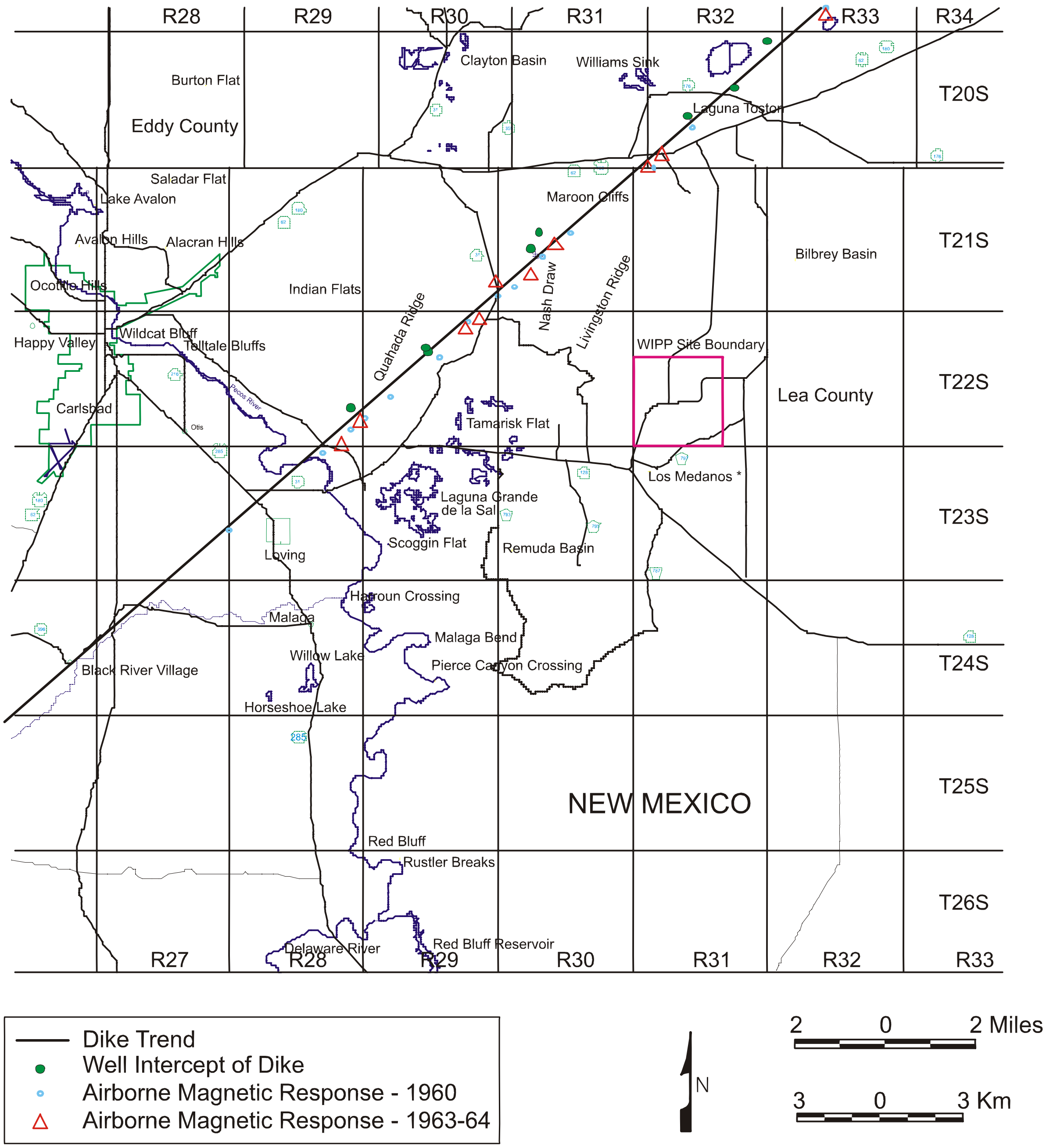
2.1.6.1 Evaporite Deformation

The most recent review of evaporite deformation in the northern Delaware Basin and original work to evaluate deformation is summarized here. More detail is provided in ***CCA*** Appendix DEF.

2.1.6.1.1 Basic WIPP History of Deformation Investigations

The Castile has been known for many years to be deformed in parts of the Delaware Basin, especially along the northern margin. Jones et al. ~~in~~ ***(***1973***)*** clearly showed the Castile to be thicker from the northwestern to northern part of the basin margin, just inside the Capitan ***R***~~r~~eef. A dissertation by Snider (1966, Figures 11 and 14) and a paper by Anderson et al. (1972, Figure 10) also presented maps showing some evidence of thicker sections of Castile next to the

[2] Calzia and Hiss (1978, ***p.*** 44) reported 32.2 to 33.9 million years. However, Powers et al. 1978 (***CCA*** Appendix GCR, ***p.*** 3-80) reported a recalculated value of 34.8 ± 0.8 million years based on a change in measured decay constant.



Source: Elliot (1976)

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Figure 2-~~22~~*27*. Igneous Dike in the Vicinity of the WIPP Site

Capitan. ERDA-6 was drilled during 1975 as part of the program to characterize an initial site for WIPP. The borehole penetrated increasingly deformed beds through the Salado into the Castile, and, at 826 m (2,711 ft) depth, the borehole began to produce pressurized brine and gas. Anderson and Powers (1978, ***p.*** 79) and Jones (1981a) interpreted beds to have been displaced structurally by as much as 289.5 m (950 ft). Some of the lower beds may have pierced overlying beds. The beds were considered too structurally deformed to mine reasonably along single horizons for a repository. Therefore, the site was abandoned in 1975, and the current site was located in 1976 (**CCA** Appendix GCR). The deformed beds around ERDA-6 were considered part of a deformed zone within about 10 km (6 mi) of the inner margin of the Capitan ***R***~~r~~eef. As a consequence, the preliminary selection criteria were revised to prohibit locating a new site within 10 km (6 mi) of the Capitan margin.

General criteria for the present site for the WIPP appeared to be met based on initial data from drilling (ERDA-9) and geophysical surveys. Beginning in 1977, the new site was more intensively characterized through geophysical surveys, including seismic reflection and drilling. Extensive seismic reflection work revealed good reflector quality in the southern part of the site and poor-quality or disturbed reflectors in a sector of the northern part of the site (see ***CCA*** Appendix DEF, Figure DEF-2.2). The area of disturbed reflectors became known as the disturbed zone, the area of anomalous seismic reflectors, or the zone of anomalous seismic reflection data. (The disturbed zone based on poor Castile seismic reflectors is completely different from the DRZ that describes the deformation around mined underground openings at the WIPP.)

Powers et al., in ***CCA*** Appendix GCR, Figures 4.4, 4.5, and 4.6, generally shows the disturbed zone beginning about 1.6 km (1 mi) north of the WIPP site center. Borns et al.~~, in~~ ***(***1983***)***, included two areas south of the WIPP site as showing the same features of the disturbed zone. Neill et al.~~, also in~~ ***(***1983***)***~~,~~ summarized the limits of the disturbed zone based on differing interpretations and included the area less than 1.6 km (1 mi) north of the site center, where the dip in the Castile begins to steepen. WIPP-11 was drilled in early 1978 about 5 km (3 mi) north of the site center over part of the disturbed zone where proprietary petroleum company data had also indicated significant seismic anomalies. The borehole encountered highly deformed beds within the Castile and altered thicknesses of halite units, but no pressurized brine and gas were found.

Less than 1.6 km (1 mi) north of the site center, seismic data indicated possible faulting of the upper Salado and the lower Rustler over the area of steepening Castile dips. Four boreholes (WIPP-18, -19, -21, -22) were drilled into the upper Salado and demonstrated neither faulting nor significant deformation of the Rustler-Salado contact. Lateral changes in the seismic velocity of the upper sections contributed to the interpretation of a possible fault and thus complicate***d*** interpretations of deeper structure.

WIPP-12 was located about 1.6 km (1 mi) north of the center of the site and drilled during 1978 to a depth of 850 m (2,785 ft) in the upper Castile to determine the significance of structure on possible repository horizons. The top of the Castile was encountered at an elevation about 49 m (160 ft) above the same contact in ERDA-9 at the site center.