Geologic Map of the San Patricio Quadrangle, Lincoln County, New Mexico

By

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New Mexico Bureau of Geology and Mineral Resources
Open-file Digital Geologic Map OF-GM 189

Scale 1:24,000

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INTRODUCTION

The Lincoln and San Patricio quadrangles lie between about 10 to 24 miles east of Ruidoso and about 47 to 61 miles west of Roswell, New Mexico on the northeast side of the Sacramento Mountains. Elevations range from 7,039 feet in the west-central part of the Lincoln quadrangle to 4,980 feet near Hondo in the southeast corner of the San Patricio quadrangle, and generally decrease from west to east. Much of the landscape is covered with grass and open woodlands composed of juniper and piñon pine (*Photo 1*). North-covered slopes are commonly more densely vegetated (*Photo 2*). South-facing slopes are less densely vegetated but commonly contain abundant cat claw and different types of small cacti. Local residents say that the landscape used to be much more open, and it has only been within the last 25-30 years that the piñon-juniper has really spread. The U.S Forest Service has recognized this proliferation and in an effort to restore the area to its previous condition has slowly been clearing selected areas by cutting and prescribed burns, one of which occurred during this study in the southwest part of the Lincoln quadrangle north of mile marker 273.

The study area is dominated by two bedrock units, the Yeso Formation and the overlying San Andres Formation, both Permian in age. During and sometime after the Permian both of these formations were folded to different degrees. Probably in the Early Tertiary the Sacramento Mountains were uplifted and tilted gently eastward. As erosion stripped off the formerly overlying and softer Mesozoic formations, the resistant dolomite and limestone layers of the San Andres Formation were exposed and today form the vast majority of surface exposures in the Sacramento Mountains. The overall gentle eastward structural dip of the San Andres Formation is between 1-2° and defines what has become known as the Pecos Slope, because all east-flowing streams in the Sacramento Mountains flow downhill into the Pecos River (*Panorama 1*).

Two streams in particular, Rio Ruidoso and Rio Bonito, which merge to become the Rio Hondo, have dissected about 800 feet down into the Pecos Slope in the Lincoln-Hondo area (both the Rio Ruidoso and Rio Bonito were flowing over their entire length during the course of this study). These streams have a long history of down-cutting that probably began when Mesozoic sediments still overlay the San Andres Formation. Some of the larger tributaries show incised meanders with steep cliff walls and dry cut-off meanders that are perched at elevations higher than the present valley floors. The modern stream valleys are filled with loosely to moderately consolidated alluvial deposits that occur as relatively flat-topped terraces in at least four distinct levels. These terraces record periodic fluctuations in the cycle of deposition and erosion that occur all over the Southwest and are thought to be in part controlled by variations in climate.

The cultural diversity of the region is a mix of mostly Spanish, Mexican, and American heritage. The region is famous/infamous today for the, albeit short, Lincoln County War, and as the stomping grounds of Billy the Kid. The myth that surrounds both originates from the competition to win the contract to provide beef to the Federal Government Army troops stationed at Fort Stanton, a few miles west of the Lincoln Quadrangle. A few of the Ranchers in the area relayed that they had parents or grandparents that were alive at that time and whose ranches have been passed down within the same families to the present (George Sisneros told me that his *father* was born in 1877!).

Those areas on the map that contain less detail because of access restrictions (private property) or lack of time were supplemented with black-and-white aerial photos dated 1936, which have a scale of approximately 1:50,000, and limited color photos dated 1994 with a scale of approximately 1:24,000. For clarity and completeness, structural symbols derived from these photos, as seen on the map, are different from those symbols obtained on the ground (see the map legend). Field work for both the Lincoln and San Patricio quadrangles was carried out between October 2008 and the first week of March, 2009. Very windy conditions were the norm.

Since landscapes in the American Southwest have changed quite dramatically within historic times several photographs and panoramas of different landscape views are included with this report to use as a comparison for future studies (see *Panoramas 2 through 12*). Please note the distortion caused by using a wide angle lens.

PREVIOUS WORK

Bachman (1954) produced a reconnaissance map of the area that was later incorporated into a geologic map and hydrologic report by Mourant (1963) of the water resources in the Hondo drainage basin. Kelly (1971) made some of the first detailed regional geologic and structural maps of the Sacramento Mountains-Pecos slope region, and subdivided the San Andres Formation into three members. Semmes (1920), Talmage (1935), and the Panhandle Geological Society (1939) examined these folds and made conclusions about their origin. Craddock (1960; and 1964) studied these folds in more detail and coined the term ‘Lincoln fold system’. Foley (1964) examined some of the folds near Lincoln and made some conclusions about their possible origin, as did Yuras (1991) on a more regional scale. At least two New Mexico Geological Society field trips have ventured through this area between Ruidoso, Hondo, and Capitan (Ulvog and Thompson, 1964; and Cather et al., 1991). Lucas (1991) made detailed observations and measurements of Triassic strata overlying the San Andres Formation immediately northwest of the Lincoln quadrangle. Rawling (2004a,b) mapped the geology in the neighboring Fort Stanton and Ruidoso Downs 7.5’ quadrangles to the west and southwest, respectively.

YESO FORMATION

The Yeso Formation is not well exposed in the study area. It commonly forms steep, rounded hills along the margins of Rio Ruidoso and Rio Bonito. The Formation consists of interbedded fine-grained quartz sandstone, siltstone, dolomite, and bedded gypsum (*Photos 3 through 6*). Much of the sandstone and siltstone is weakly cemented and erodes easily, causing overlying dolomite beds to founder and crumble. In fact most hills underlain by Yeso Formation are covered with a regolith of jumbled blocks of dolomite, making the measurement of bedding very difficult. Not surprisingly, the best exposures of the Yeso Formation are found in road-cuts along Highway 70, where the striking rusty red color of some of the sandstone and siltstone beds can be seen from miles away (*Photos 7 and 8).*

The difference in color between the red-colored and light pale yellow fine-grained sandstone and siltstone beds is quite striking. The red coloration suggests areas that have undergone oxidation, and it is possible that the pale yellow areas have undergone reduction (no studies have been done to confirm this). As far as can be observed with the available good exposures, both colors remain mostly concordant to bedding, but some are discordant to bedding (not withstanding the smear of colors down-slope due to rain-water). A good example can be seen in the road-cut at the turnoff to Devil's Canyon, about midway between mile markers 274 and 275 (*Photos 5 and 9*). The discordance suggests that the color differences may be a result of diagenesis and were not present during deposition. It is possible that the color difference is the result of oxidation/reduction fronts within groundwater, when the groundwater table was within these deposits.

Bedded gypsum is abundant within the Yeso in some areas. It is characterized by very light gray outcrops that appear banded (*Photos 10 and 11*). The banding is composed of layered and laminated relatively pure gypsum interbedded with gypsum containing darker impurities (of unknown composition). The laminae are commonly wavy and distorted, possibly as a result of differential compaction of these rheologically weak sediments. Beds of gypsum are commonly more strongly deformed than neighboring beds of siltstone or dolomite, even just meters away. Gypsum beds range from less than 1 meter thick to over 10 meters thick. The most convenient location to view gypsum within the Yeso Formation is from Highway 70 between mile markers 275 and 276. From this vantage point looking south, abundant gypsum can be seen in the steep hills on the south side of the valley. If you look closely you can also see a bed of gypsum at a very high elevation (6,000 feet) just below the highest plateau composed of the San Andres Formation.

Some dolomite beds within the Yeso Formation also contain (or used to contain) evaporate minerals. These beds have a characteristic 'porous' appearance, where they contain numerous small subcircular/subsperical randomly distributed holes about 2-5 mm across (*Photo 12*). In places these holes are still filled with what appears to be gypsum (you can scratch it with your finger nail). The porous texture is consistent with the dissolution of gypsum leaving moldic cavities behind.

As mentioned above, the easily erodable nature of the sandstones and siltstones of the Yeso Formation causes a lot of disruption of overlying, much more coherent dolomite beds. Different types of disruption were observed. In *topples*, large platy dolomite beds had been undercut until the large plates toppled over and rotated parallel to the slope. In *slumps*, dolomite beds have slumped and rotated in the opposite direction (becoming steeper into the slope). Still other beds have undergone both of these types of disruption, or have crumbled all together. These types of disruption can be very confusing and misleading because they completely change the attitude of the original bedding, resulting in erroneous measurements. I call this effect the “Yeso Messo”. Great effort was made to identify areas that had not undergone extensive disruption, particularly in steep ravines or at the tops of hills. However, because of the paucity of exposures in some areas it is quite possible that some of the strike-and-dip symbols on the map within the Yeso Formation represent disturbed strata. The reader should therefore use some caution when interpreting this information, particularly in areas where the bedding appears to be chaotic (*Photos 13 through 16*).

It is also quite possible that large areas that appear to contain coherent strata are themselves large slide or slump blocks. Only one very good example of a slump/slide was unambiguously identified in the far southeast corner of the San Patricio quadrangle where a large intact block ¼ of a mile long has dropped down on the north along the confluence of Rio Ruidoso and Rio Bonito. Here, the stratigraphy of Yeso Formation separated from the overlying San Andres Formation by an intervening sill, is preserved all the way across the block. The break along which movement occurred was interpreted to be a fault, but could just as easily be the curved detachment surface of a slump. Note also the scalloped scarp-shaped located immediately south of and uphill of the down-dropped block. Another even more impressive scarp is visible on the south side of Highway 70, between mile markers 275 and 276. It is visible as a small cliff at the very top of the hills, but it resembles a scarp even more so in aerial photos. The feature is very steep and splits into two branches in two places. This is the youngest-looking scarp in the two quadrangles, and its presence suggests that the areas down-slope may be partially slumped and disturbed.

Foley (1964) studied a small area of The Yeso Formation near Lincoln. Based on the jumbled, chaotic nature of folding within some areas of the Yeso Formation here, and the presence of what look like masses of material that have moved downhill, he concluded that at least some of the deformation within the Yeso Formation is a result of large landslides and/or slumps. The aerial photographs of some of the features that he shows in his report, particularly within his Figures 3 and 4, appear very much like large slumps. They exhibit hummocky surfaces and hills that have more-or-less level surfaces perched on top and throughout. These features occur throughout the Lincoln and San Patricio quadrangles all along the courses of the major rivers. They do indeed resemble slump blocks. Bedding within many of these features is indeed chaotic. In others it is relatively consistent. Because of this ambiguity, it is difficult to unilaterally call all of these features slumps, even if they may be such. Foley (1964) pointed out that others have also interpreted these features as slumps or landslides (Roswell Geological Society, 1951; Allen and Kottlowski, 1958). They may be correct. However, it was beyond the scope of this study to examine them in great detail and I will leave a more detailed analysis to a future study.

Because of the folding within the Yeso Formation it is difficult to estimate an exposed overall thickness of the unit. On of the most intact sections, though not one of the better exposed sections, is on the north wall of Gonzales Canyon, SSE of mile marker 276. Here the beds dip consistently to the northwest between about 20 and 40°. The exposed part of the Yeso Formation here is up to about 500 feet thick. There are no other sections of the Yeso Formation in the study area where appreciable thickness can be estimated with any certainty.

Fossils within the Yeso Formation are indistinguishable from those within the San Andres Formation. Common fossils included coiled gastropods and amonoids, elongated conical forms that resemble gastropods, and silicified brachiopod shell debris (*Photos 17 through 21*). Although not fossils, two strange, very large circular forms over 1 meter in diameter are exposed on the west wall of the canyon immediately east of Gonzolas Canyon (south of mile marker 278), less than ¼ mile upstream from the road (*Photos 22 and 23*). The origin of these forms is unknown and resembles some sort of concretion.

GLORIETA SANDSTONE

It was previously recognized that the lower parts of the San Andres Formation in the northeast Sacramento Mountains contain interbeds of pure, clean quartz sandstone (see Kues and Giles, 2004, for an overview). The beds are restricted almost exclusively to the lowermost 200 feet of the San Andres Formation. They are composed of well sorted, subrounded fine quartz grains. Most of the beds show medium to thick beds and rarely are thin-bedded. Small-scale bedding is not easy to see and thicker bedding is best seen from a distance. The unit typically develops a weak to moderate varnish, which gives the layers a darker yellowish to brownish orange color—useful in distinguishing them from the lighter gray colored carbonate beds (*Photo 24*). An almost ubiquitous feature visible on weathered outcrops is innumerable small, subspherical concretions up to about 5 mm in diameter that stand out in relief of weathered surfaces (*Photos 25 through 27*). These concretions are composed of the same fine quartz as the intervening areas but are cemented with coarse calcite spar that is barely visible with the naked eye as ‘flashing’ cleavage planes when rotated in the sunlight. Although no thin-sections were made of these features it appears that the calcite spar may be poikalitic with respect to the quartz grains.

None of the sandstone layers were mapped. Mapping the beds of sandstone within the lower portion of the San Andres Formation is not easily done at the scale of the map (1:24,000). However, even at a larger map scale of 1:10,000 or so mapping these beds would not be easy in all places. Even though in many areas the darker yellow-orange weathering makes them stand out from the limestone beds, in many other areas they appear nearly indistinguishable. Possibly a better way to map these beds would be to use an airborne or satellite-borne thermal infrared mapping spectrometer (TIMS for short). This technique is able to distinguish quite easily between quartz-rich and carbonate rocks and, in theory, should delineate both as markedly different false-colors. In practice, however, the two rock types may ‘blend together’ in places because of the presence of thin colluvium that mantles many of the lower slopes. It may be worth a try though.

The Glorieta Sandstone ‘member’, as shown in the measured section of Craddock (1964) south of Arabela, is not commonly found at the very base of the San Andres Formation, but instead up into the lower portion. The base is commonly comprised of a cliff-forming sequence of dolomite beds that are commonly slightly lighter gray in color than the overlying carbonates. Locally, this lower portion contains moldic porosity (as described above and below). In these two respects this lower portion more so resembles the dolomites in the Yeso Formation than the dolomites within the overlying San Andres Formation.

SAN ANDRES FORMATION

The San Andres Formation is mostly medium- to thick-bedded interbedded light gray dolomite and darker gray limestone (*Photos 28 through 30*). The formation contains minor orange-weathering chert that forms irregularly shaped masses both discordant and concordant to bedding (*Photo 31*). Fossils of brachiopods replaced by chert (*Photo 32*), coiled gastropods (*Photo 33*), and sand-size fossil debris are common. Amonoids, fussilinids, crinoid debris, and horn corals are sparse in this region (*Photos 34 through 38*). Long, thin conical shelled fossils could be a type of gastropod or cephalopod.

The very base of the formation in many places is composed of noticeably darker blue-gray limestone up to about 10 to 15 meters thick that is preferentially intruded by sills. Above this interval, and in areas where the blue-gray limestone is not present, the base of the San Andres Formation is composed of a cliff forming sequence of medium- to thick-bedded dolomite that is commonly lighter gray than the beds above. It commonly contains moldic porosity (*Photo 39*). In these respects this bottom portion of the San Andres Formation appears very similar to dolomite beds within the Yeso Formation. Cather and others (1991) also recognized the similarity and mentioned it within their field trip guide at mile 25.9, p. 32.

Nearly everywhere in the Lincoln quadrangle the San Andres Formation forms well layered outcrops that, from a distance, show very little disruption caused by dissolution or collapse. At the outcrop scale, however, dissolution features are common. Locally, some beds show internal brecciation with angular clasts cemented by lighter colored fine-grained dolomite and calcite (*Photos 40 and 41*). Near-vertical fractures/joints commonly show enlarged solution holes and tunnels (*Photo 42*). Translucent, amber-colored, laminated calcite also fills some fractures and cavities. However, this calcite is minor and its relationship to the opaque fine-grained carbonate cement is unclear. A few caves were noted and marked on the map. Their depths are uncertain. Beautiful circular weathering features are common (*Photo 43*) and small depressions are exploited by some species of cacti (*Photo 44*). Even though small-scale dissolution features are common, the overall medium- to thick-bedded nature of the outcrops suggests that all of the sequence is part of the lower Rio Bonito member of the San Andres Formation. As described by Kelly (1972) the overlying middle Bonney Canyon member is typically thin-bedded and more porous. He recognized this unit throughout both the Lincoln and San Patricio quadrangles, but during the current study the two members could not be distinguished with any confidence.

Very few closed depressions were observed within the San Andres Formation. These features are usually indicative of filled-in sink holes (also called ‘cenotes’), because they don’t usually form in any other way. *Photos 45 and 46* shows a small depression perched on the side of a relatively steep slope in the San Patricio quadrangle about ½ mile northwest of mile marker 281. This feature was not obvious and only identified by accident because the low morning sun created dark shadows within it. This feature is wholly within carbonate rocks of the San Andres Formation and it is difficult to interpret this feature as something other than a sinkhole. Another, slightly larger depression occurs near the northeast boundary of the San Patricio quadrangle on the ridge of a very flat divide (*Photo 47*). The rancher who lives two miles to the northwest said the depression is called Cherry Tree Lake. It appears to be a natural depression, filled with piped-in water. There are also two more natural depressions within the San Andres Formation, in the southeast corner of the Lincoln quadrangle. All together, these were the only four unambiguously identified natural depressions in the study area. As such, dissolution-induced collapse of the carbonate rocks does not appear to have been an important process in this area.

SILLS AND DIKES

All of the intrusive rocks within the map area form fine-grained sills (*Photos 48 and 49)*. No thin-sections were made but all contain plagioclase, biotite, opaques, and dark stubby minerals that appear to be pyroxene. MacKenzie and others (1992, p.133) described this type of rock as a kersantite, a variety of Lamprophyre (see also Cather et al., 1991). Nearly all of them intrude at or very close to the base of the San Andres Formation and are mostly concordant to bedding. Some dikes are visible on the north side of Devils Canyon a little more than one mile upstream from Highway 70. Locally, the very base of the San Andres contains characteristically dark blue-gray, medium-bedded micritic limestone about 10-15 meters thick. The limestone is visible in canyon walls and road-cuts all the way from near Fox Cave, west of the Lincoln Quadrangle, to at least Tinnie. For some reason, in many places the sills preferentially intruded a few meters up from the base, within this sequence of blue-gray limestone, leaving a thin sequence of blue-gray beds commonly 3-5 meters thick below the sills. However, at this scale this layer is not shown on the map. Mourant (1963) also recognized that most of the sills intrude along the contacts between the Yeso Formation, the Hondo Sandstone (renamed the Glorieta Sandstone), and the San Andres Formation.

OLDER SURFACE

The northeast portion of the San Patricio quadrangle is dominated by an area that looks very non-descript in aerial photographs. It is noteworthy because this area in particular appears to lack any obvious bedding in the aerial photos, which sets it apart from most of the rest of the study area. After examining the area on the ground, however, bedding in the carbonate rocks exists but is masked by thin soil cover and a disrupted top surface. This top surface contains abundant lighter pinkish gray carbonate fragments that are in part calcite coatings (rinds) on previously existing fragments of the San Andres Formation. Other fragments are wholly composed of this lighter gray calcite. The lighter gray fragments are commonly associated with a light brown silty soil. View on the ground, this surface is very flat and planar, more so than any other surface in the study area. It is here interpreted as a relict erosion surface, on which a thicker soil at one time developed. Most of that soil has been stripped away leaving the calcite coatings and nodules that likely formed in the Bk horizon formerly 1-2 meters below the old land surface. Subsequent pedogenesis (soil-forming processes) since then have modified this surface, and erosion has cut deep gullies into it.

QUATERNARY DEPOSITS

The Quaternary (Neogene) deposits within the study area display a range of ages. The older deposits are up higher in the landscape, are more deeply dissected, and typically contain better developed soils. The younger deposits are lower in the landscape progressively closer to the valley floors, are less deeply dissected, and contain less developed soils. The different levels that these deposits occupy probably reflect pulses of deposition and relative landscape stability, punctuated by periods of dissection and down-cutting. These cycles are thought to have been driven by changes in the rate of climate change (Mann and Meltzer, 2007, and references therein). The last relatively stable period of deposition during the Holocene is defined by the young deposits that cover the flat valley floors. Throughout much of the Southwest these Holocene deposits have been dissected by young, steep-walled arroyos that began their entrenchment apparently as recently as about 120 years ago.

All of the Quaternary deposits are composed of interbedded gravel, sand, silt, and less abundant clay, cemented to varying degrees. They fill portions of the modern valleys, which means that the current valleys were originally eroded to a greater depth, and have since been back-filled with material. Within the quadrangle they are assigned relative ages, but have also been interpreted to represent, from oldest to youngest, Early Pleistocene (**Qo**), Middle Pleistocene (**Qm**), Late Pleistocene (**Ql**), and Holocene deposits (**Qy**). Although the relative age designations are firm, the absolute age designations (Pleistocene and Holocene) are interpretations based on comparisons with similar deposits in other areas of the Southwest (Gile et al., 1981).

The oldest identified deposits are named **Qo**. These deposits are up high in the landscape (about 60 feet above the modern drainage) and protrude above the **Qm** deposits as low rounded hills. These old deposits are only exposed as small, isolated outcrops on the north side of Rio Ruidoso in the Lincoln quadrangle between mile markers 275 and 277. They are eroded and dissected, and exhibit no remaining constructional surfaces. As a result they contain no remaining soil horizons. Interestingly, these deposits commonly contain abundant large boulders of dolomite and limestone over one meter across. No younger deposits consistently contain clasts this large. The presence of these large boulders suggests that the streams that deposited these deposits had greater transport energy available during deposition of **Qo** deposits. This characteristic has been observed in other **Qo** deposits in the Southwest. These deposits signal the first recognizable change from agradation to erosion and dissection within the valleys.

The **Qm** deposits are widespread and the top surfaces are between about 30 and 50 feet above the level of the modern drainages. Excellent exposures are found all along Rio Ruidoso, in particular within the wide valley between mile markers 274 and 277 (*Photos 50 and 51*). The Bonnell Quarry, which sits on one such terrace immediately east of the turn off to Devil's Canyon, is mining the sand and gravel from these deposits. Because the **Qm** deposits are commonly deeply dissected and cut by numerous road-cuts, they display a variety of textures. In many outcrops exposed along the immediately along Rio Ruidoso, the base of the deposits is occupied by far-traveled river-gravel deposits composed of rounded pebbles to cobbles of coarse-grained feldspar porphyry, fine-grained greenish sandstone, purple to dark gray plagioclase-bearing and plag+hornblende-bearing andesites, and quartz dioritic intrusive rocks that appear very similar to the rocks in the local sills. These far-traveled rocks originated from far upstream in the Sierra Blanca region (*Photos 52 through 54*). They are typically slightly darker colored than the deposits above them which were deposited by local streams and are dominated by more angular carbonate clasts (*Photo 55*). **Qm** deposits also contain a lot of light pink silt, interpreted as lower-energy sheet wash deposited on formerly gently sloping valley floors. In a few places it is apparent that these deposits were partly eroded and then backfilled with more alluvium (*Photo 56*). Some stream-cuts show evidence of older soils buried by younger ones (*Photo 57*). Downstream, on the north side of San Patricio, **Qm** deposits cap outcrops of the Yeso Formation. Gullies have dissected both leaving the younger deposits as isolated caps to the hills (*Photo 58 and Panorama 13*). These hill-capping deposits are all at very similar elevations with respect to one another. Viewed from a distance (*Panorama 14*) it is apparent that these are the remnants of an older, once-continuous surface that existed when the river bed was 40-50 feet higher than it is today. Where exposed **Qm** deposits typically contain very well developed dark brown organic-rich surface soils overlying material strongly cemented by pedogenic carbonate (*Photo 50*). In the very southwest corner of the Lincoln quadrangle exposed in the south road-cut just east of mile marker 270 is a near-vertical contact between San Andres Formation carbonate and what is mapped as **Qm** (*Photo 59*). This may represent an old abandoned river meander that was subsequently filled with alluvium.

Deposits labeled **Ql** occur at elevations between about 20-30 feet above the level of the modern drainages. They were mostly mapped in the San Patricio quadrangle along Rio Ruidoso. Along the river in the western parts of the quadrangle it is quite clear that **Qm** and **Ql** deposits form two separate and mappable terrace levels. Downstream toward Hondo, however, there is mostly only one terrace level. Because the terrace level near Hondo is much closer to the modern stream than are the **Qm** deposits elsewhere, these deposits were mapped as **Ql**. These deposits also contain gravel, sand, silt, and minor clay, but their soil zones are not as well developed and they do not contain as much calcium carbonate cement (*Photo 60*).

Most widespread of all the Quaternary deposits are the Holocene deposits. These form the relatively flat valley floors. Upon closer examination, some of these deposits are actually composed of two and locally three different terrace levels, which were not mapped separately. These deposits are composed of fine and coarse unconsolidated materials from silt to cobbles and locally boulders closer to the mountain fronts. The most obvious feature of the **Qy** deposits is a flat valley floor dominated by silty deposits

(*Photos 61 through 63*). Even **Qy** deposits within smaller drainages that emanate from bedrock composed of nothing but carbonate of the San Andres Formation contain abundant silt. There are two obvious potential sources of this silt: (1) it could have originated from the insoluble residue left behind during dissolution of the carbonate rocks over time (although one would expect to find more clay, and less silt), and (2) it may have been imported and dropped upon the landscape as wind-blown loess, then subsequently redistributed. The second explanation seems more likely. **Qy** deposits are dissected almost everywhere by narrow, steep-walled arroyos immediately bordering the modern streams. In places, these steep-walled arroyos also reveal the presence of older soils buried by younger ones, indicating a period of surface stability followed by a period of renewed deposition. In other parts of the Southwest this fluctuation has been interpreted to be the result of long-term changes in climate. Deposits in the drainages near the northern edge of both quadrangles contain a large amount of sand, gravel, and boulders composed of very fine-grained hypabyssal granite shed from the high-standing Capitan Mountains (see Allen and Foord, 1991, for a description of the Capitan Mountain intrusive). Even so, their upper surfaces are silty and very similar to deposits containing dominantly limestone clasts. An example of a soil developed on granitic material in Pierce Canyon is shown in *Photo 64*.

PERCHED MEANDERS

Along three of the major tributaries in the area (Vorwerk Canyon, Las Chosas Canyon, and Chavez Canyon) are what are here called ‘perched meanders’. These features are old river meanders originally created by the flowing creeks that were incised into the San Andres bedrock when the creeks flowed through them. The creek beds subsequently abandoned them and these meanders were left high and dry up to 40 feet or more above the level of the modern creek bed (hence the use of the word “perched”). Four of these features were recognized and are marked on the map with an asterisk. All of them are located within the San Patricio quadrangle. Three of these perched meanders are floored by sediment. The fourth has been dissected but its alcove shape is still visible. Unfortunately, none of these features was visited during field work due to access limitations (private property).

These perched meanders are significant, especially the three that contain sedimentary deposits, because they potentially contain fragments of plants, animals, pollen, etc., that have been separated from the modern creek and preserved probably for at least several tens of thousands of years. The deposits are labeled as **Qm** on the map because of their position high in the landscape, but their exact age is uncertain. There are also at least three other abandoned meanders visible along Chavez Canyon that appear to be approximately the same age as the modern creek bed. They each contain small islands of limestone bedrock surrounded by what appears to be Holocene alluvial deposits. This relationship suggests that the meanders were incised then abandoned as the creeks cut through them and downward. Both the active channel and the meander were later back-filled with sediment probably in response to changes in climate.

POSSIBLE IMPACT CRATER

In the southeast corner of the Lincoln quadrangle, within the canyon immediately east of Gonzales Canyon, is a small circular depression that looks very much like an impact crater. The depression is nearly circular, and bowl-shaped, is 23 feet across and about 4 feet deep in the center (*Photos 65 and 66*). Its edges are sharp and nearly vertical and are surrounded by a low mound of material forming an apron arround the north half of the bowl. The depression is surrounded by silty Quaternary alluvial deposits in all directions, but the mound is composed of broken and shattered pieces of red and yellow siltstone, and minor gray limestone, all of which represent the Yeso Formation. The nearest exposures of Yeso Formation are a couple hundred feet to the south, and there is no Yeso Formation exposed in the depression itself. In this respect the low mound of material around the northern rim resembles material ejected from the crater during the impact of a meteor—'impact ejecta'. The impact itself would have excavated material from beneath the crater and, therefore, if this was an impact, the Yeso Formation is likely very close to the surface (not much greater than about 4 feet below the surface). Impact craters are commonly nearly circular, even when the impacting body hits the surface at an angle. The presence of possible impact ejecta only on the north side, however, suggests that the meteor may have approached from the south.

An alternative explanation is that this is a man-made crater created by some type of explosive. There is no other evidence for or against this possibility. Samples of consolidated siltstone from the mound were sent to a laboratory. If shocked quartz is present then the impact hypothesis is more reasonable. The age of the feature is not known, but can be constrained. The sharp vertical walls in Quaternary silt suggest it is relatively young. A full-size juniper and a 7-foot-tall piñon are growing on the mound on the north side, so the feature is older than a few years. There is a very faint old dirt road visible a few hundred meters to the east where it passes through an old wood and barbed-wire gate. The crater appears to overlap part of this old road, and if so it is younger that about 150 years (?). Ruben Chavez, who has lived near the mouth of the canyon all of his life, said the crater has been there for at least ten years.

STRUCTURE

Folds in the Yeso Formation

The Yeso Formation contains abundant, relatively tight folds with wavelengths typically a few hundred feet across (*Photos 67 through 69 and Panorama 15*). The scale of the map is a limitation to understanding the structure within the Yeso Formation. Even with the abundant attitude symbols on the map, these do not adequately portray all of the smaller, tighter folds within the Yeso Formation. A larger-scale map of at least 1:10,000 scale is more appropriate. Where discernable, the fold axes are drawn on the map. As discussed above, many areas appear chaotic, which may be the result of slumping and/or toppling. As Craddock (1960, 1964) discovered, however, there are areas where many fold axes are roughly parallel to one another. Three areas in particular where this parallelism can be seen are along the north side of Devil's canyon between about 1-2 miles upstream from Highway 70, in the road-cuts immediately north of San Patricio, and on the north side of Rio Bonito north of Lincoln itself. In these areas the dominant trend of the axial planes is northeast-southwest—roughly parallel with the fold axes in the overlying San Andres Formation in these same areas. In other areas the fold axes appear to diverge from this orientation by as much as 90°. In some of these areas beds that have a NE-SW strike can be followed across the surface as they bend into a NW-SE orientation, so at least in these areas slumping is not a valid explanation for the origin of all the folds.

So what caused the folding in the Yeso Formation? Quite a few workers have worked on this problem for a long time. Craddock (1964) listed some of the hypotheses that could have possibly been mechanisms, but, as he stated, they don't seem very likely. These include: (1) Intra-Permian deformation, (2) movements on basement faults, (3) the emplacement of the Capitan Mountains pluton, (4) drag effects created by formation of the Mescalero Arch, (5) tilting of the Sacramento Mountain block, (6) volume changes during the recrystallization of evaporates (presumably gypsum to anhydrite?), (7) surface subsidence as a result of subsurface evaporite dissolution, (8) landsliding, and (9) injection of sills. Other possible hypotheses that also don't seem very likely include salt diapirism, bolide impact, meg-tsunami, or seismically-induced foundering of water-saturated deposits.

An important result of this study is the observation that the contact between the Yeso Formation and the overlying San Andres Formation appears to be an erosional unconformity. Craddock (1964) was able to observe the contact in 37 places and concluded that the folds in the Yeso Formation die out up-section and that the contact is conformable. During the current study the contact was obscured almost everywhere by debris shed from the San Andres Formation, and in only a very few places was it visible enough to make any firm conclusions about its nature. One outstanding exposure occurs within the bottom of a creek bed in the west-central part of the Lincoln quadrangle on the west side of Section 15, T. 10 S., R. 15 E. (see Locality 1 marked on the map). Here the creek has cut down through the contact, revealing a clean cliff-face showing steeply dipping dolomite beds of the Yeso Formation directly overlain by nearly horizontal dolomite beds of the San Andres Formation (*Figure 1*). It certainly appears that the Yeso Formation beds are truncated by the contact, leading to the conclusion that the contact represents an angular unconformity. Another location where the contact is *nearly* exposed is also within the Lincoln quadrangle just over 1 mile north of mile marker 276 (see Locality 2 marked on the map and *Figure 2*). Here dolomite beds of the Yeso Formation dip moderately and appear to be truncated by dolomite beds of the San Andres Formation. Another locality (Locality 3) less than ¼ mile northwest of mile marker 278 shows gently folded San Andres Formation beds over more strongly folded beds of the Yeso Formation (*Figure 3*). Locality 4 (*Figure 4*) also shows an angular relationship between beds in both formations.

Many interpretations for the origin of the Lincoln folds have been based on the assumption that the folds in the Yeso Formation were created at the same time as and are related to the folds in the overlying San Andres Formation. If the contact indeed represents an unconformity, then the folds in the Yeso Formation are older than those in the San Andres Formation. The apparent truncation of the folds also indicates that there was a period of erosion that occurred after folding that lasted long enough to create a relatively flat, beveled plain. The problem with this interpretation is the observation that the lowermost dolomite beds of the San Andres Formation locally contain gypsum and/or moldic porosity, and look nearly identical to beds within the Yeso Formation. They therefore likely had the same depositional environment, which has been interpreted to be marginal marine/sabkha (Mack and Dinterman, 2002; Kues and Giles, 2004). Thus, the presence of an unconformity invokes the strange sequence of events where marginal marine sediments are deposited near sea level, then folded and probably uplifted in the process, partly eroded, and then brought back down to near sea level where they were subsequently overlain by sediments deposited in a very similar depositional environment. This might partly be explained by the following scenario: as Pangea was being assembled in the Permian, an oceanic plateau collided with this part of North America, crumpling the Yeso Formation and possibly older strata as well. This collision was followed by a lull in tectonism during which time the folded Yeso Formation was partly eroded, and the San Andres Formation was deposited. This period was then followed by the main collision of Gondwana which produced the deformation in the San Andres Formation. Some small-scale compressional features in the Yeso Formation are shown in *Photos 70 through 72*.

Folds in the San Andres Formation

The north half of the Lincoln quadrangle contains a structural divide known as the Mescalero arch (Kelly and Thompson, 1964; Kelly, 1971, also called it the 'Lincoln anticline'). To the west of the arch strata dip gently westward into the Sierra Blanca basin, a deep depositional basin that was an active sedimentary trap through the Mesozoic and into the Early Tertiary. East of the arch the strata dip gently to the east. The arch here is also a topographic divide. Streams radiate from the topographically highest point in this area in a radial pattern. At first glance, it appeared that the bedding also radiated away from this point, but more careful observations show the bedding to strike mostly northeast-southwest. The apparent dome, however, led Yates Petroleum Company to drill an oil exploration well here to a depth of 2,800 feet. The well showed no oil, possibly because the feature is not a full structural dome trap, but it did provide some valuable information about the types and the thicknesses of formations at depth (see cross-sections).

East of the Mescalero arch the structure within the San Andres Formation is dominated by an overall very gentle dip to the southeast. Superimposed on this regional dip is a series of gentle folds, most of which have axes trending northeast-southwest (*Photo 73*). Bedding within the limbs of some of these folds dips as much as 15-20°, though dips between 2-10° are more common. There are exceptions. Within the study area are at least three folds that appear as sharp kinks, or 'buckles' (a term widely used by previous researchers) (*Photos 74 and 75*). About 1.5 miles downstream from San Patricio is a narrow band of closely spaced folds and two near-vertical kinks (*Photo 76 and Panoramas 16 and 17*). Although this fold-band is most visible immediately north of Highway 70 it also continues south across Rio Ruidoso and north to the northern side of Rio Bonito. This corresponds to mile 26.4 on p. 32 of Cather and others (1991). The near-vertical kink was given the name White Tail buckle by Kelly (1971). The style of folding changes quite dramatically along this trend. North of Rio Bonito, almost exactly 1 mile north of mile marker 106, bedding is locally overturned in a large, east-vergent kink fold (*Panoramas 18 and 19 and Figure 5*). Although his large kink occupies a large part of the several-hundred-feet-high steep slope face, it is nearly invisible due to the fact that all of the carbonate beds weather very similarly, and because jointing has overprinted and masked much of the bedding. Further north this kink opens up and within a mile it becomes a steep syncline. Although Kelly (1971) inferred right-lateral strike-slip movement on this fold, nowhere was evidence seen for strike-slip motion.

Although the bedding bends up and down across the San Patricio quadrangle, in general it decreases in elevation southeastward until it reaches the syncline that crosses the middle of the map between mile markers 102 and 103, along Rio Bonito (*Panoramas 20 and 21*). East of this syncline the elevation of the strata gradually rises to the east side of the quadrangle and beyond. Near the east side of the San Patricio quadrangle the regional northeast-southwest strike of bedding is diverted into a more north-south orientation. Here, and immediately east of the quadrangle, a series of steep synclines and anticlines, known as the Tinnie forld belt (or the Tinnie-Dunken anticlinorium), causes the bedding to climb higher and higher in elevation, culminating in a dramatic drop-off with near-vertical bedding on the west side of the Tinnie fold belt (*Photo 77*). The Tinnie fold belt extends for over 60 miles, striking more-or-less north-south until it bends slightly to the northwest as it strikes through the northeastern corner of the quadrangle (Kelly, 1971; Bowsher, 1991, p. 86). Here, as in other areas, the fold belt is comprised of a series of closely spaced parallel folds, several of which have very steep and vertical limbs. Within the northeast corner of the San Patricio quadrangle the structural relief across the major kink fold is not known, as there are no obvious stratigraphic marker beds or horizons (*Photo 78*). Kelly (1971, p. 42) shows a nice aerial photograph of part of the Tinnie fold belt immediately east of the San Patricio quadrangle.

As mentioned above, the strike of the bedding within the San Andres Formation is mostly northeast-southwest. The southwest corner of the Lincoln quadrangle is a notable exception. Here, on the north side of highway 70 the bedding strikes northwest and dips to the southwest. The strike bends south and west into a more north-south orientation, and even strikes southwestward in the very southwest corner of the map. The west-dipping beds in this region take the San Andres Formation below the level of the Rio Ruidoso creek bed into the subsurface, causing the Yeso Formation to pinch out near the mouth of Silva Canyon. The canyon of Rio Ruidoso is narrower here and upstream, as a result, for about two miles, past Fox Cave, where an eastward dip of the San Andres Formation brings the Yeso Formation to the surface and the canyon again opens up and widens into Ruidoso Downs.

Because the Yeso/San Andres contact occurs at approximately the same elevation on opposite sides of some of the ‘buckles’, Craddock (1964) concluded that these anticlinal structures are the result of horizontal displacement. Kelly (1971) also surmised that these features are the result, in part, of strike-slip motion. The elevation of the contact alone, however, is not sufficient evidence upon which to draw that conclusion. The sharp folds in the San Patricio quadrangle displace the contact to markedly different elevations on opposite sides of the folds. None of these structures show any obvious evidence for strike-slip displacement. Aeromagnetic data (unpublished, from Inland gas Corp.), however, show some interesting patterns that suggests the possibility of right-lateral strike-slip motion in the Precambrian basement. If correct, this interpretation is at least consistent with the interpretation of strike-slip movement within Precambrian basement in other parts of the state (Karlstrom et al., 2004). Bowsher (1991) also examined aeromagnetic data of the area (from Cordell, 1983), but the data appear to show northwest-striking lineations that are nearly at right angles to the trend of the buckles exposed at the surface.

Because this study now provides a little bit better resolution of the structure in the area, it should be kept in mind by future workers that any in-depth structural study of the Yeso Formation should 'subtract out' the folding in the overlying San Andres Formation. This is particularly important in light of the interpretation that the contact between the two formations represents an unconformity. The Yeso Formation beds may not have slid along decolements bounded by the San Andres and underlying formations, but may have folded independently. Therefore, in areas where the dips in the San Andres Formation are particularly steep these steep dips should be subtracted from the dips in the Yeso Formation beds directly below in order to obtain the true original dip if the Yeso Formation beds.

Faults

In the southeastern corner of the quadrangle, near Hondo and a few miles northwest along the Rio Bonito between mile markers 107 and 285, several small faults were mapped. These structures are somewhat enigmatic in that most of them are very difficult to identify unambiguously as faults. The fault southwest of Hondo clearly cuts the stratigraphy and down-drops and rotates massive carbonate beds of the San Andres Formation down-to-the-north against red beds of the Yeso Formation. The other faults were first identified by very regular lineaments projecting across the landscape defined by grass-covered linear troughs. The tall grass within these troughs is for some reason thicker than the grass in surrounding areas (*Photo 79*). Closer examination revealed sharp breaks in bedding within the San Andres, exhibited by small cliffs several meters high and sharp changes in bedding attitudes. Where offset was observable all displacement appears to be normal (as opposed to reverse). The observation that all of these structures strike northwest-southeast, parallel to the river valleys, suggests a connection. Could these be related to incipient slumps along the steep margins of the valleys? About 1 ½ miles southwest of Hondo (near the communications tower, nearly south of mile marker 285) the small fault mapped there is notable because it appears to be rootless (*Photo 80*). Some apparent displacement is visible up higher near the top of the ridge, but lower down no displacement of the thick carbonate beds is visible. Could this and the other faults be related to cavern collapse? Small-scale dissolution features are widespread, but no extensive cavern-filling collapse breccias (or 'break-down breccias' as they are commonly called) are in evidence.

Kelly (1971, plate 1) shows two small northwest-striking faults crossing the Rio Ruidoso near Glencoe. No obvious offset was seen in the exposures here. Similarly, in the areas where the two small northeast-striking faults are shown, slightly to the north on his plate 1, no obvious offsets were seen here either. The northeast-trending fault north of Lincoln projects northeast-southwest through Priest Canyon. A sill wraps around topography in this canyon without showing any obvious displacement.

SUB-SURFACE INFORMATION

There are no rocks older than the Yeso Formation exposed within the study area. The Yeso Formation is strongly deformed and it is therefore difficult to estimate the thickness of this unit. Only two boreholes have been drilled in the study area, both of which are in the central part of the Lincoln quadrangle (*Table 1*). As mentioned above, he Muñoz Canyon AAN Fed. No. 1 well was drilled on what appeared to be a dome, on the Mescalero Arch at the head of Muñoz Canyon. This well was drilled to a depth of 2,800 feet. Another well, the Nosker 1-Y well, was supposedly drilled near the highway near Glencoe (near the meat seller; James Brannigan personal communication), but the cadastral location places it far from there and may be inaccurate. This information was obtained from the New Mexico Energy Library in Roswell, New Mexico. The thickness of the Yeso Formation and of underlying formations was estimated from these two wells and extrapolated eastward towards boreholes drilled east of the San Patricio quadrangle. Since the mechanism that created the tight folds within the Yeso Formation is still not clear, the extent to which pre-Yeso formations are deformed (if indeed they are) is also uncertain. As a result, all of the formations in the subsurface are shown as relatively undeformed layers, as other researches have done. This is probably an oversimplification, but it is better to keep things simple than to invoke a complex structure where it is not understood. Based on the cross-section interpretation the greatest thickness of the San Andres Formation is about 800 feet. Based on the log of the Muñoz Canyon AAN Fed. No. 1 well the Yeso Formation is 1,685 feet thick, and the Abo Formation is 370 feet thick. Precambrian bedrock was encountered at a depth of 2,480 feet below the surface.

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UNIT DESCRIPTIONS

Quaternary Deposits

Qy **Holocene alluvial deposits.** These deposits were mapped separately from the remainder of the Quaternary surficial deposits because they are relatively easy to identify and are important because these are areas that may be prone to flooding. They are composed of weakly consolidated interbedded gravel, silt, and clay. They commonly form relatively flat deposits at the bottom of the wider drainages. They characteristically contain abundant dark, organic- and clay-rich soils at the surface. The deposits are commonly incised up to about 2-3 meters by the modern drainages, where vertical faces locally show older soil horizons. As mapped, this unit locally contains at least two and possibly more terrace levels that might be mappable with larger-scale aerial photos.

Qy_1 **Holocene alluvial deposits, older member.** This subdivision of **Qy** was mapped separately only in areas along the major rivers where it was obvious that it formed an older deposit higher in the landscape. The Hurd Gallery in San Patricio rests close to the edge of one such terrace where it sits elevated from the lower **Qy** terrace by about 2-3 meters. Where exposed in road-cuts, these deposits are composed of interbedded silt and gravel. The top surface is mostly covered with fine silt.

Qp **Playa deposits.** Mostly weakly consolidated silt and clay. This unit is fills two natural depressions in the southeast corner of the Lincoln quadrangle and one in the northeast corner of the San Patricio quadrangle. The depression in the San Patricio quadrangle has the name 'Cherry Tree Lake', according to James McDaniels who lives about two miles to the northwest of the lake.

Ql **Late Pleistocene alluvial deposits.** Interbedded silt, fine sand, and gravel. Exposed in some road and stream-cuts not far from the confluence of Rio Ruidoso and Rio Bonito. These deposits contain interbedded silt and locally derived gravel, but are less cemented than the **Qm** deposits and typically contain weakly developed pedogenic carbonate horizons. A good exposure is on the north side of Hondo. These deposits form flat constructional surfaces that reside about 20 feet above the Holocene deposits (**Qy**).

Qm **Middle Pleistocene alluvial deposits.** Interbedded silt, fine sand, and gravel. Good exposures are found in the Highway 70 road-cuts which show abundant tan silt interbedded with coarse subangular to subrounded gravel and small boulders. The lower portions near the large rivers commonly contain rounded river deposits up to about 1-2 meters thick, overlain by silt and carbonate-clast alluvial deposits. Some exposures show multiple soil zones, some of which are moderately cemented by pedogenic carbonate. These deposits form flat constructional surfaces that reside about 40 feet above the Late Pleistocene deposits (**Ql**).

Qo **Early Pleistocene alluvial deposits.** Coarse conglomerate containing clasts up to large boulders 1-2 meters across. Forms a few small rounded dissected remnants in the

Lincoln quadrangle. No soil zones remain. Poorly exposed, and typically strongly cemented by calcium carbonate.

Tertiary Intrusive Rocks

Ti Intrusive rock (Tertiary?). The textures of all sills in the area are all very similarly fine- to medium-grained. All contain plagioclase, biotite, opaques, and dark stubby minerals that appear to be pyroxene. MacKenzie and others (1992, p.133) described this type of rock as a kersantite, a variety of Lamprophyre (see also Cather et al., 1991). Nearly all of them intrude at or very close to the base of the San Andres Formation and are mostly concordant to bedding. These rocks typically weather into small spheroidal boulders and fine sand. The thickness of these sills is typically from several feet up to about 60 feet, though locally exceeds 150 feet.

Paleozoic Rocks

Ps San Andres Formation (Permian). Medium- to thick-bedded dolomite and limestone. Dolomite beds are typically light gray-colored, whereas limestone beds are commonly darker gray. Many beds contain sand-sized broken fossil debris surrounded by a matrix composed of micrite and more commonly microspar. Some beds contain faint, parallel laminae parallel to bedding. Other beds are massive and appear bioturbated. Orange-weathering chert is minor but widespread and is composed of granular microcrystalline quartz. The chert commonly forms irregularly shaped masses up to several tens of centimeters across that is both discordant and concordant to bedding. Common larger fossils include coiled gastropods up to about 5 cm across and less abundant nautiloids up to about 10 cm. Smaller recognizable fossils include crinoid stem segments, disarticulated brachiopods (commonly up to 2 cm and replaced by chert), and sparse fussilinids. The carbonate beds are interbedded with well sorted, fine- to medium-grained quartz sandstone from 1-10 meters thick, which probably represent intertonguing Glorietta Sandstone. The sandstone beds occur throughout the interval of the San Andres Formation, but are most common and thicker in within a few hundred feet of the base. Sandstone beds typically weather light orange to brown and in most outcrops contain abundant calcite-cemented BB-size concretions up to 2-3 mm across. Maximum thickness in cross-section is about 800 feet.

Py Yeso Formation (Permian). Interbedded fine-grained quartz sandstone, siltstone, dolomite, and bedded gypsum. Siltstone is commonly rusty red and pale yellow. Dolomite beds are locally fossiliferous and contain silicified brachiopod and crinoid fragments, abundant coiled gastropods, aminods, and possibly cephalopods. Dolomite beds locally contain moldic porosity with some pores still filled with gypsum. Gypsum beds are typically sub-horizontally banded and are locally thicker than 10 meters. Exposures are poor and typically mantled by regolith. The thickness obtained from the log of the Muñoz Canyon AAN Fed. No.1 well is 1,685 feet.

Pa Abo Formation (Permian). Shown only in the cross-sections. The thickness obtained from the log of the Muñoz Canyon AAN Fed. No.1 well is 370 feet.