Prepared in cooperation with the Colorado Water Conservation Board

Hydrostratigraphic Framework of the Raton, Vermejo, and Trinidad Aquifers in the Raton Basin, Las Animas County, Colorado

Scientific Investigations Report 2006–5129

U.S. Department of the Interior
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DIRK KEMPTHORNE, Secretary

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Conversion Factors

Inch/Pound to International System

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Energy (natural gas)[1]	
cubic foot (ft^3)	1,027	British thermal unit (Btu)
cubic foot (ft^3)	0.01	therm (approximate)
thousand cubic feet (Mcf)	1	dekatherm (10 therms)

[1]American Gas Association (2006).

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Hydrostratigraphic Framework of the Raton, Vermejo, and Trinidad Aquifers in the Raton Basin, Las Animas County, Colorado

By Kenneth R. Watts

Abstract

Exploration for and production of coalbed methane has increased substantially in the Rocky Mountain region of the United States since the 1990s. During 1999–2004, annual production of natural gas (coalbed methane) from the Raton Basin in Las Animas County, Colorado, increased from 28,129,515 to 80,224,130 thousand cubic feet, and the annual volume of ground water coproduced by coalbed methane wells increased from about 949 million gallons to about 2,879 million gallons. Better definition of the hydrostratigraphic framework of the Raton, Vermejo, and Trinidad aquifers in the Raton Basin of southern Colorado is needed to evaluate the long-term effects of coalbed methane development on the availability and sustainability of ground-water resources.

In 2001, the U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, began a study to evaluate the hydrogeology of the Raton Basin in Huerfano and Las Animas Counties, Colorado. Geostatistical methods were used to map the altitude of and depths to the bottoms and tops (structure) and the apparent thicknesses of the Trinidad Sandstone, the Vermejo Formation, and the Raton Formation in Las Animas County, based on completion reports and drillers' logs from about 1,400 coalbed methane wells in the Raton Basin. There was not enough subsurface control to map the structural surfaces and apparent thicknesses of the aquifers in Huerfano County. Geostatistical methods also were used to map the regional water table in the northern part of Las Animas County, based on reported depth to water from completion reports of water-supply wells. Although these maps were developed to better define the hydrostratigraphic framework, they also can be used to determine the contributing aquifer(s) of existing water wells and to estimate drilling depths of proposed water wells. These maps of the hydrostratigraphic framework could be improved with the addition of measured sections and mapping of geologic contacts at outcrops along the eastern and western margins of the Raton Basin.

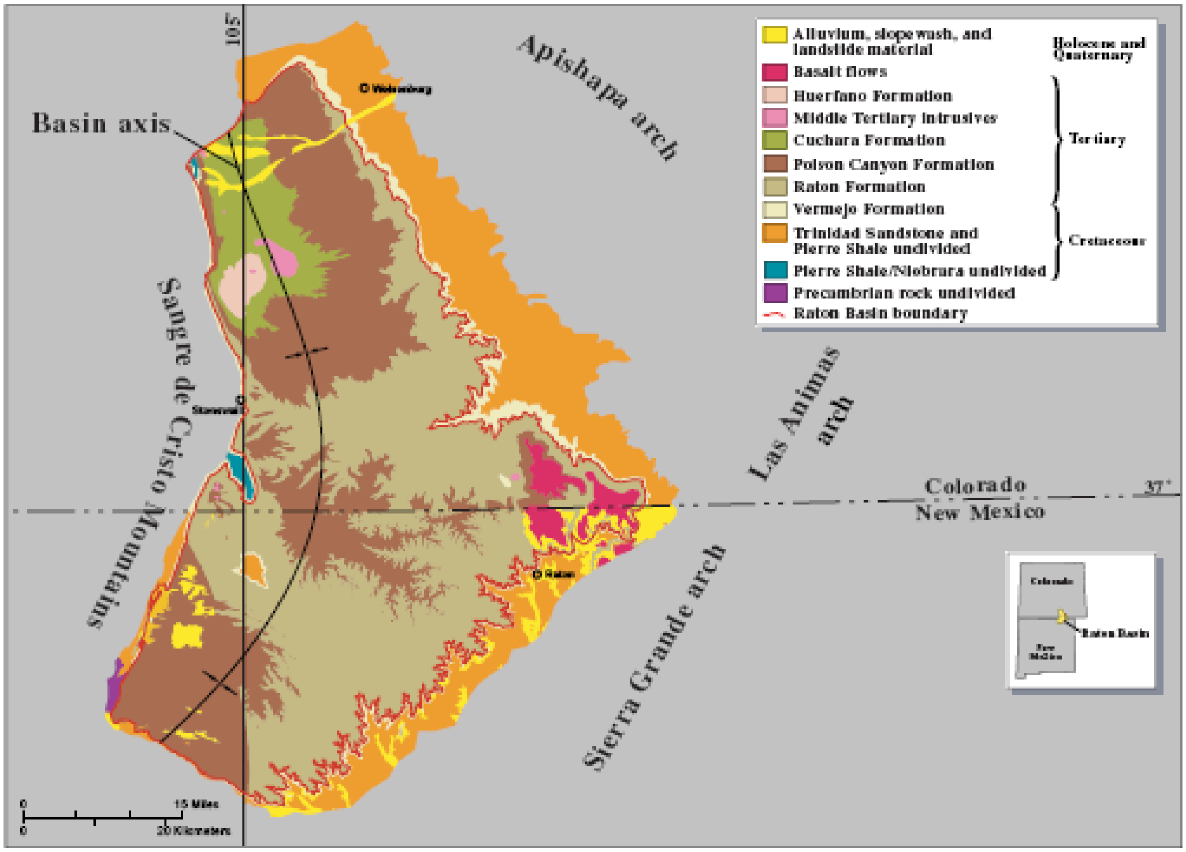
Introduction

Exploration for and production of coalbed methane (CBM) has increased substantially in the Rocky Mountain region of the United States since the 1990s. Where coalbeds also are aquifers, the reduction in hydrostatic pressure needed to produce methane may have unintended consequences, including reduction of water levels in nearby water-supply wells and mining of ground water. CBM production from the Raton Basin in Huerfano and Las Animas Counties, Colorado (fig. 1), has increased substantially since 1999. Production of natural gas (coalbed methane) from coals in the Vermejo and Raton Formations in Las Animas County increased almost threefold during 1999–2004, from 28,129,515 thousand cubic feet (Mcf) during 1999 to 80,224,130 Mcf during 2004 (Colorado Oil and Gas Conservation Commission, variously dated). The volume of ground water coproduced by CBM wells in Las Animas County during 1999–2004 also increased about threefold, from 22,597,972 barrels (about 949 million gallons) during 1999 to 68,557,832 barrels (about 2,879 million gallons) during 2004.

Because domestic and livestock water-supply wells are completed in coal beds and associated sandstones in the Raton Basin, water-well owners and resource managers are concerned that CBM production locally may affect ground-water availability and sustainability. As a result of these concerns, the U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, began a study in 2001 to evaluate the hydrogeology in the Raton Basin of Colorado. A better understanding of the hydrostratigraphic framework, including the external geometry (structure and thicknesses), the internal geometry (heterogeneity), discharge and recharge conditions, and ground-water levels and fluid pressures in the principal hydrostratigraphic units, is needed to evaluate the potential effects of CBM production on ground-water availability and sustainability.

Previous studies of the hydrostratigraphic framework of the Raton Basin (Abbott and others, 1983; Geldon, 1989) were limited because of the paucity of subsurface data. Subsurface

A



(Geology from Flores and Bader, 1999, their figure SR–1)

B

Base from U.S. Geological Survey County Map Series, 1979, 1:50,000
Albers Equal-Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian105°30'W

Figure 1. (*A*) Generalized geologic map of the Raton Basin, Colorado and New Mexico and (*B*) location of the study area and the Raton Basin in Colorado.

data, available from logs and completion reports of CBM wells that have been drilled since the 1990s, permit subsurface mapping of the Raton-Vermejo-Trinidad aquifer (Geldon, 1989) as three distinct hydrostratigraphic units: the Raton, Vermejo, and Trinidad aquifers.

Purpose and Scope

The purpose of this report is to provide an improved definition of the hydrostratigraphic framework of the Raton, Vermejo, and Trinidad aquifers in Las Animas County, Colorado. The study area (fig. 1) was restricted to the portion of the Raton Basin in Las Animas County because not enough data were available to map the hydrostratigraphic framework with confidence in Huerfano County. Contour maps are presented for the Trinidad Sandstone, the Vermejo Formation, and the Raton Formation that show (1) the generalized configuration and altitude of their bottom and top surfaces; (2) the generalized depth from land surface to their bottom and top surfaces; and (3) their generalized apparent thicknesses. Maps also are presented that show the generalized configuration and altitude of the regional water table and the generalized depth from land surface to the water table in part of Las Animas County. The contours shown on the maps in this report and the data points on which they were based are available electronically as spatial data at URL *http://water.usgs.gov/lookup/getgislist*. Table 1 lists file names and an abbreviated description of the spatial data prepared for this study. The file names are a combination of the report number (SIR-06-5129) and a data descriptor. For example, the name of the spatial data set of contours of the generalized altitude of the top of the Trinidad Sandstone is SIR-06-5129_alt_top_trinidad_con.

Hydrogeologic Setting

The Raton Basin (fig. 1*A*) is an asymmetrical structural trough in southeastern Colorado and northeastern New Mexico that contains 10,000 to 25,000 ft of sedimentary rocks that range in age from Pennsylvanian to Eocene (Geldon, 1989). As much as 10,000 ft of clastic sedimentary rocks of Late Cretaceous and Tertiary age overlies the Late Cretaceous-age Pierre Shale in the Raton Basin in Colorado (table 2). The Raton Basin lies between the Sangre de Cristo Mountains on the west and the Apishapa, Las Animas, and Sierra Grande arches on the east (fig. 1*A*). The eastern side of the study area is defined by an escarpment formed by resistant ledges of the Trinidad Sandstone. The western side of the basin is defined by uplifted sedimentary rocks, which are warped vertically. Igneous rocks (dikes, sills, and stocks) intruded the sedimentary rocks. Spanish Peaks, prominent igneous intrusions (stocks), dominate the landscape along the Huerfano–Las Animas County line (fig. 2). Dikes, which are tabular igneous intrusions that cut across the bedding of the sedimentary rocks, form vertical ridges because the igneous rocks are more resistant to erosion than the surrounding sedimentary rocks. In some places, dike swarms that radiate from the Spanish Peaks intersect a set of subparallel dikes that trend easterly across the study area (fig. 2). Sills, tabular igneous bodies parallel to bedding, intruded the middle part of the Raton Formation and are exposed in the Purgatoire River valley about 10–20 mi west of Trinidad and about 10–15 mi northwest of Trinidad (fig. 2). South-southeast of Trinidad on the Raton Mesa, basalt flows overlie the Tertiary-age Poison Canyon and Raton Formations (fig. 2). Relatively narrow and thin alluviums of Pleistocene and Holocene age (not shown in fig. 2) fill stream valleys cut into the sedimentary rocks and cap pediments (Geldon, 1989, his fig. 26).

Table 1. Spatial data for the Raton, Vermejo, and Trinidad aquifers in Las Animas County, Colorado.

[Spatial data available at URL *http://water.usgs.gov/lookup/getgislist*]

Spatial data file name	Data type	Data description
sir-06-5129_seo_wells_point	Points	Location and selected attributes of water wells (Colorado Division of Water Resources (2003).
sir-06-5129_alt_bottom_trinidad_con	Points	Locations and selected attributes of oil and gas wells.
sir-06-5129_cogcc_production_point	Points	Annual gas and water production by oil and gas wells during 1999–2004.
sir-06-5129_formation_tops_point	Points	Depth to tops of selected hydrostratigraphic units.
sir-06-5129_alt_bottom_trinidad_con	Contours	Generalized altitude of the bottom of the Trinidad Sandstone.
sir-06-5129_alt_top_trinidad_con	Contours	Generalized altitude of the top of the Trinidad Sandstone.
sir-06-5129_alt_top_vermejo_con	Contours	Generalized altitude of the top of the Vermejo Formation.
sir-06-5129_alt_top_raton_con	Contours	Generalized altitude of the top of the Raton Formation.
sir-06-5129_depth_bottom_trinidad_con	Contours	Generalized depth below land surface to the bottom of the Trinidad Sandstone.
sir-06-5129_depth_top_trinidad_con	Contours	Generalized depth below land surface to the top of the Trinidad Sandstone.
sir-06-5129_depth_top_vermejo_con	Contours	Generalized depth below land surface to the top of the Vermejo Formation.
sir-06-5129_depth_top_raton_con	Contours	Generalized depth below land surface to the top of the Raton Formation.
sir-06-5129_thickness_trinidad_con	Contours	Generalized thickness of the Trinidad Sandstone.
sir-06-5129_thickness_vermejo_con	Contours	Generalized thickness of the Vermejo Formation.
sir-06-5129_thickness_raton_con	Contours	Generalized thickness of the Raton Formation.
sir-06-5129_alt_water_table_con	Contours	Generalized altitude of the water table.
sir-06-5129_depth_water_table_con	Contours	Generalized depth below land surface to the water table.

Table 2. Hydrostratigraphic section of the Raton Basin (modified from Geldon, 1989).

[--, not defined]

<table>
<tr><th>System</th><th>Series</th><th>Formation and member</th><th>Maximum thickness[1] (feet)</th><th>Description</th><th colspan="2">Hydrostratigraphic unit</th></tr>
<tr><td colspan="7">Sedimentary rocks</td></tr>
<tr><td rowspan="2">Quaternary</td><td>Holocene</td><td>Stream alluvium</td><td>10–70</td><td>Clay to boulder-sized detritus.</td><td colspan="2" rowspan="2">Alluvial aquifers.</td></tr>
<tr><td>Pleistocene</td><td>Pediment alluvium</td><td>40–50</td><td>Clay to boulder-sized detritus.</td></tr>
<tr><td rowspan="5">Tertiary</td><td rowspan="2">Eocene</td><td>Huerfano Formation</td><td>2,000</td><td>Variegated shale and sandstone with basal conglomerate.</td><td colspan="2">Huerfano aquifer (?).</td></tr>
<tr><td>Cuchara Formation</td><td>5,000</td><td>Pink and white sandstone with shale layers.</td><td colspan="2" rowspan="2">Cuchara–Poison Canyon aquifer (Geldon, 1989).</td></tr>
<tr><td rowspan="3">Paleocene</td><td>Poison Canyon Formation</td><td>2,500</td><td>Tan, gray, and olive sandstone, conglomerate, and shale.</td></tr>
<tr><td>Raton Formation, Upper[2]</td><td>100–300</td><td>Gray, green, and tan siltstone, sandstone, and shale.</td><td rowspan="5">Raton-Vermejo-Trinidad aquifer (Geldon, 1989)</td><td rowspan="3">Raton aquifer.</td></tr>
<tr><td>Raton Formation, Middle[2]</td><td>800–1,000</td><td>Dark-gray, carbonaceous, and silty shale with coal and sandstone lenses.</td></tr>
<tr><td>Tertiary and Cretaceous</td><td>Paleocene and Upper Cretaceous</td><td>Raton Formation, Lower[2]</td><td>1–250</td><td>Tan to gray sandstone and conglomerate.</td></tr>
<tr><td rowspan="3">Cretaceous</td><td rowspan="3">Upper Cretaceous</td><td>Vermejo Formation</td><td>65–590</td><td>Dark-gray, carbonaceous, and silty shale with coal and sandstone lenses.</td><td>Vermejo aquifer.</td></tr>
<tr><td>Trinidad Sandstone</td><td>40–340</td><td>Tan to gray sandstone with thin silty shales.</td><td>Trinidad aquifer.</td></tr>
<tr><td>Pierre Shale</td><td>1,800–2,300</td><td>Dark-gray shale with limestone and sandstone layers.</td><td colspan="2">Pierre confining unit.</td></tr>
<tr><td colspan="7">Igneous rocks</td></tr>
<tr><td rowspan="3">Tertiary</td><td>Pliocene–Miocene</td><td>Basalt flows (extrusive rocks)</td><td>--</td><td>Basalt and associated tuff, breccia, and conglomerate.</td><td colspan="2">Potentially an aquifer but generally unsaturated.</td></tr>
<tr><td rowspan="2">Miocene</td><td>Intrusive rocks, stocks</td><td>--</td><td>Syenodiorite, granodiorite, granite, and syenite porphyry.</td><td colspan="2">Potentially an aquifer where fractured.</td></tr>
<tr><td>Intrusive rocks, dikes and sills</td><td>--</td><td>Granite to gabbro in composition.</td><td colspan="2">Flow barriers.</td></tr>
</table>

[1]All formations present in the area are locally removed by erosion. Thickness or range in thickness given represents measured thickness revealed in outcrops and drill holes (Geldon, 1989).

[2]On the basis of completion reports for coalbed methane wells in Las Animas County, the reported thickness of Raton Formation, the combined thicknesses of the Upper, Middle, and Lower members, ranges from 1,100 to 1,900 feet.

The Trinidad Sandstone and the Vermejo, Raton, Poison Canyon, and Cuchara Formations are the primary water-bearing rocks that overlie the Pierre Shale in the study area. Geldon (1989) defined two principal aquifers in the study area, the Cuchara–Poison Canyon and the Raton-Vermejo-Trinidad aquifers. Thin alluvial deposits along the Apishapa and Purgatoire Rivers and their tributaries also are water bearing but are limited in extent. Ground water in the study area that has less than 10,000 milligrams per liter (mg/L) dissolved solids occurs in the sedimentary rocks that overlie the Pierre Shale. An estimated 1,500 water-supply wells in the study area are completed in the coal, sandstone, and conglomerate in these rocks or in alluvium that is hydraulically connected with them. Coal beds in the Vermejo and Raton Formations also are the sources of methane for CBM wells and the ground water which must be pumped to produce the methane.

Geldon (1989) provides an analysis of the ground-water hydrology of the Raton Basin in Colorado and New Mexico. The aquifers in the study area are recharged by infiltration of precipitation on outcrops in upland areas. Regional ground-water flow generally is from west to east, except where intercepted by valleys cut into the rock. Most ground-water flow occurs in the permeable rocks (coal, conglomerate, and sandstone) but also occurs in fractures in other, less permeable rocks. Ground water is stored in both the permeable rocks and less permeable rocks (siltstone and shale). Ground-water flow generally is lateral and parallel with bedding but also flows downward where fractures connect permeable rocks. Local ground-water flow from stream divides to valleys intercepts much of the regional ground-water circulation.

The volume of ground water pumped by about 1,500 water-supply wells in the study area is unknown; however, estimated annual ground-water use for all of Las Animas County during 2000 was 1,055 Mgal (U.S. Geological Survey, 2004a; Hutson and others, 2004). During 1999–2004, the cumulative volume of ground water coproduced by CBM wells from the Raton and Vermejo Formations in Las Animas County was about 299 million barrels (about 12,558 Mgal) (Colorado Oil and Gas Conservation Commission, variously dated). During 1999–2004, the volume of ground water coproduced by CBM wells in Las Animas County also increased about threefold, from 22,597,972 barrels (about 949 million gallons) during 1999 to 68,557,832 barrels (about 2,879 million gallons) during 2004 (fig. 3). Average annual ground-water production by CBM wells in the study area during 1999–2004 was about 2,093 Mgal, which is about twice the 1,055 Mgal of estimated ground-water withdrawals for all other uses in Las Animas County during 2000.

The response of fluid pressure in hydrostratigraphic units to changes in recharge and discharge rates primarily is controlled by the three-dimensional (spatial) distribution of lithology. Lithology (rock type) is a primary control of porosity. The hydraulic and storage properties of rocks depend on the amount, size, and interconnection of pores. Understanding the external geometry (hydrostratigraphic framework) of the Trinidad Sandstone and Vermejo and Raton Formations is an initial step in improving understanding of ground-water flow in the Raton Basin. Other hydrogeologic factors that affect ground-water flow in the study area and that also need better definition, but which were not evaluated during this study, include the internal geometry of the hydrostratigraphic units and the effects of faults, fractures, and igneous intrusions (dikes and sills) on ground-water flow.

Data

Data used for this study were retrieved from two agencies of the Colorado Department of Natural Resources, the Division of Water Resources, and the Colorado Oil and Gas Conservation Commission (COGCC). Water-well data for this study were obtained from the database and files of the State Engineer's Office (SEO) of the Colorado Division of Water Resources (Colorado Division of Water Resources, 2003). Selected data for water wells can be accessed at the SEO Web site at URL *http://water.state.co.us/*. Data for oil and gas (CBM) wells were retrieved from the COGCC database (Colorado Oil and Gas Conservation Commission, variously dated). Locations, geologic, construction, and production data, and scanned documents for oil and gas wells can be accessed at the COGCC Web site at URL *http://www.oil-gas.state.co.us/*.

The digital geologic map of Colorado (Green, 1992) was used to define the surface geology at wells. The digital geologic map of Colorado can be accessed, in a spatial data format, at URL *http://pubs.usgs.gov/of/1992/ofr-92-0507/colorado.htm*. The geologic map of the Trinidad quadrangle (Johnson, 1969) was used to estimate the locations and altitudes of geologic contacts at outcrop. The geologic map of the Trinidad quadrangle can be accessed, as an image, at URL *http://ngmdb.usgs.gov/ImageLibrary/*.

Water Wells

Well data were acquired in 2003, and the locations of water wells in the SEO database were reported in Universal Transverse Mercator (UTM) coordinates (zone 13, NAD 27, meters). The UTM coordinates are calculated from the location reported by the well driller or owner. Most of the study area south of the Purgatoire River is the Maxwell Grant (fig. 2), which is a land grant that does not have official township, range, and section descriptions. Consequently, water wells located in the Maxwell Grant generally do not have UTM coordinates in the SEO database. Minimum accuracy of water-well locations is the nearest quarter-quarter section, the nominal 40-acre tract in which the well is located; however, many well locations also are reported as distances in feet from the north or south and from the east or west section lines. Accuracy of distances of water wells from section lines is not reported. Assuming that a well is located in the center of the 40-acre tract, it is 660 ft from the sides of the tract and, thus, location error for the well could be as much as about 933 ft ($\sqrt{(2*660\text{ ft}*660\text{ ft})} \approx 933$ ft). In addition to well locations, the SEO database includes well-permit and ownership information and, generally, well depth, depths to the tops and bottoms of perforated or screened intervals, reported depth to water, and reported well yield. Generally, the altitude of the land surface at the well and the aquifer in which the well is completed are not reported in the SEO database.

Coalbed-Methane Wells

Since January 2003, locations of oil and gas wells are reported to a precision of five (5) decimals of a degree (about 3 ft) using NAD 83, as required by COGCC rule 308A (Colorado Oil and Gas Conservation Commission, 2003). However, wells installed before adoption of rule 308A may have less accurate locations. Currently (2006), accuracy and vertical datum of land-surface altitudes of oil and gas wells are not specified in COGCC rules.

The primary source of subsurface geologic data for this study consisted of depths to formation tops and bottoms listed on "scout cards" for CBM wells. A scout card is a summary

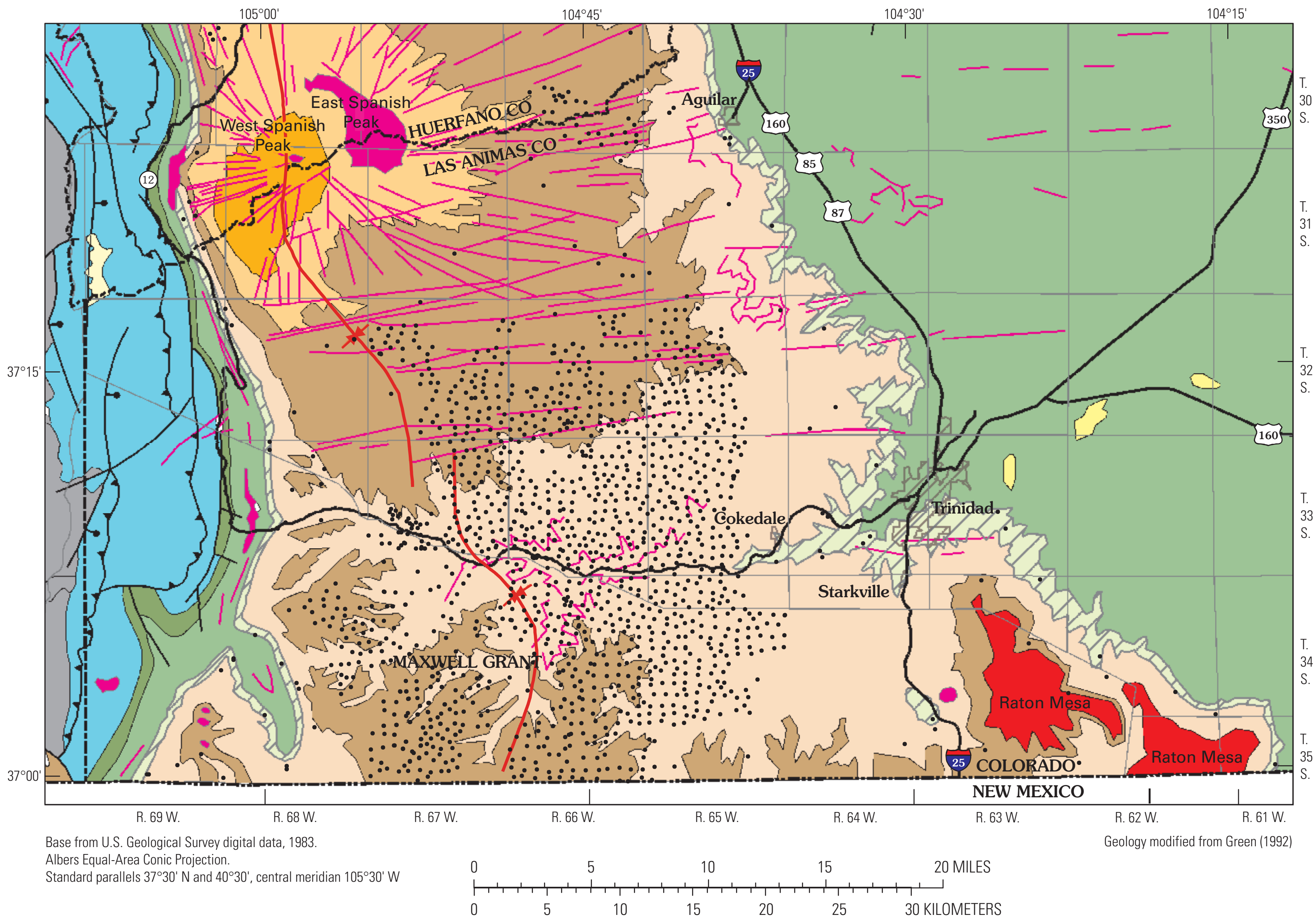


Figure 2. Generalized geologic map and locations of oil and gas wells in the Raton Basin, Las Animas County, Colorado, 2004.

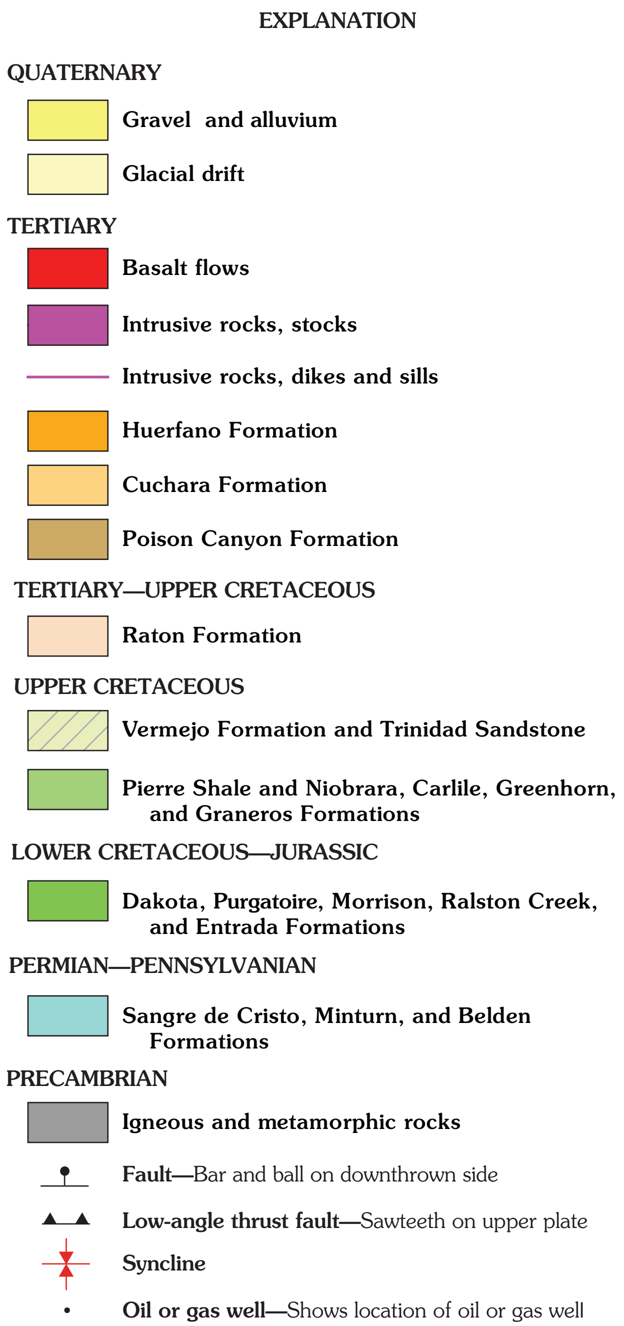


Figure 2.—Continued.

of information for an oil or gas well that includes location, geologic, well-completion, and other data for the well. Depths to selected stratigraphic horizons from drilling and completion reports of CBM wells, which are referred to as “log top” and “log bottom” on the scout cards, were entered into a relational database for computation of altitudes of the bottom and top and thicknesses of the Trinidad Sandstone and the tops of the Vermejo and the Raton Formations. The reported depths to formation tops and bottoms were screened to ensure that reported depths of formations were in stratigraphic order (increasing geologic age with depth) and that calculated thicknesses of the formations were within reasonable limits.

Geologic Maps

The digital geologic map of Colorado (Green, 1992) was used to identify the surface geology at water wells and CBM wells. Because the subsurface data used in this study primarily are data for CBM wells and most CBM wells are located several miles from the basin boundaries, there is little subsurface data to define the altitudes of formation tops and bottoms near outcrops. Therefore, altitudes of selected points along mapped geologic contacts between selected stratigraphic units were estimated from the 1:250,000-scale geologic map of the Trinidad quadrangle (Johnson, 1969).

Vertical Datum

The land-surface altitude at water wells and at CBM wells that were used for this study were estimated, on the basis of reported location, using geographic information (GIS) software and the National Elevation Dataset (NED) at a resolution of 1/3 Arc Second (U.S. Geological Survey, 2004b). The NED is a raster (geospatial grid) of land-surface altitudes, which can be accessed at URL *http://seamless.usgs.gov/*. At a resolution of 1/3 Arc Second each raster value represents the altitude of an area of about 100 m^2 (about 929 ft^2). Horizontal datum for the NED is the North American Datum of 1983 (NAD 83) and the vertical datum is the North American Vertical Datum of 1988 (NAVD 88). The altitudes (raster values) are given in meters (m) but were converted to altitudes in feet (ft) above NAVD 88 for this study. Vertical accuracy of the NED is approximately one-half the contour interval of the original source data, which in the study area were 7.5-minute topographic quadrangles with contour intervals of 20 or 40 ft. Because the land surface in the study area is rugged with local relief of several hundred feet, inaccurate geographic coordinates for a well could result in large error in the estimated land-surface altitude. The difference between NED-estimated altitude and reported altitude for 1,305 CBM wells in the study area ranged from 0.01 to about 929 ft with a median difference of about 15 ft; 25 percent of the differences were less than 7.3 ft, and 25 percent of the differences exceeded 29 ft. The causes of these differences in reported and estimated altitude at oil and gas wells include error in the altitude estimated from the NED (±10–20 ft), errors in reported altitudes of wells, vertical-datum correction of reported altitude (3.27–4.45 ft), and errors caused by inaccurate horizontal coordinates of wells.

Vertical datum corrections are needed to convert altitude that is referenced to National Geodetic Vertical Datum of 1929 (NGVD 29) to altitude referenced to NAVD 88. The vertical-datum correction increases from northeast to southwest across the study area, from about 3.27 to 4.45 ft. Because altitudes at water wells and CBM wells were estimated from the NED, which is referenced to NAVD 88, they did not need datum corrections. Altitudes of geologic contacts at outcrop were estimated from the geologic map (Johnson, 1969) but a datum correction was not applied because the error resulting from the estimation method likely was substantially larger than the datum correction.

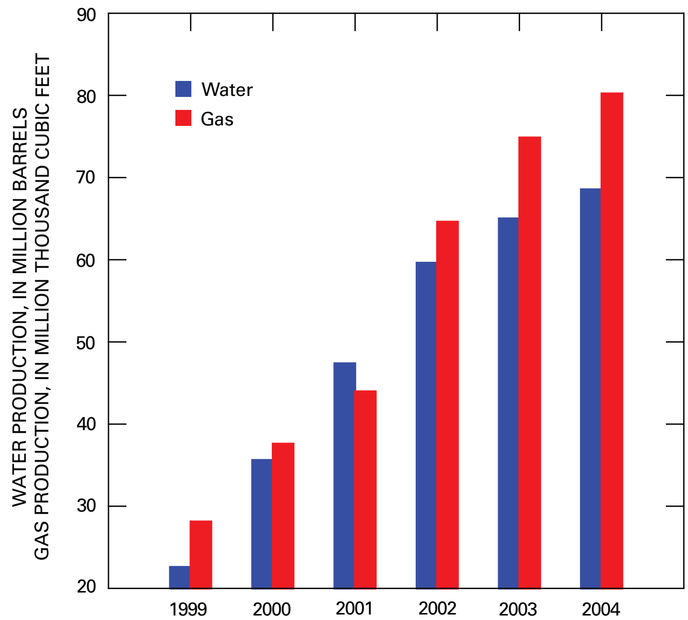


Figure 3. Annual ground-water and gas production by CBM wells in the study area, 1999–2004.

Geostatistical Methods and Computer Contouring

The two methods commonly used for interpolation (mapping) of geologic surfaces are deterministic-interpolation and geostatistical methods. Deterministic-interpolation methods predict values at unmeasured locations from measured values at known locations, based on either the extent of similarity of values or the degree of smoothing. Geostatistical methods predict values at unmeasured locations on the basis of the statistical properties of the measured points and the spatial configuration of the sample points around the prediction location. Both deterministic and geostatistical methods can be implemented in GIS and either can produce similar interpretations.

Deterministic methods work well if data are regularly spaced and there is little local-scale variability in the data; however, deterministic methods may work poorly if data are sparse, locations are clustered, or local-scale variability is large. Geostatistical methods have the following advantages: the variance between data points is a function of distance and direction between points; local-scale variability can be relatively large; and errors of prediction are estimated. Geostatistical methods may not provide a unique solution and, because geostatistical methods are basically linear-regression methods, tend to smooth (underestimate) variability. Geostatistical methods, rather than deterministic-interpolation methods, were used in this study to map the hydrostratigraphic framework because the subsurface data were relatively variable at local scales.

Kriging is a geostatistical method that can be used to determine the optimal weighting of measurements at measured or sampled locations for prediction at unmeasured or unsampled locations and for estimating the uncertainty associated with those predictions (Bossong and others, 1999). A rigorous discussion of the theoretical aspects of kriging is beyond the scope of this report, and the interested reader is referred to Davis (1986) and to Bossong and others (1999).

Kriging is based on the concept of regionalized variables. A regionalized variable has properties intermediate between a truly random variable and a completely deterministic variable and consists of two components, commonly referred to as the "drift" (trend) and the "residual" (Davis, 1986). The drift consists of the average or expected value of the variable within a neighborhood and is the slowly varying (nonstationary) part of the variable. The residual is the difference between the expected value (drift) and the actual (measured) value. When there is a known or suspected trend in the variable, for example, the altitude of a sloping water table or the surface of a geologic formation that has been folded, the trend is first removed from the point values and the detrended data (residuals) are fit to a mathematical function.

Mathematical functions are used in kriging to describe the variability of the data as a function of distance and, if needed, direction. Figure 4 shows four mathematical functions commonly used in kriging—the exponential, Gaussian, linear, and spherical functions. In figure 4, the semivariance (γ_h) is one-half the sample variance between measured values or , if drift is present, the residual; h is the distance between measurement points for which γ_h is calculated; the nugget (g) is the value of γ_h for data near $h = 0$ when nearby values are not identical; the sill (s) is the value of γ_h which approaches the sampled population's variance and at which the data are not spatially correlated; and, the range (r) is the distance, h, at which γ_h approaches the sample variance and beyond which data values are not spatially correlated. Equations for these mathematical functions are given in Bossong and others (1999). The shape of the graphs of the functions shown in figure 4 are all similar in that they have a sill and a range but differ in shape near $h = 0$.

Development of geostatistical models, for this study, consisted of the following general steps: (1) trend analysis to determine if the spatial mean of the data was nonstationary (had trends) or stationary (did not have trends); (2) removal of the drift (trends) from the data, if the spatial mean was nonstationary; (3) variogram analysis to fit a theoretical mathematical function to the sample variogram; (4) evaluation of anisotropy to compute directional sample variograms, if needed; and (5) evaluation of cross-validation statistics.

Trend removal is done when the spatial mean value is nonstationary, using either ordinary or universal kriging. The type of trend may be selected based on knowledge of the shape of the surface. A constant trend subtracts the mean value from the data. A first-order trend is simply a sloping plane, which

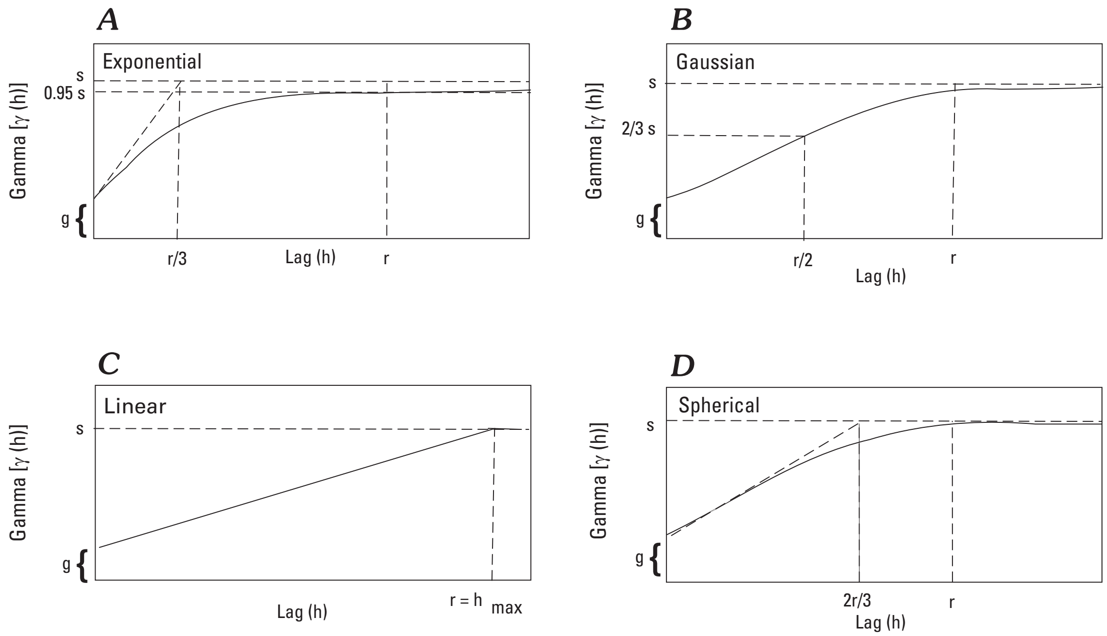


Figure 4. Theoretical variograms of (*A*) exponential, (*B*) Gaussian, (*C*) linear, and (*D*) spherical functions.

is defined by a linear equation, a second-order trend is defined by a quadratic equation, and a third-order trend is defined by a cubic equation.

In kriging, the semivariance (γ_h) for the sample data is calculated and a sample variogram, a graph of the semivariance (γ_h) plotted against lag (*h*), is fit to one of the mathematical functions. Lag (*h*) is used in the variograms rather than *h* because, typically, there are not enough data pairs at each finite distance to calculate a valid γ_h; therefore, γ_h is estimated based on a finite range (lag) of distances. The objective of fitting a variogram is to find a mathematical function that characterizes the spatial continuity of a regionalized variable as a function of distance. The mathematical function that best fits the sample data is determined by trial and error. Because geological data from gas, oil, and water wells generally are widely spaced, on the order of 1,000 ft or more, there generally are not enough closely spaced data to define the shape of the variogram near zero lag ($h = 0$). Consequently, the sample variograms were not particularly sensitive to which mathematical function was used.

Simple kriging may be adequate to predict variables, which do not have a substantial trend in the spatial mean value of the variable. Ordinary kriging can be used for data that seem to have a trend. However, there is no way to decide, based on the data alone, whether the observed pattern is the result of autocorrelation among the residuals or a trend. A polynomial regression with the spatial coordinates as the explanatory variables is used to predict the drift in universal kriging. As with ordinary kriging, there is no way to decide whether the observed pattern is the result of autocorrelation among the residuals or a trend, on the basis of the data alone.

Cross-validation statistics are computed from the measured values and the predicted values from kriging. Prediction error for a measurement equals the measured value minus the predicted value. Mean prediction error is the mean of the prediction errors and should be near 0. Because the mean prediction error depends on the scale of the data, the prediction standardized errors also are calculated. The prediction errors divided by the prediction standard errors equals the prediction standardized errors. Root-mean-squared error is the square root of the mean of the prediction errors squared and should be minimized. The average standardized error is the mean of the prediction errors divided by the prediction standard errors and should be near zero (0). The root-mean-squared-standardized error should be close to 1 if the prediction standard errors are valid. If the root-mean-squared-standardized error is greater than 1, the variability of the predictions is underestimated; if the root-mean-squared-standardized error is less than 1, the variability of the predictions is overestimated.

The general procedure used to prepare the structure and apparent thickness maps consisted of the following steps:

1. Point values of the altitudes of the formation top were calculated as land-surface altitude (estimated from the NED) at the CBM well minus the reported depth to the formation top or were altitudes of geologic contacts that were estimated from the geologic map of the Trinidad quadrangle (Johnson, 1969). Point values of formation thickness were calculated from the reported depths to the tops of successive stratigraphic units.

2. Spatial trends in the variable (tops or thicknesses) were evaluated to determine whether the variable was stationary (no trend) or nonstationary (trend). Because the trend

analyses indicated that variables were nonstationary, a geostatistical method that incorporated trends was used to model the residuals, the difference between the trend (drift) and the point values.

3. Because trends were indicated by the trend analyses of the variables, ordinary kriging, as implemented in ArcMap™ 9.1 (Environmental Systems Research, Inc., 1999–2005), was used to develop variogram models to predict values of the altitude of the tops or the thicknesses of the formations. Several types of theoretical mathematical functions (spherical, exponential, and Gaussian) and parameter sets (lag distances, anisotropy, and ratio of global to local drift) were evaluated by trial and error, to find an acceptable fit of the sample variogram to a theoretical mathematical function. Anisotropy refers to spatial variability that is dependent on the direction of measurement. Drift (trend) in spatial variability can be global, local, or a combination of global and local. The ratio of global to local drift determines the size of the neighborhood in which a polynomial equation is fit to detrend the data. If the ratio of global to local drift is 1:0, the neighborhood is global and the data are detrended by removing regional trends; if the ratio of global to local drift is 0:1, the neighborhood is local and the data are detrended by removing local trends. The software generates grids of predicted values and standard errors for the variables and output grid spacing ranged from about 780 to 970 ft. The differences in grid spacing result from differences in the number and distribution of data points for the variables. The selected mathematical function and parameter sets were those that resulted in cross-validation statistics with a mean error (of prediction) near zero, the smallest root-mean-squared error, an average standardized error approximately equal to the root-mean-squared error, and a root-mean-squared-standardized error of about 1.

4. Contour lines were computer generated from the output grid values to show lines of equal altitude of a surface or thickness of the hydrostratigraphic unit. The computer-generated contours were smoothed, using an ArcMap generalization tool, to smooth the contour lines. The smoothed contours were edited, using ArcEdit, an extension of Arc (Environmental Systems Research, Inc., 1982–2000) to remove small closed contours, which likely were artifacts of the computer-generated contouring.

5. Grid values were generated from the smoothed and edited contour lines using TOPOGRID, an ARC™ 8.0.2 command. Derivative maps were prepared from mathematical combinations of the grids. For example, the depth to the top of the Trinidad Sandstone was calculated by subtracting the grid of the altitude of the top of the Trinidad Sandstone from the NED (a grid of the land-surface altitude). The values of the resultant grid were then contoured and the contours were smoothed and edited.

Hydrostratigraphic Framework of the Raton, Vermejo, and Trinidad Aquifers

Better definition of the hydrostratigraphic framework (external geometry) of the Trinidad Sandstone and the Vermejo and Raton Formations are needed to increase understanding of ground-water flow in the Raton Basin. Other hydrogeologic factors that also need better definition include the spatial variability within these formations (their internal geometry) and the effects of faults, fractures, and igneous intrusions (dikes and sills) on ground-water flow. Because lithology is a primary control on the porosity and permeability of sedimentary rocks, understanding the effects of changes in fluid pressure requires knowledge of internal and external geometries of the hydrostratigraphic units.

A hydrostratigraphic unit is a “formation, group of formations, or part of a formation, which by virtue of its porosity or hydraulic properties has a distinct influence on the storage and movement of ground water” (American Nuclear Society, 1980). A permeable hydrostratigraphic unit is an aquifer, and an impermeable or relatively impermeable hydrostratigraphic unit is a confining unit. An aquifer is “a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs” (Lohman and others, 1972). The definition of a gas or oil reservoir is similar to that of an aquifer, except that the fluids of interest are gas and oil. A confining unit is “a body of impermeable material stratigraphically adjacent to one or more aquifers... its hydraulic conductivity may range from nearly zero to some value distinctly lower than that of the aquifer” (Lohman and others, 1972).

Table 2 (modified from Geldon, 1989) summarizes the hydrostratigraphic section for the Tertiary- and Cretaceous-age rocks that overlie the Cretaceous-age Pierre Shale in Colorado and New Mexico. The Pierre Shale is considered a regional confining unit because it substantially restricts the flow of ground water and, for the purposes of this study, is considered the base of the hydrostratigraphic framework. The two principal aquifers in the Raton Basin that overlie the Pierre confining unit are the Cuchara–Poison Canyon and the Raton-Vermejo-Trinidad aquifers (Geldon, 1989). The Cuchara–Poison Canyon aquifer, with a maximum combined thickness of about 7,500 ft in Huerfano County (table 2), was considered to be a single aquifer because of compositional similarity of the Poison Canyon and Cuchara Formations (Geldon, 1989). The Raton-Vermejo-Trinidad aquifer, with a maximum combined thickness of about 2,480 ft (table 2), also was defined on the basis of compositional similarity of the Vermejo and Raton Formations and of similarity between sandstone layers in these formations and those in the Trinidad Sandstone (Geldon, 1989).

By definition, the porosity or hydraulic properties of a hydrostratigraphic unit (aquifer or confining unit) have a distinct influence on the storage and movement of ground water (American Nuclear Society, 1980). Because the Cuchara–Poison Canyon and Raton-Vermejo-Trinidad aquifers, as defined by Geldon (1989), consist of thick sequences of interbedded and discontinuous sandstones, shales, and coals, in which hydraulic and storage properties vary spatially, the aquifers, as defined, are likely so heterogeneous and anisotropic that the spatial distribution of their properties could only be defined in a probabilistic manner. Subdivision of the Cuchara–Poison Canyon and Raton-Vermejo-Trinidad aquifers, on the basis of differences in their lithologic composition, allows definition of more distinctive (less heterogeneous) hydrostratigraphic units.

Subsurface data are available only to refine the definition of the Raton-Vermejo-Trinidad aquifer in Las Animas County. Fewer CBM wells have been drilled in Huerfano County and where the Huerfano and Cuchara Formations overlie the Poison Canyon Formation in Las Animas County (fig. 2), thus, it is not possible to map subsurface configurations of the Huerfano, Cuchara, and Poison Canyon Formations. Because the Vermejo and Raton Formations are the primary targets for CBM exploration and production in the Raton Basin and more than a 1,400 CBM wells have been drilled in the study area, refinement of the hydrostratigraphic framework was limited to Las Animas County. Also, there were enough subsurface data to subdivide the Raton-Vermejo-Trinidad aquifer into three distinct aquifers: the Raton, Vermejo, and Trinidad.

The sedimentary rocks, which make up the Raton-Vermejo-Trinidad aquifer, the Trinidad Sandstone, the Vermejo Formation, and the Raton Formation, were formed from clastic sediments and organic matter that were deposited by different processes in distinct sedimentary environments. These included barrier-island, delta-front, and coastal deposits in the Trinidad Sandstone; fluvial-dominated-delta-plain deposits in the Vermejo Formation, and alluvial-plain deposits in the Raton Formation (Clarke and Turner, 2002). The rocks that formed from these sediments were subsequently uplifted, warped, fractured, and intruded and altered by igneous rocks.

Subdivision of the Raton-Vermejo-Trinidad aquifer, on the basis of stratigraphy (indirectly the sedimentary depositional environment), results in hydrostratigraphic units in which rock types, the primary control on the hydraulic and storage properties, are internally more consistent. Detailed analysis and correlation of geophysical logs and cores could provide a better understanding of the spatial distribution of hydraulic and storage properties within these aquifers but is beyond the scope of this study.

Raton Aquifer

The Raton aquifer consists of the Raton Formation. The Raton Formation (table 2) consists of interbedded sandstone, siltstone, silty shale, and lenticular beds of coal. The Raton Formation was deposited on an upper alluvial plain, characterized by various modes of aggradation and erosion (Flores, 1984). Deposition on the alluvial plain was interrupted by several types of fluvial sedimentation. Rapid uplift of the source area to the west caused widespread erosion of the highland and concurrent deposition of a basal conglomerate. The basal conglomerate, which consists of medium- to coarse-grained channel sandstones with lenses and stringers of conglomerate, probably was deposited in basin-margin braided streams merging basinward into meandering streams. After deposition of the basal conglomerate, sandstones were deposited mainly in meandering streams at the same time that interbedded thin coal, carbonaceous shale, mudstone, and sandstone beds accumulated in flood plains and back swamps. Crevasse splays periodically interrupted and filled low-lying areas during floods. Though some thick coal beds were deposited locally in the lower coal zone, most coal swamps that formed in the flood basins were well drained, small, and shallow, which limited peat accumulation and resulted in thin, lenticular coal beds.

Geldon (1989) reported that the thickness of the Raton Formation ranged from about 1,000 to 1,600 ft. However on the basis of completion reports from 126 CBM wells in Las Animas County, reported thickness of the Raton Formation ranges from about 1,100 to 1,900 ft, where it is not eroded (is overlain by the Poison Canyon Formation). Net coal thickness is about 100 ft, with as many as 40 coal beds, which are characteristically lenticular, 1 to 10 ft thick, and with limited lateral continuity of about 500 to 1,000 ft (Clarke and Turner, 2002).

The Raton Formation includes upper, middle, and lower members (Wood and others, 1951). The three members of the Raton Formation are not distinguishable, except by stratigraphic position, and recognition of them was based primarily on the lateral persistence of sandstone zones at outcrop. The lower member differs from the middle and upper members, because it contains a basal conglomerate, which thins eastward and becomes finer grained (Wood and others, 1956). Generally, the lower contact of the Raton Formation with the Vermejo Formation, as indicated by the basal conglomerate, is erosional, but locally, the contact may be conformable. Coal, conglomerate, and sandstone in the Raton Formation are capable of transmitting substantial quantities of water to wells. Because of the interbedded and lenticular nature of its strata, the Raton aquifer is a highly heterogeneous and anisotropic aquifer. Definition of the internal geometry of the Raton Formation likely will require detailed analysis of core and geophysical logs and a probabilistic approach to approximate aquifer heterogeneity.

Vermejo Aquifer

The Vermejo aquifer consists of the Vermejo Formation. The Vermejo Formation consists of gray to dark-gray, carbonaceous, and sandy shale with lenses of sandstone and coal. The sediments and coals of the Vermejo Formation were deposited in contemporaneous fluvial-deltaic and back-barrier coastal plains fronted by barrier-bar and delta-front sandstones of the Trinidad Sandstone (Flores and Tur, 1982). Lower alluvial plains dissected by meandering streams separated by flood basins characterized the upper part of the Vermejo Formation. Sand-filled stream channels and fine-grained sequences of silt and mud were laid down in flood plains associated with crevasse splay and minor crevasse-channel sandstone. Coal beds in the lower part of the formation formed in poorly drained back barrier coastal swamps and in swamps adjacent to distributary channels of delta plains. The thinner sandstone beds are stratified and laminated, whereas the thicker beds are lenticular and cross-stratified (Wood and others, 1956). Thickness of the Vermejo Formation in the study area, as indicated by completion reports from 888 CBM wells, ranges from 65 to 590 ft. The Vermejo Formation contains as many as 15 coal beds that generally are 3 to 6 ft thick, with a total coal thickness of 5 to 45 ft (Clarke and Turner, 2002). Coal beds in the Vermejo Formation generally are thicker, more regular in thickness, and more laterally persistent (1,000 to 3,000 ft) than those in the Raton Formation. The contact of the Vermejo Formation with the underlying Trinidad Sandstone is conformable (Wood and others, 1956). A conformable contact indicates that the strata do not show physical evidence of erosion or significant breaks in deposition (Bates and Jackson, 1980). The Vermejo aquifer is a heterogeneous and anisotropic aquifer but, on the basis of lateral persistence and thickness of coal beds, it likely is less heterogeneous than the Raton aquifer. Detailed analysis of core and geophysical logs and a probabilistic approach likely would be needed to approximate the heterogeneity of the Vermejo aquifer.

Trinidad Aquifer

The Trinidad aquifer consists of the Trinidad Sandstone. The Trinidad Sandstone is tan to gray sandstone that contains occasional thin beds of silty shale. The bedding is usually tabular but locally is lenticular and varies from medium to massive. The Trinidad Sandstone grades into and intertongues with the underlying Pierre Shale, and their contact is conformable (Wood and others, 1956). The Trinidad was deposited in contemporaneous delta-front and interdeltaic-barrier-bar environments, as the sea regressed eastward. The delta-front deposits include distributary-mouth-bar and distributary-channel sandstones (Flores and Tur, 1982). The barrier-bar deposits consist of middle shoreface, river-estuarine-inlet, and beach sandstones that are overlain by the fluvial-deltaic and back-barrier deposits of the Vermejo Formation. Clarke and Turner (2002) report that stacked channel sands in the upper part of the Trinidad Sandstone indicate reworking of distributary-mouth bars. Thickness of the Trinidad Sandstone, as indicated by completion reports from 214 CBM wells, ranges from 40 to 340 ft. The Trinidad Sandstone thickens to the north across the study area, with the maximum reported thickness in Huerfano County. In comparison with the Raton and Vermejo Formations, the Trinidad Sandstone is a relatively homogeneous aquifer.

Structure and Apparent Thickness of the Raton, Vermejo, and Trinidad Aquifers

The configurations of the top and bottom surfaces (the external geometry) of the Trinidad Sandstone and the Vermejo and Raton Formations were mapped, using a combination of geostatistical models and grid calculations. Reported stratigraphic picks (depths to tops of the formations from drilling and completion reports) for about 1,400 CBM wells, estimated land-surface altitude at the wells, and the estimated altitudes of selected geologic contacts from the geologic map of the Trinidad quadrangle (Johnson, 1969) were used with geostatistical models to estimate the altitudes of the tops of the Trinidad Sandstone and the Raton Formation and the apparent thicknesses of the Trinidad Sandstone and Vermejo Formations. The altitudes of the bottom of the Trinidad Sandstone and top of the Vermejo Formation were calculated from the altitudes of the top of the Trinidad Sandstone and the apparent thicknesses of the Trinidad Sandstone and the Vermejo Formation, respectively. The thickness of the Raton Formation was calculated as the difference between altitudes of the tops of the Raton and Vermejo Formations.

Descriptions of Geostatistical Models and Cross-Validation Statistics

Descriptions of the geostatistical models and the cross-validation statistics are listed in table 3. Table 3 includes the method of kriging, the type or order of drift (trend), the ratio of global to local drift, the theoretical mathematical functions that were used to fit the sample variograms, variogram fitting parameters (lag, range, sill, and nugget), and cross-validation statistics for the selected geostatistical models. The geostatistical models listed in table 3 were the models that had mean errors of prediction nearest to zero, the smallest root-mean-squared errors, average standardized errors nearest the root-mean-squared errors, mean standardized errors near zero, and root-mean-squared-standardized errors nearest to one.

All the geostatistical models (table 3) used ordinary kriging and assumed first-order trends to compensate for global (regional) drift (trend) in the variables. All but one of the models used the spherical function (fig. 4) to model the semivariance of the variable as a function of distance; the model of thickness of the Vermejo Formation used the Gaussian function (fig. 4). All of the geostatistical models, except that for the water table, assume a first-order global trend to compensate for regional drifts (trends) in the variables and lag

Table 3. Geostatistical models, model fitting parameters, and cross-validation statistics.

						Model fitting parameters[1]				Cross-validation statistics				
Variable	Number of data points	Kriging method	Trend order	Drift ratio (global: local)	Math-ematical function	Lag (meter)	Range (meter)	Sill (square feet)	Nugget (square feet)	Mean error (feet)	Root-mean-squared error (feet)	Average standardized error (feet)	Mean standardized error (feet)	Root-mean-squared standardized error (feet)
Trinidad Sandstone, top	822	Ordinary	1	1:0	Spherical	3,750	44,450	242,620	0.0	8.19	212.0	80.9	–0.015	1.00
Trinidad Sandstone, thickness	213	Ordinary	1	1:0	Spherical	3,600	40,866	0	1,241.2	–1.35	35.9	36.2	–0.037	0.99
Vermejo Formation, thickness	904	Ordinary	1	1:0	Gaussian	3,600	42,104	6128.5	3,121.2	–0.51	64.5	57.6	–0.010	1.10
Raton Formation, top	689	Ordinary	1	1:0	Spherical	3,600	42,672	249,800	8,450.5	1.04	148.0	134.0	0.002	1.00
Water table	646	Ordinary	1	1:1	Spherical	2,700	23,346	92,316	5,389.0	–2.92	146.5	107.4	–0.01	1.06

[1]The length unit of the geographic coordinate system for spatial data is meter (m), but the length unit of the vertical datum is foot (ft).

distances of 3,600 or 3,750 m. The geostatistical model of the water table also assumed a first-order trend that was equally divided between global and local drift and a lag distance of 2,700 m. [The length unit of the geographic coordinate system for the spatial data is meter (m) but the length unit of the vertical datum is foot (ft).] The ranges (distances beyond which semivariance is not a function of distance) for geostatistical models of the formation tops, apparent thicknesses, and water table are large (table 3), indicating spatial correlation of the residuals (measurement minus drift) over large distances. The sills (the semivariance beyond which the data are not spatially correlated) for the geostatistical models of formation tops and of the water table are relatively large and those for the apparent thicknesses are relatively small, partly a result of the relative differences in scale of their values. The larger the nugget is compared to the sill, the more local-scale variability there is in the data, and the less important the correlation between neighboring locations becomes (Bossong and others, 1999). The nuggets for the geostatistical models of altitudes of formation tops and the water table are small in comparison to their respective sills, indicating that variability is primarily global (regional) in scale. The nuggets for the geostatistical models of apparent thicknesses are large in comparison to their sills, indicating that more of the variability is local scale. The geostatistical model of the apparent thickness of the Trinidad Sandstone has a sill of zero and a large nugget, indicating that, after regional drift (trend) is removed, all the variability in the residuals is local scale.

The cross-validation statistics for the models (table 3) indicate that the geostatistical models predict the selected variables reasonably well. However, the altitude of the top of the Trinidad Sandstone is overestimated, as indicated by its mean prediction error of 8.19 ft. In addition, its average standardized error is much smaller than its root-mean-squared error, indicating that the variability of the predictions is underestimated. However, other combinations of types of drift (constant and second-order trends), ratios of global to local drift, mathematical functions (exponential and Gaussian), and lag distances, did not improve fit of the geostatistical model of the top of the Trinidad Sandstone.

Calculated Surfaces

The altitude of the bottom of the Trinidad Sandstone (top of the Pierre Shale) and the top of the Vermejo Formation (bottom of the Raton Formation) were calculated from the final grids of the altitude of the top of the Trinidad Sandstone and of the apparent thicknesses of the Trinidad Sandstone and Vermejo Formation, respectively. The altitude of the bottom of the Trinidad Sandstone was calculated by subtracting the apparent thickness of the Trinidad Sandstone from the altitude of the top of the Trinidad Sandstone. Similarly, the top of the Vermejo Formation was calculated by adding the apparent thickness of the Vermejo Formation to the altitude of the top of the Trinidad Sandstone. Apparent thickness of the Raton Formation was calculated as the difference between the top of the Raton Formation and the top of the Vermejo Formation.

The altitude of the bottom of the Trinidad Sandstone, top of the Vermejo Formation and the apparent thickness of the Raton Formation were calculated, rather than modeled, for several reasons. There were only 215 data points available to model the altitude of the bottom of the Trinidad Sandstone. Trend analysis of the 215 values for thickness and bottom altitude of the Trinidad Sandstone indicated that thickness is relatively uniform and the altitude of the bottom of the Trinidad Sandstone is more variable because it is folded into a complex shape with large variance. Therefore, thickness of the Trinidad Sandstone could be modeled with smaller error than the altitude of its bottom surface. Calculation of the altitude of the bottom surface of the Trinidad Sandstone by subtraction of its thickness from the altitude of its top also ensured that the altitude of the bottom would not be greater than the altitude of the top.

A comparison of preliminary cross-validation statistics for geostatistical models of the thickness of the Vermejo Formation and the altitude of its top indicated that the model of thickness had better cross-validation statistics. The geostatistical model of thickness had a smaller mean error, –0.51 compared to –5.18; a smaller root-mean-squared error, 64.5 compared to 209; a smaller average standardized error, 57.6 compared to 87, which also more closely approximated the root-mean-squared error; and a root-mean-squared-standardized error nearer one (1), 1.1 versus 1.8. Additionally, calculation of the altitude of the top of the Vermejo Formation by addition of thickness of the Vermejo Formation and altitude of the top of the Trinidad Sandstone ensured that the surfaces would not cross.

Because the top of the Raton Formation is exposed at outcrop in a large part of the study area (fig. 2) and is an erosional surface, the thickness of the Raton Formation, in areas of outcrop, varies not as a function of the original formation thickness but ranges from values near zero, at the outcrop of its contact with the Vermejo Formation, to its original thickness, at outcrop of its contact with the Poison Canyon Formation. Because kriging is basically a regression technique and the preponderance of thickness values for the Raton Formation are in areas of outcrop, the trend in thickness values that are affected by erosion would overwhelm the thickness values where it had not been eroded and result in a poor prediction of thickness of the Raton Formation in the subsurface.

Structural Surfaces

The external geometries of the Raton, Vermejo, and Trinidad aquifers are defined by the structural surfaces on the geologic contacts between the hydrostratigraphic units. Figures 5–8 show the generalized configuration and altitude of the bottom and top of the Trinidad Sandstone and the tops of

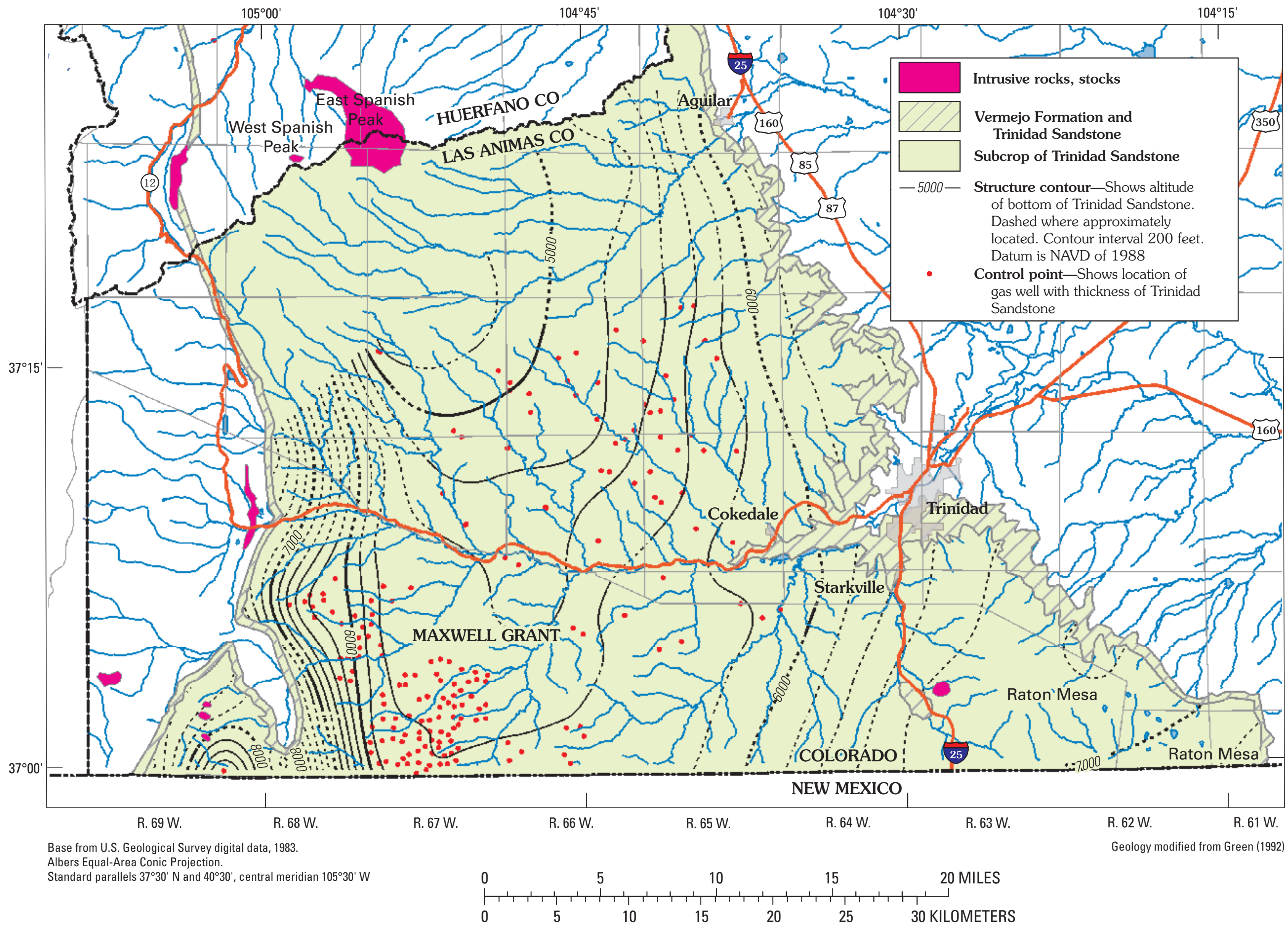


Figure 5. Generalized configuration of the bottom of the Trinidad Sandstone in Las Animas County, Colorado.

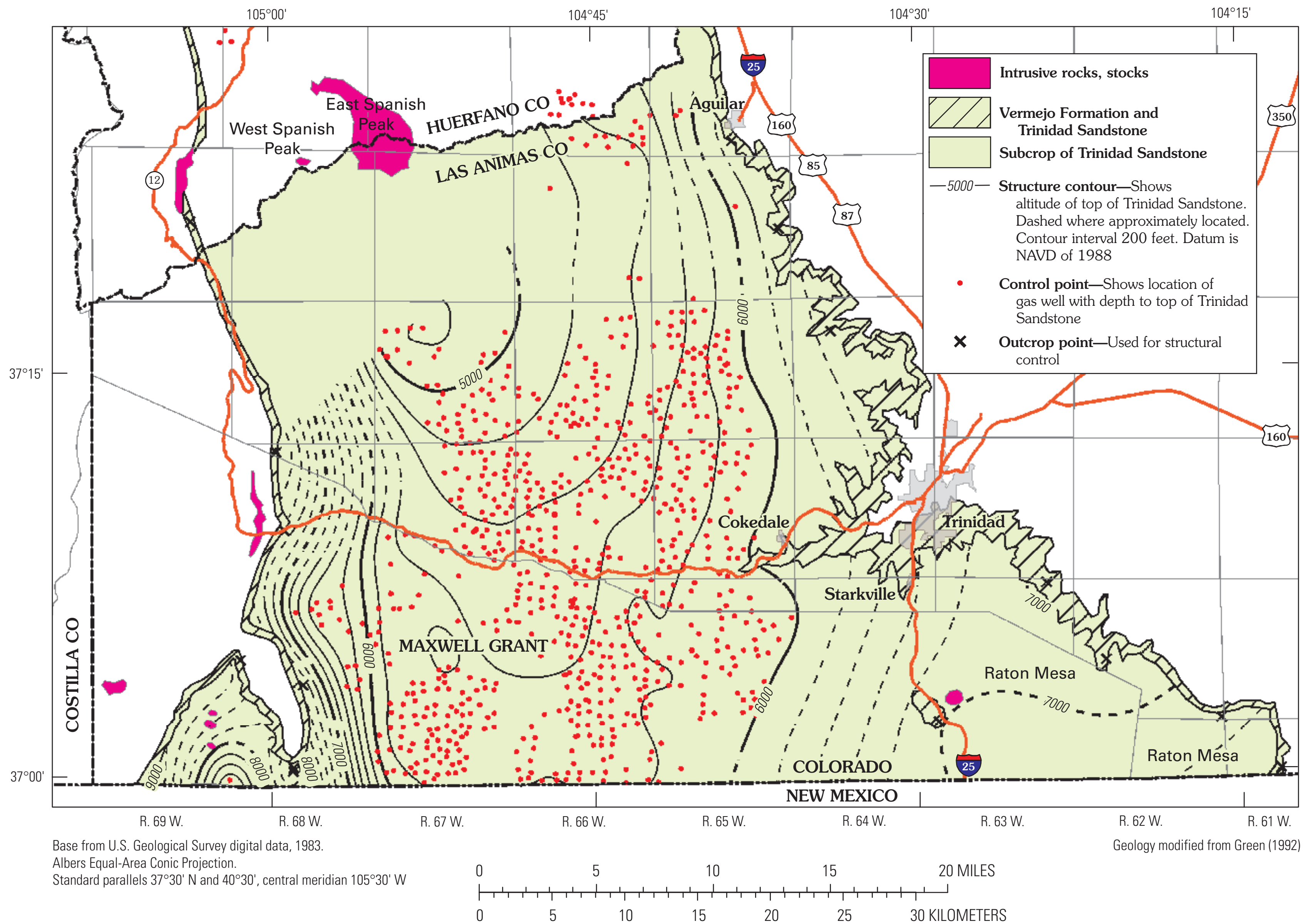


Figure 6. Generalized configuration of the top of the Trinidad Sandstone in Las Animas County, Colorado.

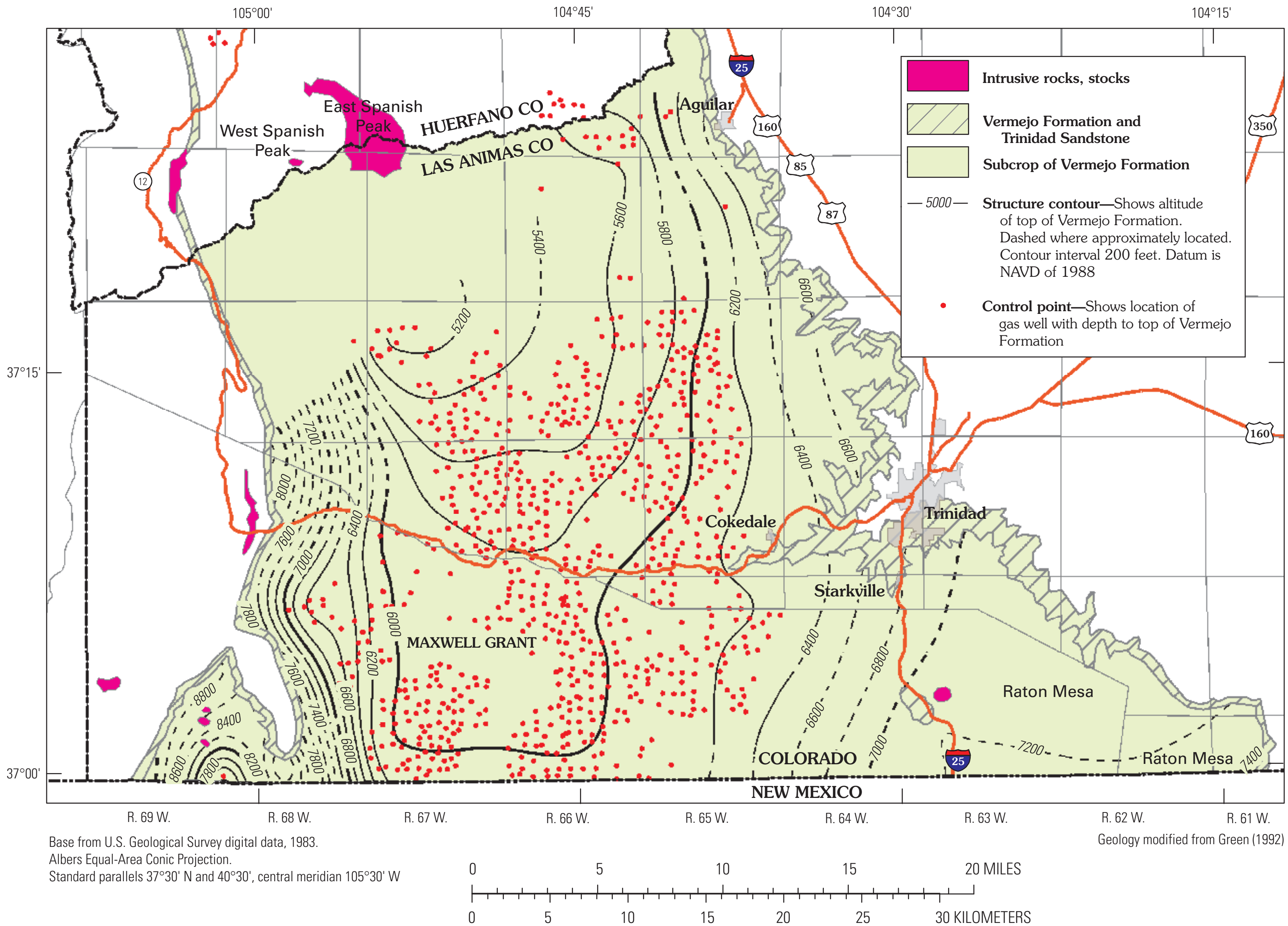
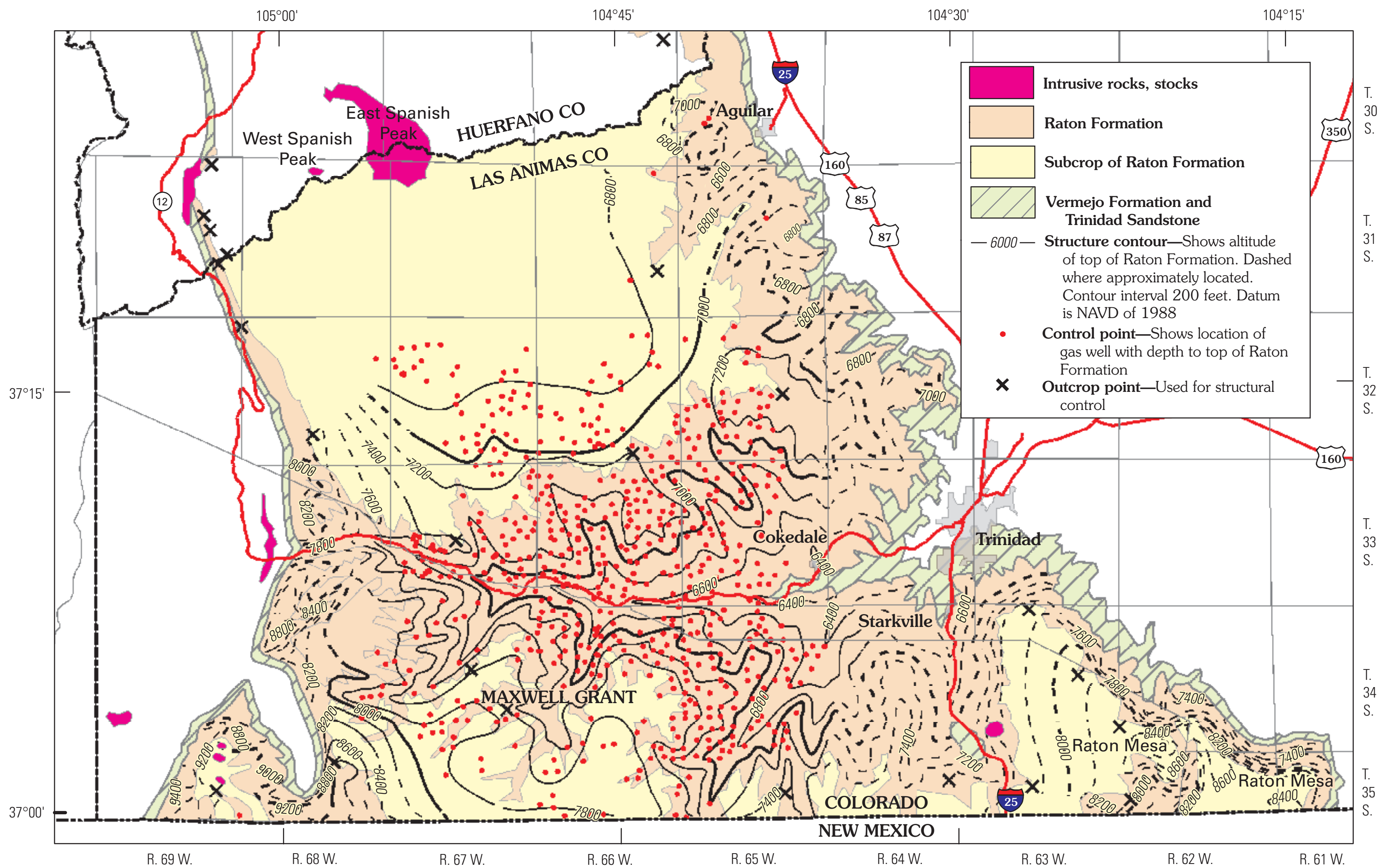


Figure 7. Generalized configuration of the top of the Vermejo Formation in Las Animas County, Colorado.



Base from U.S. Geological Survey digital data, 1983.
Albers Equal-Area Conic Projection.
Standard parallels 37°30' N and 40°30', central meridian 105°30' W

Geology modified from Green (1992)

0 5 10 15 20 MILES
0 5 10 15 20 25 30 KILOMETERS

Figure 8. Generalized configuration of the top of the Raton Formation in Las Animas County, Colorado.

the Vermejo and Raton Formations, respectively. The surfaces are well defined, where there is adequate subsurface control from CBM wells, but are poorly defined in the northern part of the study area, near Spanish Peaks, and along the eastern and western margins of the Raton Basin. The contours (figs. 5–8) are dashed where there is little subsurface control. The configuration of the top of the Trinidad Sandstone (fig. 6) is similar to that previously mapped (Geldon, 1989, his fig. 43). Measurements of the altitudes of formation contacts at outcrop and additional subsurface control likely would improve the definition of the structural surfaces along the margins of the Raton Basin.

Depth to Bottoms and Tops

The generalized depths to the bottom and top of the Trinidad Sandstone and to the tops of the Vermejo and Raton Formations (figs. 9–12, respectively) were calculated, using the spatial analyst tools in ESRI ® ArcMap™ 9.1 (Environmental Systems Research, Inc., 1999–2005), as the difference between the estimated altitude of the land surface, from the NED, and the altitude of the respective surface (figs. 5–8). Computer-generated lines of equal depth to the top of stratigraphic units were smoothed and edited. Because the surfaces represent contacts between successive stratigraphic units, the top of one stratigraphic unit is equivalent to the bottom of the overlying stratigraphic unit, unless the overlying unit has been removed by erosion. The depths to the bottom and top of the Trinidad Sandstone and to the tops of the Vermejo Formation (figs. 9–11) are equivalent to the thickness of the rocks overlying those surfaces. Except where overlain by basalt flows, the thickness of the rock overlying the top of the Raton Formation (fig. 12) is equivalent to the combined thickness of the Poison Canyon, Cuchara, and Huerfano Formations. The contours of depth to the bottom of the Trinidad Sandstone and to the tops of the Trinidad Sandstone and Vermejo and Raton Formations from land surface are shown as dashed lines (figs. 9–12) because the depths are generalized from the difference between two estimated surfaces.

Apparent Thicknesses

Maps of the generalized thickness of the Trinidad Sandstone (fig. 13), the Vermejo Formation (fig 14), and the Raton Formation (fig. 15), though previously estimated using geostatistical models, also were calculated, using the spatial analyst tools in ESRI ® ArcMap™ 9.1 (Environmental Systems Research, Inc., 1999–2005), as a grid of the edited altitude of the top of a stratigraphic unit minus a grid of the edited altitude of the top of the underlying stratigraphic unit. Lines of equal thickness of the stratigraphic units were computer generated from the resultant grids and were smoothed and edited. The contours of equal apparent thicknesses of the Trinidad Sandstone and Vermejo and Raton Formations are shown as dashed lines (figs. 13–15) because they are generalized from the difference between two estimated surfaces. Detailed measured (geologic) sections at outcrops along the eastern and western sides of the study area could improve the maps of formation thickness and provide a better understanding of the spatial variability of lithology (internal geometry) of these aquifers in the subsurface.

The apparent thicknesses of the Trinidad Sandstone (fig. 13), the Vermejo Formation (fig. 14), and the Raton Formation (fig. 15) equal the altitude of the top of the respective formation minus the altitude of the top of the underlying formation. Apparent thicknesses of the selected formations were calculated using grids of the edited contours shown in figures 5–8. For example, the apparent thickness of the Trinidad Sandstone equals the altitude of the top of the Trinidad Sandstone (fig. 6) minus the altitude of the bottom of the Trinidad Sandstone (fig. 5).

The thicknesses are referred to as “apparent thicknesses” because the formations dip from the horizontal and the formations’ thicknesses, which are calculated from reported formation tops and bottoms or from figs. 5–8, are not measured perpendicular to the bedding planes of the formations. Correction of apparent thickness is larger than 5 percent when the dip angle is larger than about 18º from horizontal. For example, near the western side of the study area, where bedding dips steeply, approaching 90º, formation thicknesses are overestimated. The thickness of a dipping formation, the thickness perpendicular to the bedding plane, is equal to the product of apparent thickness of the formation and the cosine of the angle of dip. For example, if the apparent thickness is 100 ft and the angle of dip is 60º, the true formation thickness is 50 ft (100 ft * cosine (60º) = 100 ft * 0.50 = 50 ft). When estimating the transmissive and storage properties of a dipping aquifer from apparent thickness and average material values, the calculated values will overestimate the true values, unless apparent thickness is corrected for the angle of dip.

Regional Water Table

A potentiometric surface is defined as a surface that represents a static head, a water level that is not affected by pumping (Lohman and others, 1972). The water table is the potentiometric surface in an unconfined water body at which the pressure is atmospheric (Lohman and others, 1972). Where the water level is confined or varies appreciably with depth in an unconfined aquifer, the potentiometric surface is meaningful only if it describes the static head along a particular specified surface or stratum in that aquifer (Lohman and others, 1972).

Most water-supply wells in the Raton Basin probably are drilled just deep enough to obtain an adequate supply of water. Few recent measurements of water levels are available for the study area, in State and Federal databases. However, the SEO database includes the reported depth to water, at the time the

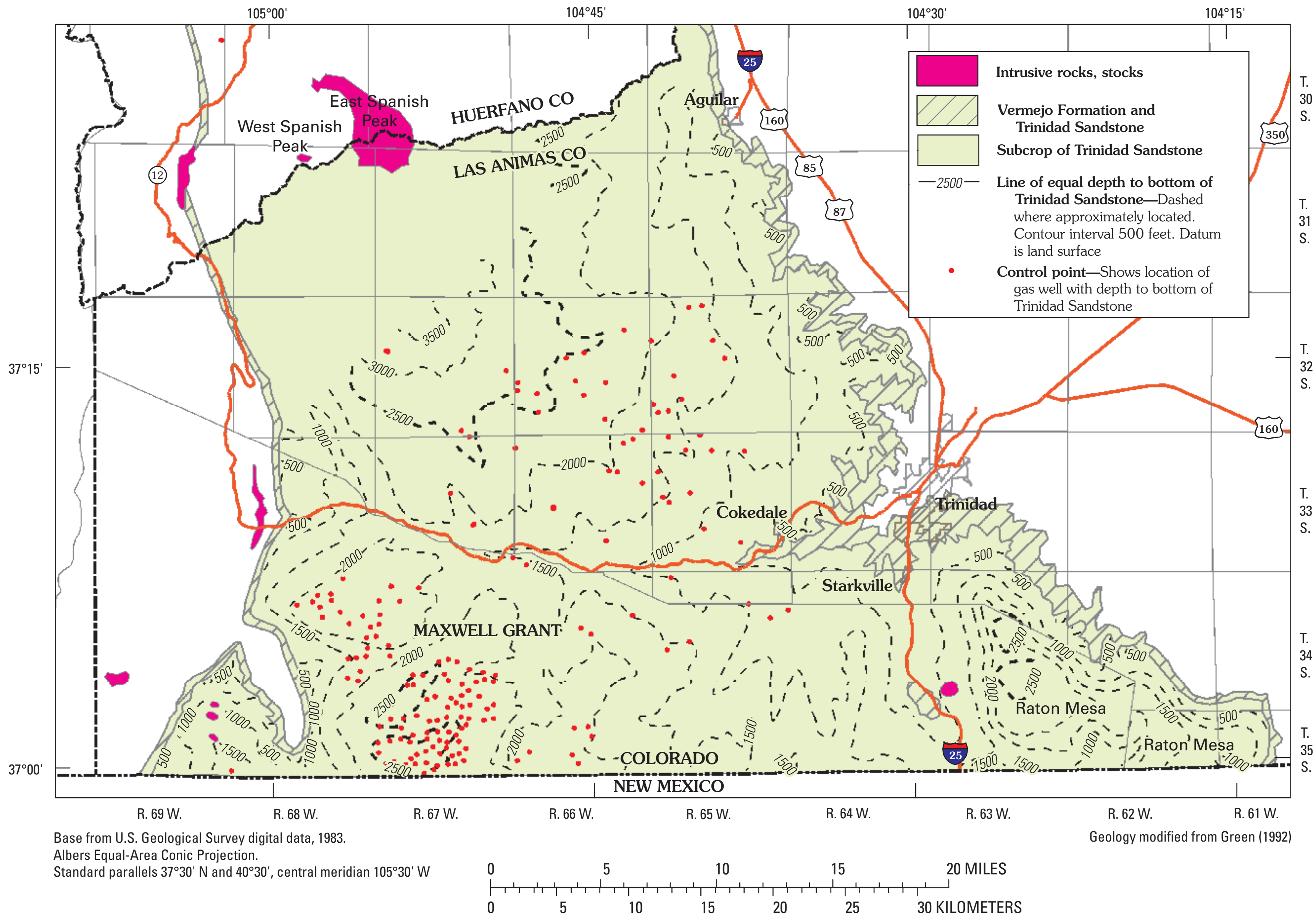


Figure 9. Generalized depth to the bottom of the Trinidad Sandstone in Las Animas County, Colorado.

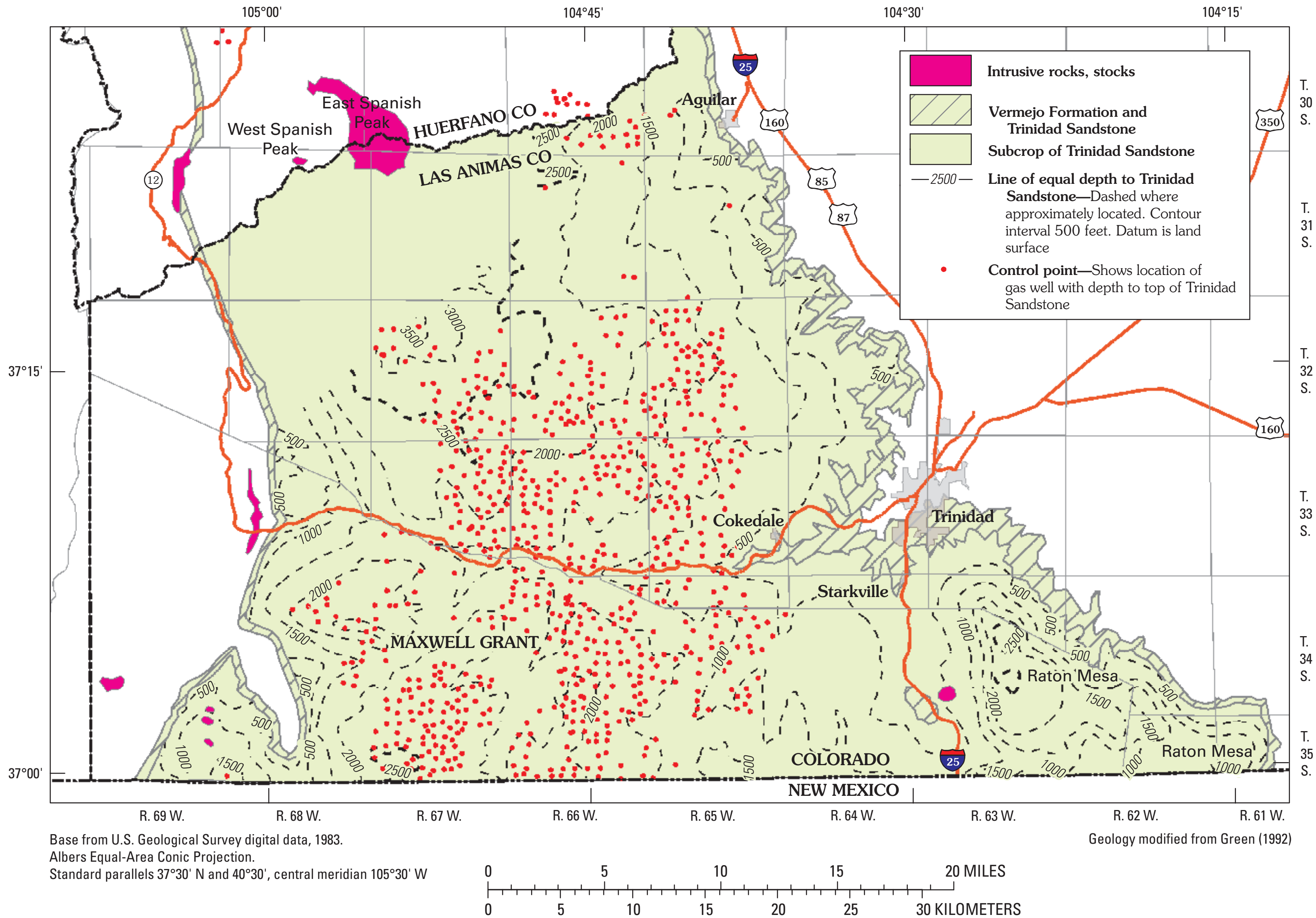
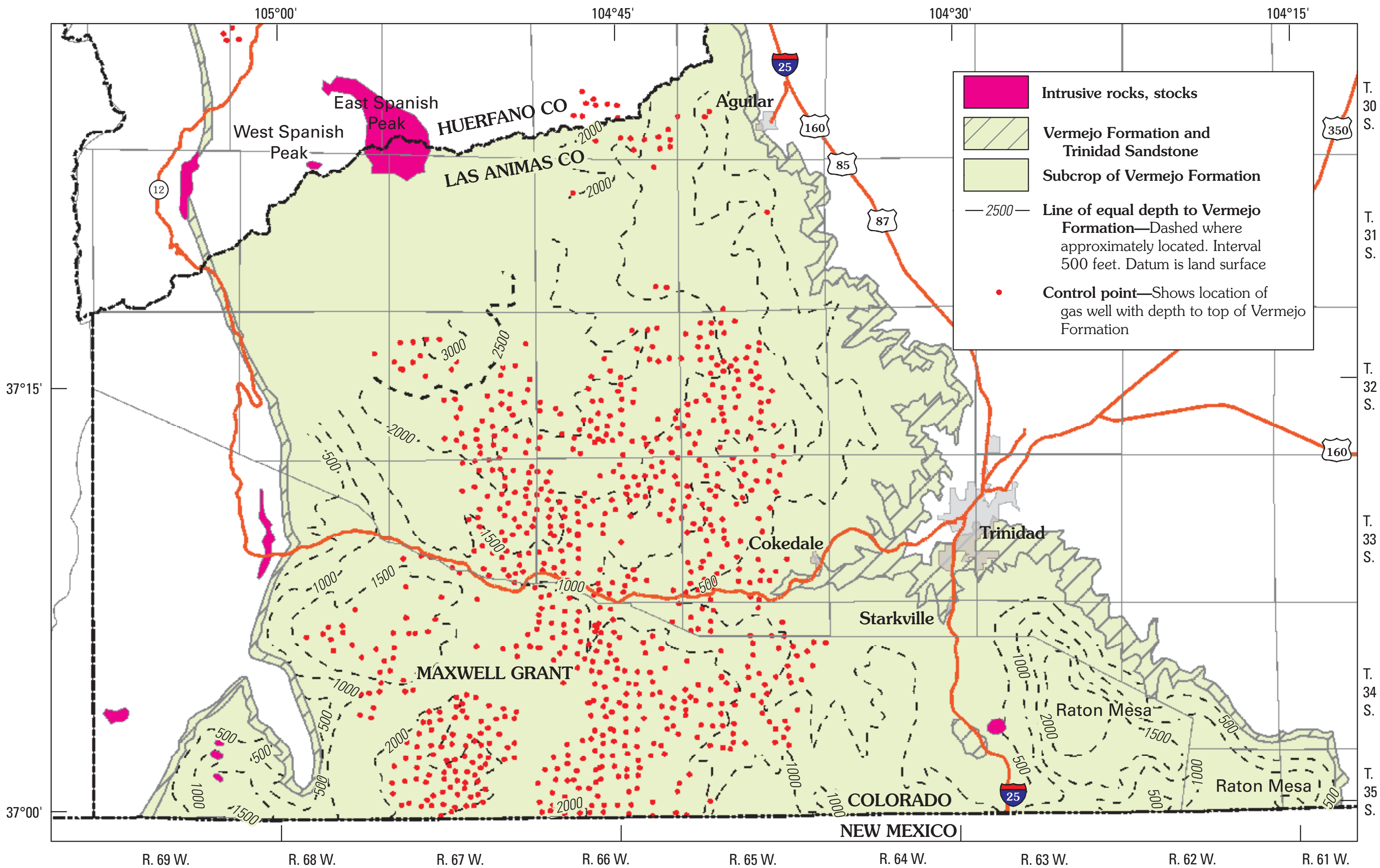


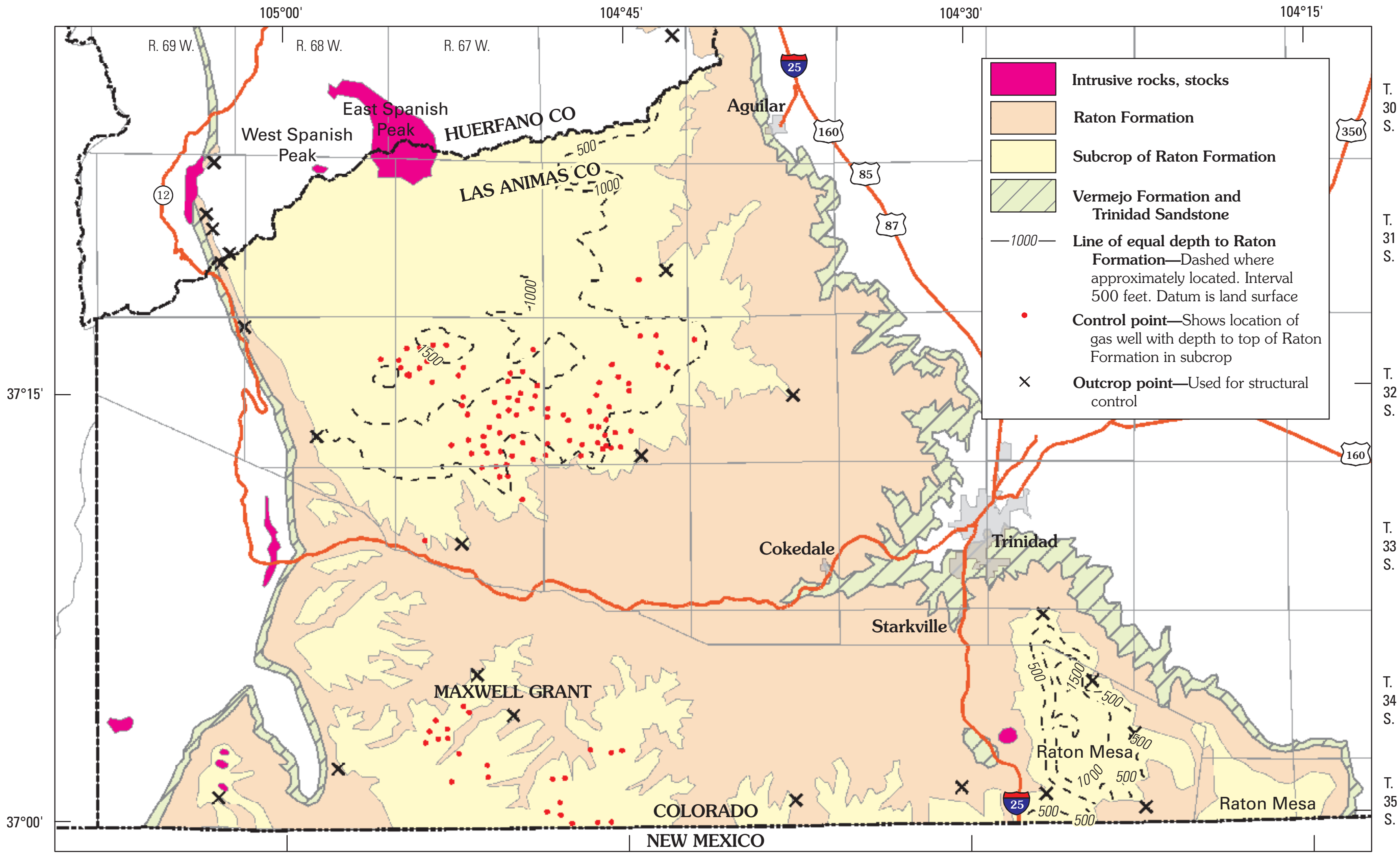
Figure 10. Generalized depth to the top of the Trinidad Sandstone in Las Animas County, Colorado.



Base from U.S. Geological Survey digital data, 1983.
Albers Equal-Area Conic Projection.
Standard parallels 37°30' N and 40°30', central meridian 105°30' W

Geology modified from Green (1992)

Figure 11. Generalized depth to the top of the Vermejo Formation in Las Animas County, Colorado.



Base from U.S. Geological Survey digital data, 1983.
Albers Equal-Area Conic Projection.
Standard parallels 37°30' N and 40°30', central meridian 105°30' W

0 5 10 15 20 MILES
0 5 10 15 20 25 30 KILOMETERS

Geology modified from Green (1992)

Figure 12. Generalized depth to the top of the Raton Formation in Las Animas County, Colorado.

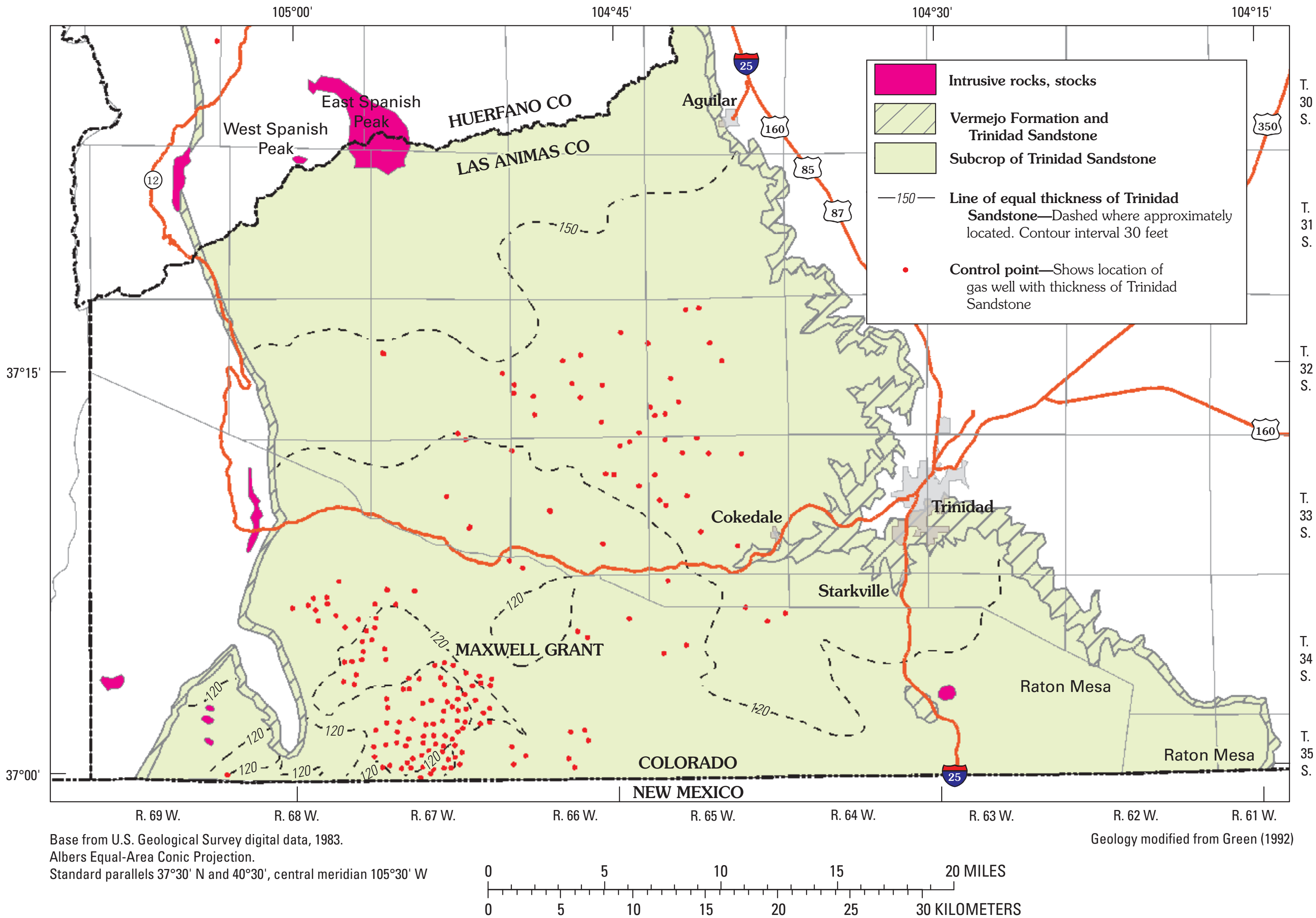


Figure 13. Generalized apparent thickness of the Trinidad Sandstone in Las Animas County, Colorado.

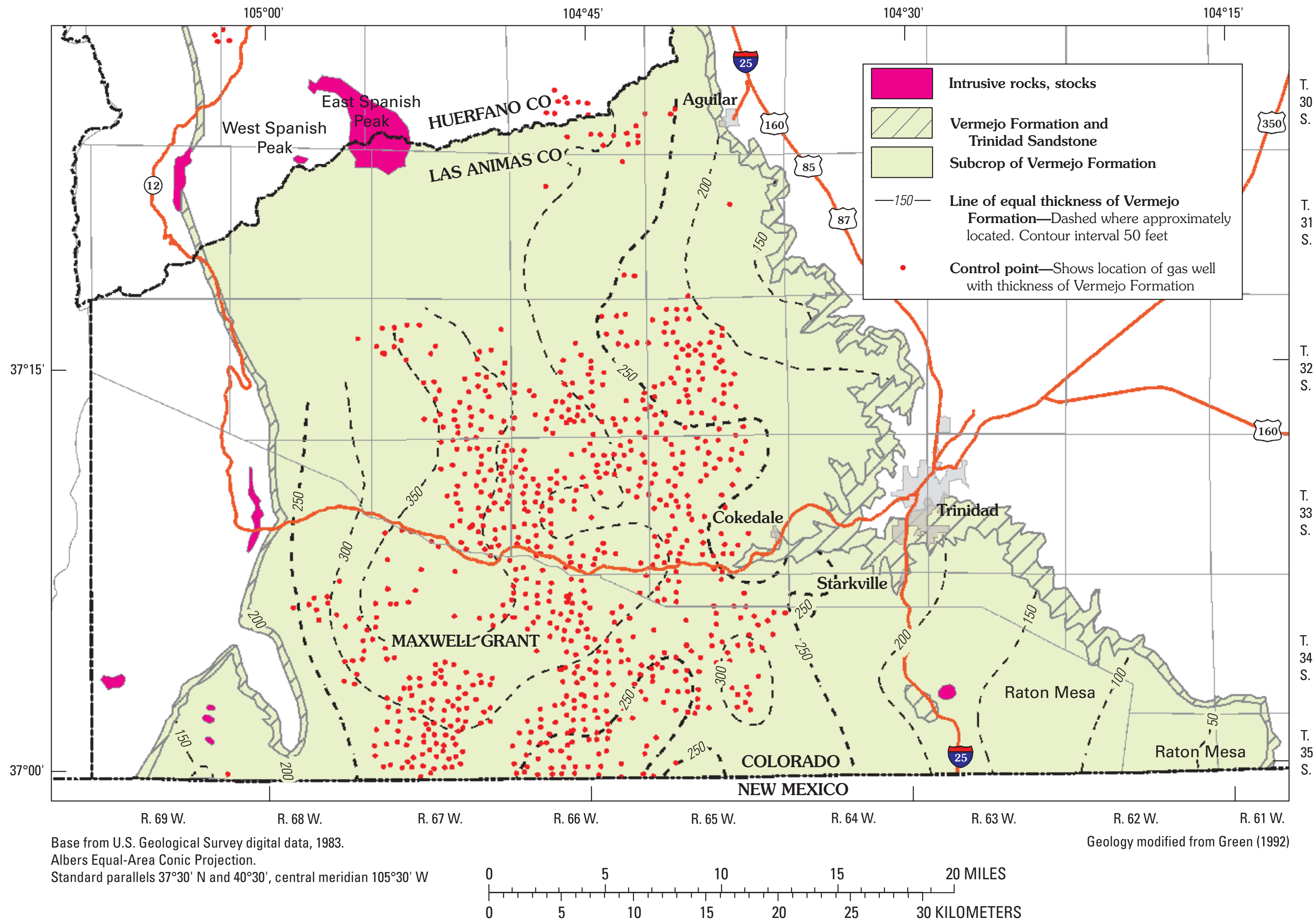


Figure 14. Generalized apparent thickness of the Vermejo Formation in Las Animas County, Colorado.

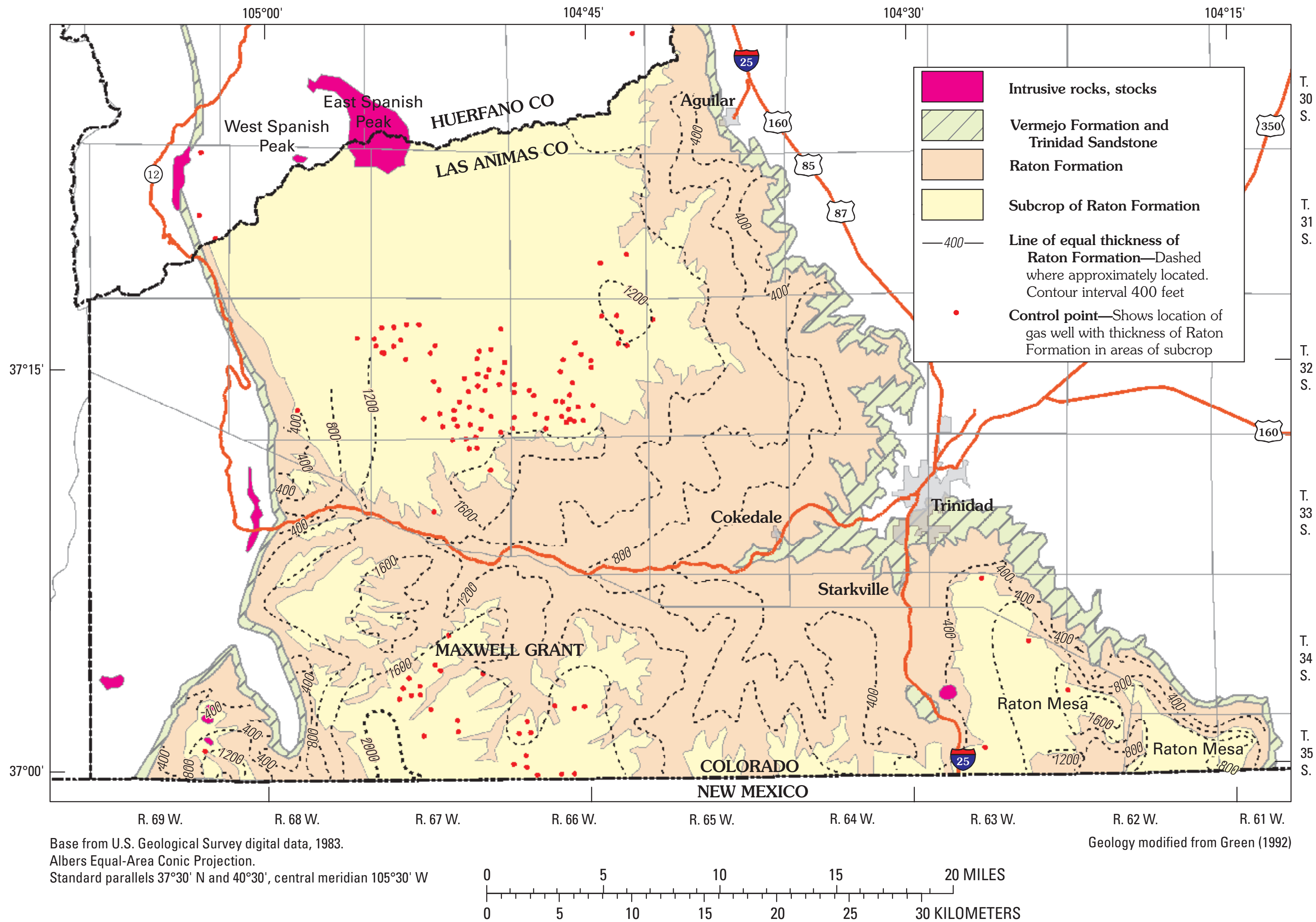


Figure 15. Generalized apparent thickness of the Raton Formation in Las Animas County, Colorado.

wells were completed, in wells completed at various depths within the Huerfano Formation and the alluvial, Cuchara–Poison Canyon, Raton, Vermejo, and Trinidad aquifers. These reported water levels may represent water levels other than the water table that were measured over a period of decades.

The configuration of the regional water table in the northern part of the study area, primarily north of the Purgatoire River, was estimated from reported depth to water in water wells. In the study area, the depths of water wells that had reported depth-to-water values ranged from 8 to 710 ft below land surface. However, only depth-to-water values from wells that are less than 250 ft deep and that were estimated on the basis of reported well depth, estimated land-surface altitude, and figs. 5–8 to be completed in the uppermost aquifer at the well location were used to map the configuration of the long-term regional water table. The aquifer in which a water well was completed was estimated on the basis of the altitude of the bottom of the water well (estimated land-surface altitude minus well depth) relative to the altitudes of the bottom and top of the Trinidad Sandstone and tops of the Vermejo and Raton Formations (figs. 5–8). Only reported depth-to-water values from water wells that are less than or equal to 250 ft deep and that are completed in the uppermost geologic unit, as shown on the digital geologic map of Colorado (Green, 1992), were used in developing the map of the long-term regional water table (fig. 16). Shallow water wells near the Purgatoire or Apishapa Rivers and their tributaries likely are completed in alluvial aquifers but were considered to be completed in the underlying formation.

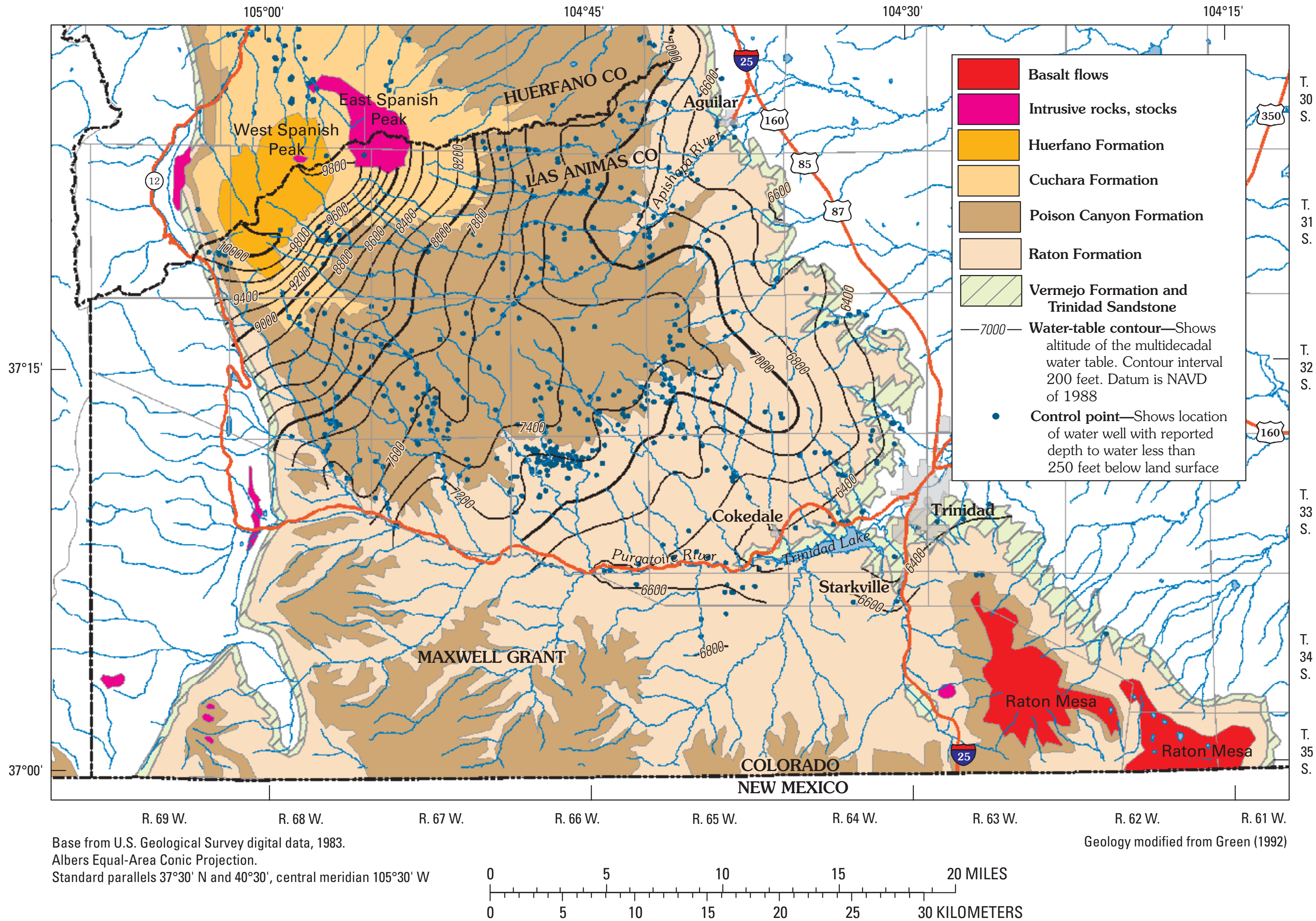
Geostatistical methods, similar to those used to model the structural surfaces, were used to model the altitude of the regional water table (fig. 16). The altitude of the water table at wells was calculated as the estimated altitude of the land surface at the well minus the reported depth to water. Because the range of dates of the reported water-level data in the SEO database is many decades, the regional water table (fig. 16) is assumed to represent average long-term conditions. A map of the potentiometric surface of the Raton-Vermejo-Trinidad aquifer during April–July 1981 (Geldon, 1989) has a configuration similar to the long-term regional water table shown in figure 16.

The estimated depth to the water table (fig. 17) is the depth at which one can expect to measure water levels in wells drilled just into the water table. The generalized depth-to-water surface (fig. 17) equals the estimated land-surface altitude minus the long-term regional water-table altitude. The estimated depth to water is greater than 600 ft on the flanks of the Spanish Peaks and, locally, in an area about 6 mi north-northwest of Trinidad (fig. 17). Estimates of depth to water greater than 250 ft, the maximum depth of wells used to model the water table (fig. 16), occur because the depth to water was calculated as the difference between the land-surface altitude and the water-table altitude. The apparent discrepancy between the estimates of depth to water that are greater than the reported depths to water result from differences in the types of surfaces. The water table is a smooth surface and the land surface is an erosional surface, with relatively large local relief. Although it generally is assumed that the water table mimics the topography of the land surface, in areas where streams have cut deeply into the rock, the streams act as drains and the slope of the water table is more subdued than the slope of the land surface. Consequently, ground-water levels under drainage divides likely are affected more by the relative height of nearby drains than by the height of the land surface on the divide.

Limitations and Other Uses of Hydrostratigraphic Maps

The intended use of the hydrostratigraphic maps (figs. 5–15), the long-term regional water-table map (fig. 16), and depth-to-water map (fig. 17) is to provide a framework for evaluation of the availability and sustainability of ground-water resources in the Raton Basin in Las Animas County, Colorado. A better understanding also is needed of the internal geometry (spatial variability of hydraulic and storage properties) of the Raton, Vermejo, and Trinidad aquifers; of both the internal and external geometry of the Cuchara–Poison Canyon aquifer; and of the three-dimensional fluid-pressure regime of the Raton Basin aquifers to evaluate the ground-water resources in the Raton Basin. The hydrostratigraphic maps of the Raton, Vermejo, and Trinidad aquifers are reasonably accurate in areas where there is adequate subsurface control from CBM wells; however, where there is little subsurface control along the eastern and western sides of the study area, accurate surveying of geologic contacts and measurements of formation thickness (measured sections) could substantially improve accuracy in the estimated surfaces and thicknesses. Detailed analyses of geophysical logs, cores, and measured sections and probabilistic methods of data analyses likely would be needed to approximate the spatial distribution of lithology (internal geometry) within the hydrostratigraphic units.

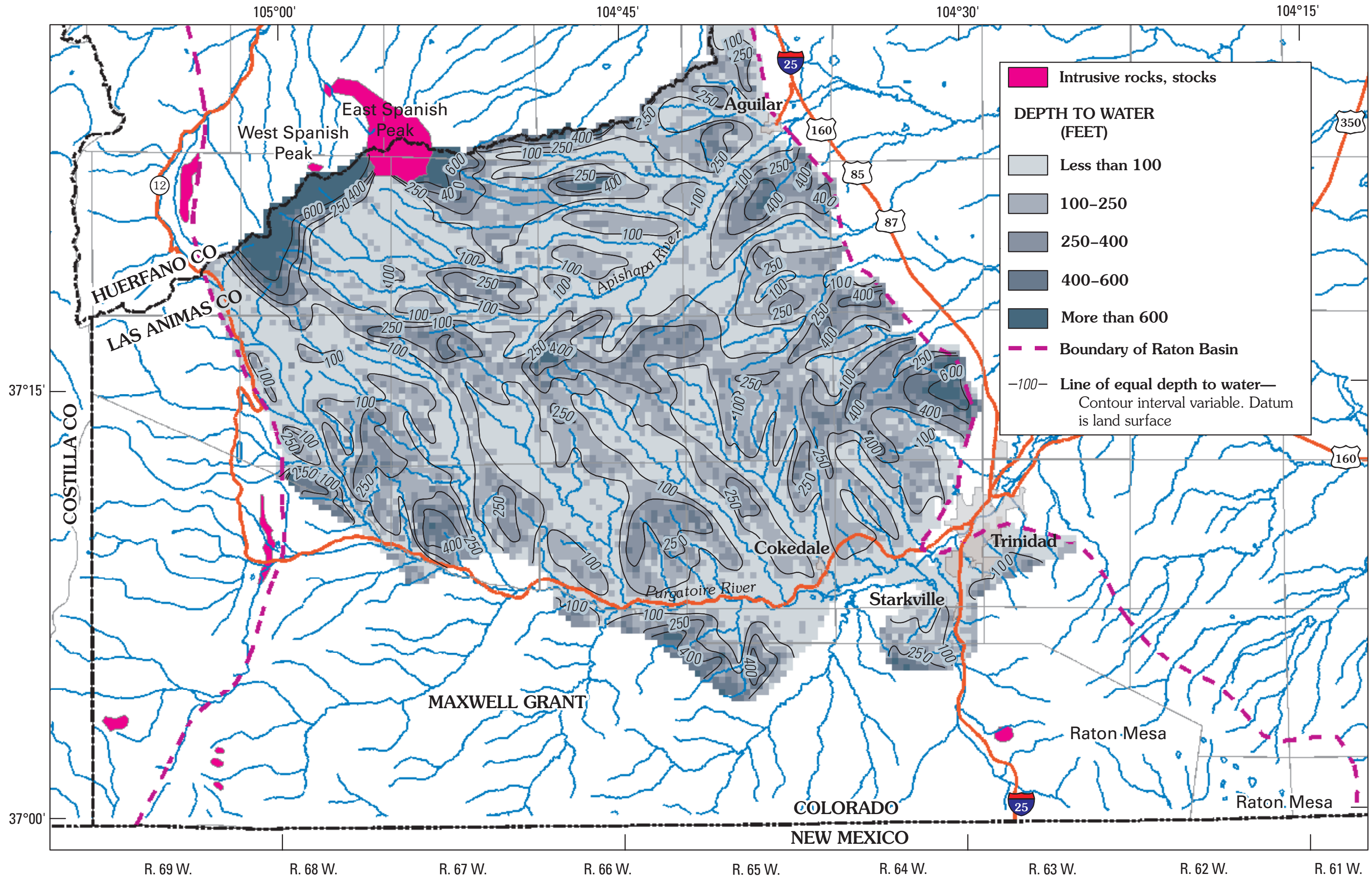
The hydrostratigraphic maps (figs. 5–15) that were developed to better define the hydrostratigraphy of the Raton, Vermejo, and Trinidad aquifers also can be used for other purposes. For example, if the contributing aquifer or aquifers in which a water-supply well is completed is not identified in the SEO database, it can be estimated using figures 5–8 or 9–12. If the location, land-surface altitude, and depths of the completed interval of a water well are known, then figures 5–8 can be used to estimate the aquifer or aquifers in which a well is completed; or if only the location and depths are known, then figures 9–12 can be used to estimate the aquifer or aquifers in which a water well is completed. Figures 9–12 also can be used to estimate the depths to the Raton, Vermejo, and Trinidad aquifers for new wells. Figures 16–17 can be used to estimate the minimum depth that a new well likely would have to be drilled to reach the regional water table.



Base from U.S. Geological Survey digital data, 1983.
Albers Equal-Area Conic Projection.
Standard parallels 37°30' N and 40°30', central meridian 105°30' W

Geology modified from Green (1992)

Figure 16. Generalized configuration of the long-term regional water table in the northern part of the study area.



Base from U.S. Geological Survey digital data, 1983.
Albers Equal-Area Conic Projection.
Standard parallels 37°30' N and 40°30', central meridian 105°30' W

Geology modified from Green (1992)

0 5 10 15 20 MILES
0 5 10 15 20 25 30 KILOMETERS

Figure 17. Estimated depth to water below land surface in the northern part of the study area.

Summary

Exploration for and production of coalbed methane has increased substantially in the Rocky Mountain region of the United States since the late 1990s. Annual production of natural gas in Las Animas County, Colorado, increased about threefold from 28,129,515 in 1999 to 80,224,130 thousand cubic feet in 2004. The annual volume of ground water coproduced by gas wells in Las Animas County increased from about 949 million gallons in 1999 to about 2,879 million gallons in 2004. Because coal beds and associated sandstones also are aquifers in the Raton Basin, water-well owners and resource managers are concerned that coalbed methane production may affect the availability and sustainability of local ground-water supplies. In 2001, the U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, began a study to compile and evaluate the hydrogeology in the Raton Basin of Colorado. A better understanding of the hydrostratigraphic framework of the Raton Basin is needed for quantitative evaluation of the ground-water resources.

As a result of much additional subsurface data from logs and completion reports of CBM wells, the Raton-Vermejo-Trinidad aquifer could be mapped as three distinct hydrostratigraphic units (aquifers). Geostatistical methods were used to prepare the maps showing the hydrostratigraphic framework of the Raton, Vermejo, and Trinidad aquifers and the generalized configuration of the water table in the Raton Basin, Las Animas County.

The maps, though primarily prepared for defining the hydrostratigraphic framework, also may be useful in estimating depths of proposed water wells and in assigning aquifer designations to existing water wells. The structure and thickness maps of the Trinidad Sandstone and the Vermejo and Raton Formations could be improved with surveying of geologic contacts and measurements of geologic sections at outcrops along the eastern and western margins of the Raton Basin. Additional study is needed to define spatial variability of hydraulic and storage properties and to determine fluid pressure within the Raton, Vermejo, and Trinidad aquifers.

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