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COAL MATURATION AND GEOTHERMAL HISTORY, WEST-CENTRAL NEW MEXICO

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Abstract—Coal maturation data from five regions in west-central New Mexico near the southern boundary of the Colorado Plateau exhibit a relatively uniform level of thermal maturation. While variance (nested ANOVA) and "F" test analyses indicate a relatively minor increase in thermal maturation from the southern San Juan Basin and Gallup regions to the Salt Lake region, which is located in the volcanically-active Jemez lineament, thermal burial history analyses show that differences in maturation levels between the various regions may be due to differences in coal ages, burial depths and/or background heat flow. Model results suggest an average coal burial depth of about 1 km or slightly greater. The effect of recent intrusive activity in the study area on coal maturation is expected to be minimal. The lack of a definite increase in coal maturation across the study area allows several possible suggestions to be made with respect to the Colorado Plateau-Basin and Range province (Datil-Mogollon subprovince) transition. If the transition occurs in the study area, then thermal processes are either deeper, younger or more localized (smaller and widespread) than in the Colorado Plateau-Basin and Range province transition along the northwestern periphery of the Plateau. Alternatively, if large-scale thermal events have been occurring in the upper mantle and crust, they are doing so sufficiently south of the study area that the thermal influence has not been observed.

INTRODUCTION

Late Cretaceous sediments containing coal deposits are present in the study area, located on the southern portion of the Colorado Plateau in west-central New Mexico (Fig. 1). Because maturation levels reflect the thermal history of coal deposits, analysis of coal maturation data from the study area may yield some constraints on the post-Late Cretaceous tectonic history of the southern Colorado Plateau.

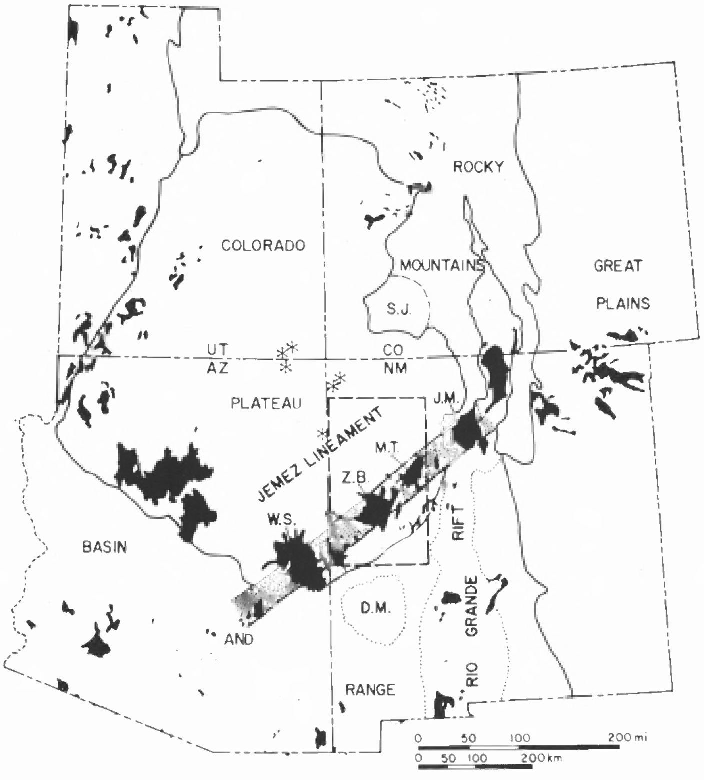

FIGURE 1. Map showing distribution of late Cenozoic (<11 my, shaded areas) volcanic fields in Arizona, Colorado, New Mexico and Utah (after Aldrich and Laughlin, 1984). Volcanic field names: W.S., White Mountains-Springerville; Z.B., Zuni-Bandera; M.T., Mount Taylor; J.M., Jemez Mountains. D.M. and S.J. indicate the location and approximate areal extent of the Datil-Mogollon and San Juan volcanic fields. Asterisks indicate Oligocene volcanic rocks (Naeser, 1971). The Jemez lineament is located by the stippled area. The study area is located between the W.S. and Z.B. volcanic fields (box, dashed line).

The locations of the five coal maturation regions which are considered in this paper suggest the potential for significant differences in thermal histories between the regions (Figs. 1, 2). For example, the Salt Lake coal field (region I, SL in Fig. 2) is located within the volcanically active Jemez zone. Two of the regions, Datil Mountains and Pinehaven (regions II and III, respectively, in Fig. 2), are located adjacent to the Jemez zone. The remaining two regions, Gallup and the southern San Juan Basin (regions IV and V, Fig. 2) are located toward the interior of the Colorado Plateau and away from much of the relatively recent tectonic activity associated with the peripheral regions of the Colorado Plateau.

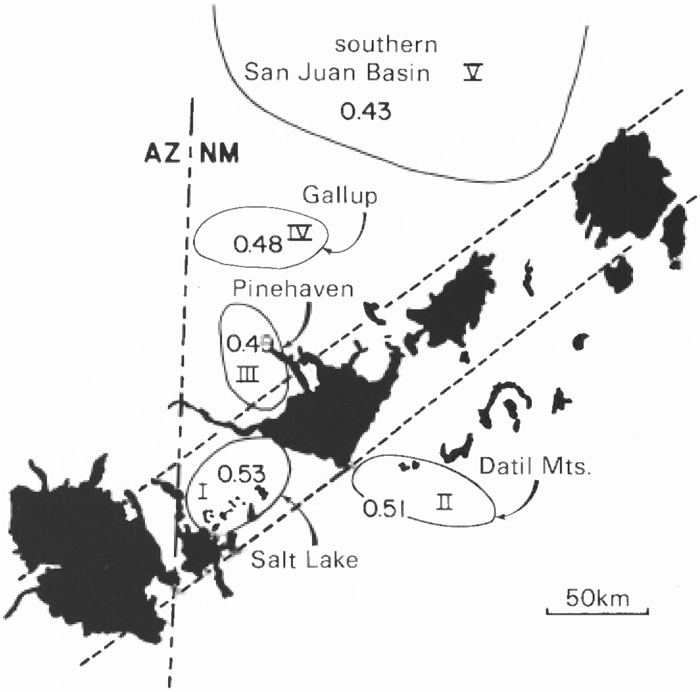

FIGURE 2. Map of study area showing distribution of coal maturation data. Heavy dashed line represents the Arizona-New Mexico state line. Parallel dashed lines represent boundaries of the Jemez zone (Aldrich and Laughlin, 1984). Dark shaded areas represent volcanic rocks. Stippled areas represent coal-maturation-data regions (Table 1). Values within the coal-maturation-data regions are the mean vitrinite reflectance for the regions in percent vitrinite reflectance (Table 1; map after Aldrich and Laughlin, 1984).

Based upon geologic and geophysical data, the Colorado Plateau may be characterized as a relatively undeformed, uplifted crustal block with recent volcanism, seismicity and high heat flow generally limited to the Plateau margins (Keller et al., 1979; Thompson and Zoback, 1979; Bodell and Chapman, 1982; Eggleston and Reiter, 1984). The Colorado Plateau has experienced considerable Laramide deformation, reflected by the presence of numerous monoclines (Kelley, 1955; Davis, 1978; Anderson, 1986). A variety of mechanisms have been proposed to explain many of the tectonic features of the Colorado Plateau (e.g., Davis, 1978; Bird, 1979; Bodell and Chapman, 1982; Eggleston and Reiter, 1984). Of primary interest to this study is the Jemez zone, a northeast-trending chain of late Tertiary-Quaternary volcanic fields, part of which lies near the southern border of the Plateau within the study area (Fig. 1; Chapin et al., 1978).

Late Tertiary and Quaternary volcanism along the Jemez zone appears to be a result of a changing regional stress regime across a pre-existing zone of weakness in the lithosphere (Chapin et al., 1978; Aldrich and Laughlin, 1984). Radiometric dates indicate volcanic activity in the study area from late Miocene to Quaternary time (Bradbury, 1966; Laughlin et al., 1979, 1980; Callender et al., 1983; Aubele et al., 1986; Minier et al., 1988).

In addition to the volcanic rocks present in the study area, geophysical data indicate the presence of magmatic intrusions at relatively shallow depths in the crust. Ander and Heustis (1982) suggest that a gravity anomaly over the Zuni-Bandera volcanic field is probably caused by a shallow mafic intrusion. Anomalously high electrical conductivity at shallow depths also suggests magma intrusion in the crust along the Jemez zone (Ander et al., 1984). Heat-flow data are consistent with the presence of upper crustal heat sources and/or ground-water convection (Minier et al., 1988; Minier and Reiter, in prep.). There does not appear to be a profound heat-flow trend associated with the Jemez zone; high heat-flow, observed both within and away from the Jemez zone, may be controlled by basement fractures related to monocline development (Minier and Reiter, in prep.).

This paper discusses analyses which evaluate regional variability of coal maturation levels, and the effects of burial depth, heat flow and intrusive activity on coal maturation levels. Implications of these analyses with respect to the transition from the southern Colorado Plateau to the Datil-Mogollon subprovince of the Basin and Range province are presented.

COAL MATURATION DATA

In the present study, coal maturation data have been examined in order to provide constraints on potential thermal histories for the study area. The thermal maturation of coal, which is exponentially dependent on temperature but linearly dependent on time, essentially integrates through time the total heating the coal has experienced since its deposition (Dow, 1977; Waples, 1981). The coal maturation data used in this study, discussed below in terms of vitrinite reflectance, are summarized in Table 1 and Figure 2. The coal maturation data within the study area have been divided into several regional data sets for statistical analyses (Fig. 2, Table 1). The average vitrinite reflectance values for each region indicate that the coals have relatively low thermal maturation levels (low rank bituminous, Table 1; Dow, 1977).

The coal maturation data indicate a rather uniform level of thermal maturation for the study area (Fig. 2). There does not appear to be a profound trend of increasing coal maturation toward areas of volcanic activity as is apparent going northward across the San Juan Basin (i.e., 0.40 to 1.10% across the San Juan Basin: Clarkson, 1984). Results of thermal models (discussed later) suggest that the difference in burial times (about 19 my) between the Fruitland Formation coals of the southern San Juan Basin (Group V, Fig. 2) and the coals south of the southern San Juan Basin (Groups I–IV, Fig. 2) can account for much of the relatively small difference in thermal maturation levels between the two areas. The level of maturation in the Salt Lake region (within the volcanically active Jemez zone, Fig. 2, Table 1) appears to be somewhat elevated with respect to the level of maturation in the surrounding regions (i.e., the Datil Mountains, Pinehaven, Gallup and southern San Juan Basin regions; Fig. 2, Table 1).

TABLE 1. Data groups used for variance and "F" test analyses for vitrinite reflectance data. Data are from Fieldner et al. (1936), Allen and Balk (1954), Fassett and Hinds (1971), Chapin et al. (1979), Frost et al. (1979), Tabet (1981), Osburn (1982), Anderson and Mapel (1983) and Campbell (1984, unpublished data). Data originally presented in terms of percent volatile matter have been converted to percent vitrinite reflectance using the correlation scale of Dow (1977).

Region		N sites	N samples	R (sites) (% Ro)	R(samples) (% Ro)
I	Salt Lake	33	144	0.53±0.11	0.53±0.11
II	Datil Mtns.	18	26	0.51±0.10	0.50±0.11
III	Pinehaven	5	8	0.49±0.09	0.47±0.09
IV	Gallup	28	68	0.48±0.05	0.47±0.05
V	s. San Juan B.	17	17	0.43±0.09	0.43±0.09

R(sites) is the mean site vitrinite reflectance and standard deviation within a region. R(samples) is the mean sample vitrinite reflectance and standard deviation within a region. N sites is the number of data sites within a region. N samples is the number of data samples within a region. The Kolmogorov-Smirnov test does not lead to rejection of normality at about the 5% significance level for data regions I, II and III (Lindgren and others, 1978). The sample distributions for regions IV and V are somewhat skewed but appear to be approximately normal (Dixon and Massey, 1983).

A nested analysis of variance model, after Snedecor and Cochran (1973), was applied to the coal maturation data to examine several levels of variance in the maturation data (described in Table 2). The largest components of variance estimated are generally the "between samples within sites" (up to a standard deviation of about 0.10% vitrinite reflectance, Table 2). Standard deviations for "between sites within regions" and "between regions" are less than about 0.05% vitrinite reflectance. In other words, most of the variance in the maturation data comes from different data taken at the same site.

An approximate "F" test was also applied to the components of variance results to determine whether regional differences in vitrinite reflectance exist (see Graybill, 1961; Reiter et al., 1985; Table 3). Perhaps the most statistically significant regional difference in coal maturation levels is between the Salt Lake region and the southern San Juan Basin and Gallup regions; i.e., differences in mean maturation levels between the Salt Lake region and the latter two regions are probably not due to chance alone (regions I and IV; and regions I and V; Table 3). Comparisons between other regions do not seem to exhibit statistically significant differences in mean maturation levels. Similar results in differentiating regions were obtained by applying the students' t-test to the sample-site maturation values; however, the t-test does not nest the components of variance (Minier, 1987).

Although some of the maturation levels are statistically different, it is important to evaluate the geologic significance of the differences, since for large enough numbers of samples even very slight differences may be detected as statistically significant (Lindgren et al., 1978). Vitrinite reflectance measurements of a coal-seam sample generally yield a normal distribution about the mean, with a standard deviation in the data of about 0.10% vitrinite reflectance (Stach et al., 1982). Similar standard deviations of the data are inferred from the "between samples within site" variance estimates in Table 2 (estimated standard deviations "d" between samples within sites, 0.028 to 0.102% vitrinite reflectance) which in almost all cases are much greater than the "between regions" variance estimates. Thus, while differences in the mean levels of maturation for some of the various regions within the study area may be statistically significant, the geologic significance of the difference between means may be slight or perhaps questionable.

The lack of a profound trend in the coal maturation data is consistent with observations of heat-flow data in the study area. Regional trends in heat flow are not observed in the study area (Minier and Reiter, in prep.). The heat-flow data suggest that post-Cretaceous thermal events which may be associated with the southern Colorado Plateau have been initiated relatively recently and/or are occurring at relatively great depths, as compared to the Colorado Plateau-Basin and Range province tran-

TABLE 2. Variance analyses for vitrinite reflectance data sets. Analyses after presentations in Snedecor and Cochran (1973). Standard deviations also presented for comparison in percent vitrinite reflectance.

Regions	d^2 d (% Ro)	w^2 w (% Ro)	r^2 r (% Ro)
I,II,III,IV,V	0.00790 (0.089)	0.00098 (0.031)	0.00139 (0.037)
I,II,III,IV	0.00790 (0.089)	0.00106 (0.033)	0.00101 (0.032)
I,II,III	0.01023 (0.101)	0.00123 (0.035)	0.00019 (0.014)
I,II	0.01044 (0.102)	0.00118 (0.034)	0.00014 (0.012)
I,III	0.01019 (0.101)	0.00132 (0.036)	0.00052 (0.023)
II,III	0.00837 (0.091)	0.00208 (0.046)	-0.00073 (NA)
III, IV	0.00088 (0.030)	0.00214 (0.046)	-0.00033 (NA)
IV,V	0.00079 (0.028)	0.00275 (0.052)	0.00052 (0.023)
I,IV	0.00787 (0.089)	0.00086 (0.029)	0.00165 (0.041)
I,V	0.01041 (0.102)	0.00085 (0.029)	0.00438 (0.066)

Region I - Salt Lake; Region II - Datil Mountains; Region III - Pinehaven; Region IV - Gallup; Region IV - southern San Juan Basin.
d^2, d - variance and standard deviation estimates "between samples within sites", standard deviation in parentheses
w^2, w - variance and standard deviation estimates "between sites within regions", standard deviation in parentheses
r^2, r - variance and standard deviation estimates "between regions", standard deviation in parentheses
NA - not applicable, standard deviation estimate not calculated since variance estimate less than zero.
Note: Negative values reflect that the variance components are estimated by the nested analysis of variance (see Snedecor and Cochran, 1973; Reiter and others, 1985).

TABLE 3. "F" test analyses for various vitrinite reflectance regions. Analyses after Graybill (1961) and Dixon and Massey (1983).

Regions	degrees of freedom	F	P
I,II,III,IV,V	4, 67	6.113	$P < 0.01$
I,II,III,IV	3, 53	4.966	$P < 0.01$
I,II,III	2, 62	1.403	$0.25 \leq P < 0.50$
I,II	1, 46	1.421	$0.10 < P < 0.25$
I, III	1, 70	1.600	$0.10 < P < 0.25$
II, III	1, 16	0.2564	$0.50 < P < 0.75$
III, IV	1, 32	0.0721	$0.75 < P < 0.90$
IV, V	1, 45	3.716	$0.05 < P < 0.10$
I, IV	1, 22	12.15	$P < 0.01$
I, V	1, 80	11.83	$P < 0.01$

Region I - Salt Lake; Region II - Datil Mtns.; Region III - Pinehaven; Region IV - Gallup; Region V - southern San Juan Basin.
Degrees of freedom are approximated (Graybill, 1961; Reiter and others, 1985). F is the "F" value used in the statistical test. P values are discussed in the text; the smaller the P value the more confidence one may have that the difference in means of the various regions is not due to chance alone and thus is real.

sition along the northwestern periphery of the Plateau, or are in the form of relatively small, widely spaced intrusions (Minier and Reiter, in prep.). If the thermal sources associated with the Datil-Mogollon volcanic field are of the same scale as those in the San Juan volcanic field, one might expect to see a trend in coal maturation within about 75 km of the thermal source. From the relatively uniform maturation data across the study area it appears that the thermal source associated with the Datil-Mogollon volcanic field must be at least 75 km south of the study area. Alternatively, the thermal source beneath the Datil-Mogollon volcanic field may have occurred over a shorter time period than the San Juan thermal source (i.e., the Datil-Mogollon volcanic field may not have been thermally replenished in the subsurface as proposed for the San Juan volcanic field: Clarkson and Reiter, 1988). A third possibility may be the absence of a regional hydrothermal influence on coal maturation. It seems likely that ground-water flow has swept heat from the San Juan volcanic field into the San Juan Basin and as such has influenced the regional distribution of coal maturation in the Basin (Clarkson and Reiter, 1988).

ANALYSIS OF THERMAL-BURIAL HISTORIES

Burial depth considerations

Coal maturation levels may be predicted using estimates of coal thermal-burial histories (Waples, 1980, 1981). Such geothermal models may incorporate surface temperature variations due to paleoclimate and uplift, with models of the burial history of the coals in the study area. Burial histories are somewhat constrained by present sediment thicknesses, sediment ages, erosional unconformities and estimated rates of deposition/erosion. The Time-Temperature Index of maturation (TTI) method has been used to calculate maturation levels for geothermal models of the study area (Waples, 1980; Clarkson, 1984). The calculated values of vitrinite reflectance are compared to observed levels of thermal maturation. Analyses of coal maturation data, when combined with heat-flow data and volcanic age dates, may help define the post late-Cretaceous thermal history of the area and constrain tectonic models for the late Cenozoic evolution of the southern Plateau boundary.

The level of maturation of the Fruitland Formation coals in the southern San Juan Basin may be closely matched by thermal models which use a generalized San Juan Basin geologic history with a steady-state heat flow (Clarkson, 1984; Clarkson and Reiter, 1987). Because of the proximity of the southern San Juan Basin to the southern part of the study area and because the heat-flow data suggest the background heat flow for the southern part of the study area may be similar to or perhaps somewhat greater than the heat flow for the southern San Juan Basin, the generalized steady-state thermal history model of Clarkson (1984) has been extended to predict coal maturation levels for the entire study area.

Clarkson (1984) presents a burial history for the Fruitland Formation coals in the southern San Juan Basin which, when combined with a steady-state thermal model, yields calculated levels of maturation in good agreement with observed values. The thermal model assumes steady-state surface heat flow of 67 mW/m² which is the approximate average of measurements of the present-day heat flow in the southern San Juan Basin (Clarkson, 1984). The thermal model presented by Clarkson (1984) is modified here to predict coal maturation levels in the southern part of the study area.

Coals in the present study area are located within Upper Cretaceous sediments which have been deposited approximately 95 to 89 my, except for the Fruitland Formation coals in the southern San Juan Basin which were deposited about 75 to 71 my (Molenaar, 1977; Hook, 1983; Campbell and Roybal, 1984). Deposition in the Salt Lake region since Late Cretaceous time (92 my) has been interrupted by periods of weathering and erosion (Guilinger, 1982). Late Tertiary-Recent erosion occurred regionally, including much of the study area (Molenaar, 1977). Present burial depths of coals in the study area are generally less than burial depths of Fruitland Formation coals in the southern San Juan Basin. For example, coal samples from the Salt Lake, Datil Mountains and Pinehaven regions are from depths in the range of 0 to 0.1 km (samples in the Gallup region were obtained from depths of 0 to approximately 0.2 km), whereas samples in the southern San Juan Basin were obtained from depths of 0 to 1 km (see references given in Table 1). Therefore, modification of the thermal model presented by Clarkson (1984) of the southern San Juan Basin for use in the present study area requires extending the model history from about 72 my to about 92 my and decreasing the present-day depth of burial (Molenaar, 1977; Fig. 3, model 1). Transient temperature effects (for example due to sedimentation) are not incorporated into the present model. The coal temperature at a given time is approximated by multiplying the steady-state tem-

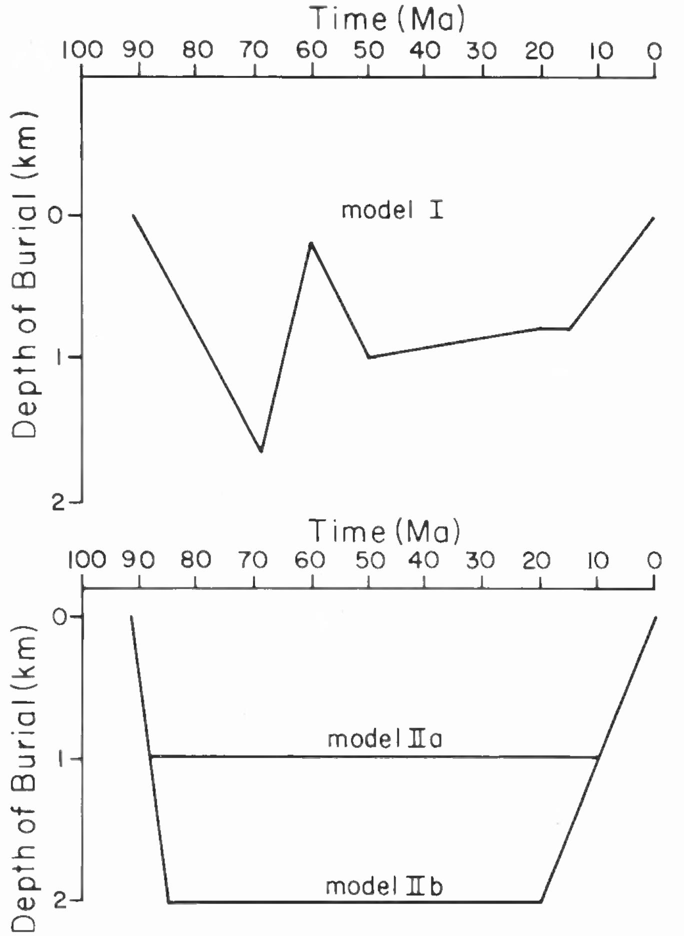

FIGURE 3. Top, model I, burial history for coals in the study area (modified from burial history for the Fruitland Formation coals in the southern San Juan Basin: Clarkson, 1984). Bottom, models IIa and IIb, burial histories for coals in the study area modified from general San Juan Basin burial histories (after Clarkson, 1984).

perature gradient by the burial depth of the coal and adding the surface temperature. The modified burial history is generally consistent with the limited amount of stratigraphic information available for the area (Molenaar, 1977; Guilinger, 1982). However, detailed stratigraphic studies yielding burial histories more representative of the study area would be most useful.

The level of maturation predicted by the modified burial history (Fig. 3, model I) is about 0.47% vitrinite reflectance and agrees well with the observed values for the coals in the Pinehaven and Gallup regions (0.47–0.49% vitrinite reflectance, Table 1). Somewhat higher temperatures, perhaps due to deeper burial depths or higher heat flow, are required to match the observed coal maturation levels in the Salt Lake and Datil Mountains regions (Table 1, Fig. 2).

More generalized, hypothetical thermal models may now be considered in order to illustrate the effect of burial depth on the level of coal maturation. For the present, such generalized models consist of coal deposition at 92 my with rapid burial followed by a constant depth of burial at 1 or 2 km (Fig. 3, models IIa and IIb, respectively). Erosion beginning about 10 or 20 my reduces the depth of the coal burial to present-day depths (Fig. 3). These generalized models, with 1 or 2 km burial depths, result in calculated values of vitrinite reflectance of 0.46 or 0.63%, respectively. Average values of vitrinite reflectance for the coal regions in the study area south of the San Juan Basin range from 0.47 to 0.53% (Table 1). If model II is, in the first order, appropriate for the study area, an average coal burial depth somewhat greater than 1 km would be appropriate.

The results presented above for models I and II suggest that the relatively small differences in the level of maturation between the various regions within the study area could easily result from differences in the burial histories of the regions. In each of the above models the level of maturation was calculated assuming a steady-state heat flow of 67 mW/m^2. Because the regional heat flow for the study area is somewhat uncertain, the level of maturation has also been calculated for the burial histories presented above with regional heat flows of 59 and 75 mW/m^2. Comparison of the observed levels of maturation with the levels of maturation calculated above for the various burial histories and regional heat flows (Tables 1 and 4, respectively) allows some first order conclusions to be made. In order for the calculated level of maturation to agree with the observed values ($\sim$0.47 to 0.53% vitrinite reflectance), certain combinations of burial history and regional heat flow must be present. For example, a relatively shallow burial history (average burial depth $\lesssim$1–1.5 km, models I and IIa, Fig. 3) requires the regional heat flow to be slightly greater than the present average heat flow of the interior Colorado Plateau (i.e., >59–65 mW/m^2). Alternatively, relatively deep burial histories (average burial depth 2 km, model IIb, Fig. 3) imply the regional heat flow has been similar to that of the Plateau interior, i.e. $\lesssim$59–65 mW/m^2. It must be kept in mind, however, that a steady-state regional heat flow was assumed for the analyses. Magmatic activity, which may locally increase heat flow for periods of time shorter than the burial history of the coal, is now considered.

Effects of intrusive activity, extensive sills

In the previous section the effects of various burial histories on coal maturation levels were investigated for regions with steady heat flow. Magmatic intrusion may, however, temporarily increase subsurface temperatures and heat flows, thus affecting levels of coal maturation. As such, the effects of transient heat-flow events are now briefly examined.

Consider the transient temperature anomaly associated with the emplacement of an extensive sill; Figure 4 illustrates the temperature distribution at various times. The mathematical treatment of this problem is presented in Lachenbruch et al. (1976). The thermal effect of sill intrusion on coal maturation will depend on coal burial depth, roof thickness (depth to sill, "a" in Fig. 4), sill thickness ("d" in Fig. 4) and initial temperature of the intrusion. The anomalous temperature (temperature above background) experienced by coal buried at 1 and 2 km depth is illustrated as a function of time after sill emplacement in Figures 5 and 6, respectively. The curves A through E represent the anomalous temperatures (at 1 and 2 km depth, Figs. 5 and 6) resulting from sills of various thickness intruded at depths of 2 to 5 km. In general it may be noted that the deeper the depth of burial (i.e., the closer the coal is to the intrusion), the greater the anomalous temperatures. The temperature anomaly resulting from sill emplacement may be combined with the coal burial history to illustrate the effect of the intrusion on coal maturation levels.

As a simple illustration, consider two examples of coals buried at depths of 1 or 2 km for the last 92 my. Such a burial history is a first order approximation of the various burial histories previously presented for the study area (Fig. 3). The level of thermal maturation has been calculated for this simple burial history with and without emplacement of the sills modeled in Figures 5 and 6 (background temperatures assumed to be 41°C and 61°C at 1 and 2 km depth, respectively, Table 5). The results presented in Table 5 reflect the influence of sill emplacement on coal maturation. For comparison, the expected level of maturation without sill intrusion is also presented in Table 5. Anomalous coal temperatures, which remain elevated for a period of time sufficient to increase maturation levels, are associated with relatively thick, shallow sills (Table 5, Figs. 4, 5 and 6).

Effects of intrusive activity, local prismatic intrusions

The pattern of volcanic activity and the spatial variability of heat-flow data in the study area suggest that magmatic activity in the study area may presently occur as shallow, local intrusions rather than areally extensive sills. The influence of a local intrusion (for example, the

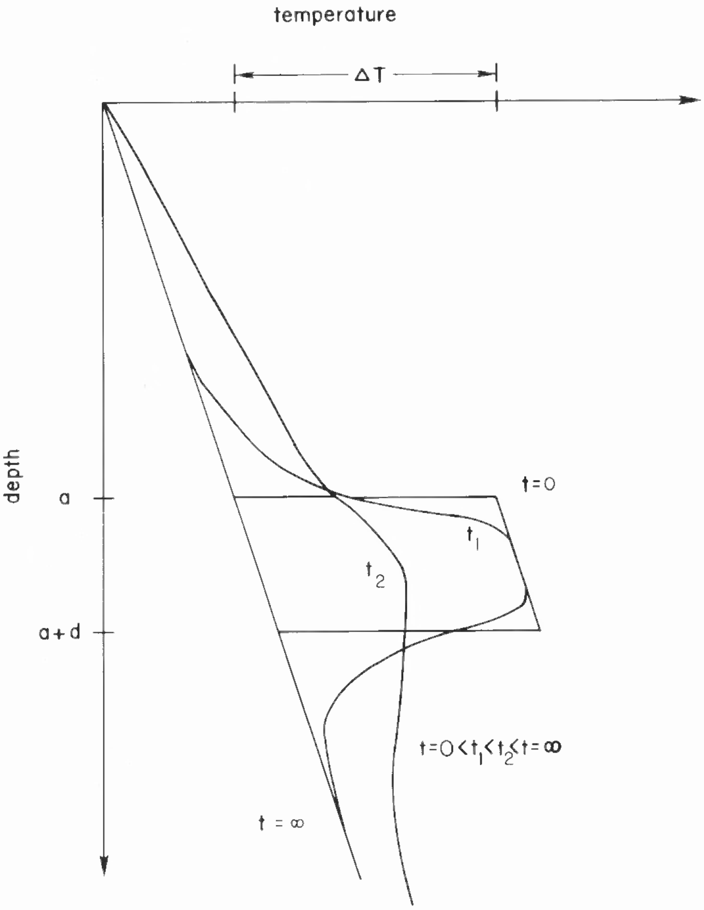

FIGURE 4. Illustration of temperature versus depth at several times "t" after an instantaneous temperature increase "ΔT" at depth "a" to "a+d" (after Lachenbruch et al., 1976).

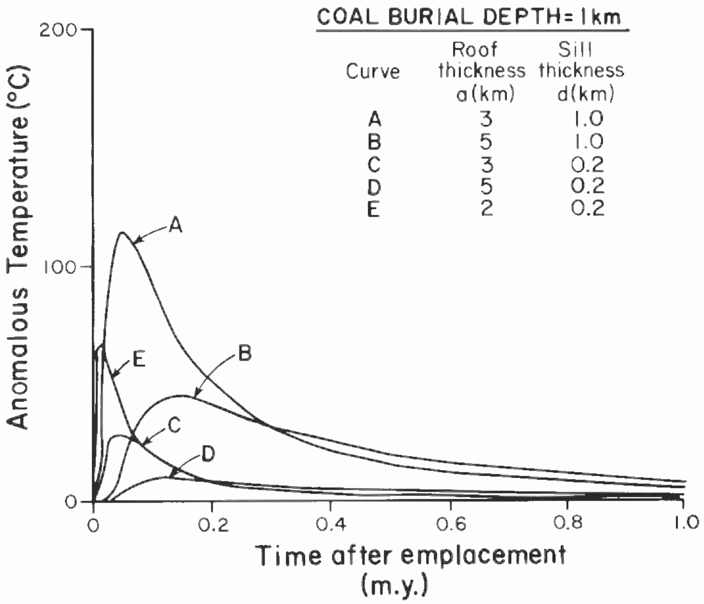

FIGURE 5. Anomalous temperature of coal as a function of time "t" after sill emplacement. Burial depth of coal is 1 km. Initial temperature of sill is assumed to be 1200°C (for the calculation the initial temperature of the sill was increased to 1600°C to account for the release of latent heat during magma solidification; see Minier et al., 1988).

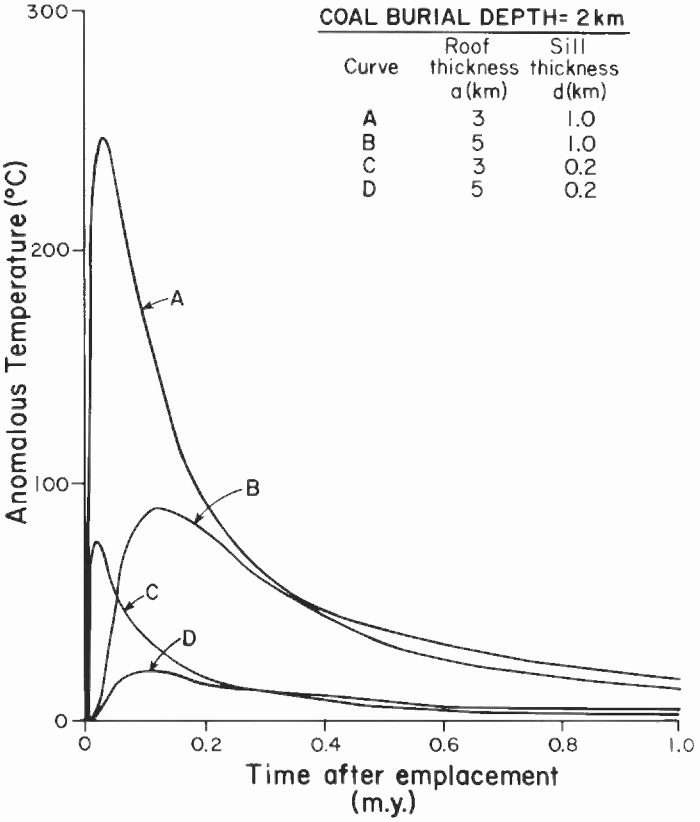

FIGURE 6. Anomalous temperature of coal as a function of time "t" after sill emplacement. Burial depth of coal is 2 km. See caption for Figure 5 regarding the initial temperature of the sill.

TABLE 4. Summary of calculated levels of coal maturation in % vitrinite reflectance for several burial-history models and heat flows, Q. The burial-history models I and II are discussed in the text and illustrated in Figure 3.

Model	Q= 59 mW/m^2	Q= 67 mW/m^2	Q=75 mW/m^{2}2
I	0.44	0.47	0.51
IIA	0.44	0.46	0.50
IIB	0.62	0.68	0.82

TABLE 5. Estimated levels of thermal maturation of coal resulting from emplacement of an extensive sill (Figure 4). Values are in % vitrinite reflectance. Thermal models A through E are discussed in the text and illustrated in Figures 4, 5 and 6.

Model	Roof Thickness a (km)	Sill Thickness d(km)	% Vitrinite Reflectance Coal Burial Depth 1km	
			1km	2km
A	3.0	1.0	0.50	>5.0
B	5.0	1.0	0.41	0.62
C	3.0	0.2	0.41	0.56
D	5.0	0.2	0.40	0.55
E	2.0	0.2	0.41	NA
Without Sill Emplacement			0.40	0.55

rectangular prismatic intrusion illustrated in Fig. 7) on surface temperatures is discussed in Lachenbruch et al. (1976). The effects of a local intrusion on coal maturation were calculated for a prismatic intrusion of characteristic width 1 and 5 kms ("2m" in Fig. 7). The intrusion thicknesses and depths modeled are the same as in the sill emplacement models in Table 5 (0.2 and 1 km thick, 2, 3 and 5 km depth). The results presented in Table 6 are the maximum expected resulting maturation levels because they have been calculated for coals lying above the center of the intrusion (i.e., where the temperature anomaly will be the greatest: Lachenbruch et al., 1976).

Due to lateral cooling, rectangular prismatic intrusions will have a diminished effect on coal-maturation levels as compared to areally extensive sills of comparable thickness and emplacement depths (Tables 5 and 6). It is also noted that the intrusion must be rather extensive (probably several km or more) and rather shallow to affect maturation levels (Table 6, models A2 and E2 are the only models affecting maturation levels).

The thermal analyses discussed above illustrate the potential influence of magmatic intrusions on coal-maturation levels. The results seem to suggest that coal-maturation levels will record mainly the emplacement of relatively shallow, thick, rather extensive intrusions. Relatively shallow intrusions are better able to increase the temperature of the coal; intrusions that are relatively thick and extensive are able to maintain the elevated temperatures for longer periods of time. Due to lateral cooling, local intrusions (as compared to areally extensive sills) are much less effective in raising the level of thermal maturation of coals. The coal maturation data indicate a relatively low level of thermal maturation with little variabilty across the study area (Tables 1 and 2). The lack of anomalously high maturation values in the study area suggests that the effect of transient heat sources on coal maturation is minimal; which, via the above discussion, does not preclude their existence. The slightly higher % vitrinite reflectance values in the Salt Lake region, as compared with the Pinehaven or Datil Mountains regions (0.53% versus 0.45% or 0.51%) is interesting because this small increase in thermal maturation is what might be qualitatively expected from intrusive activity.

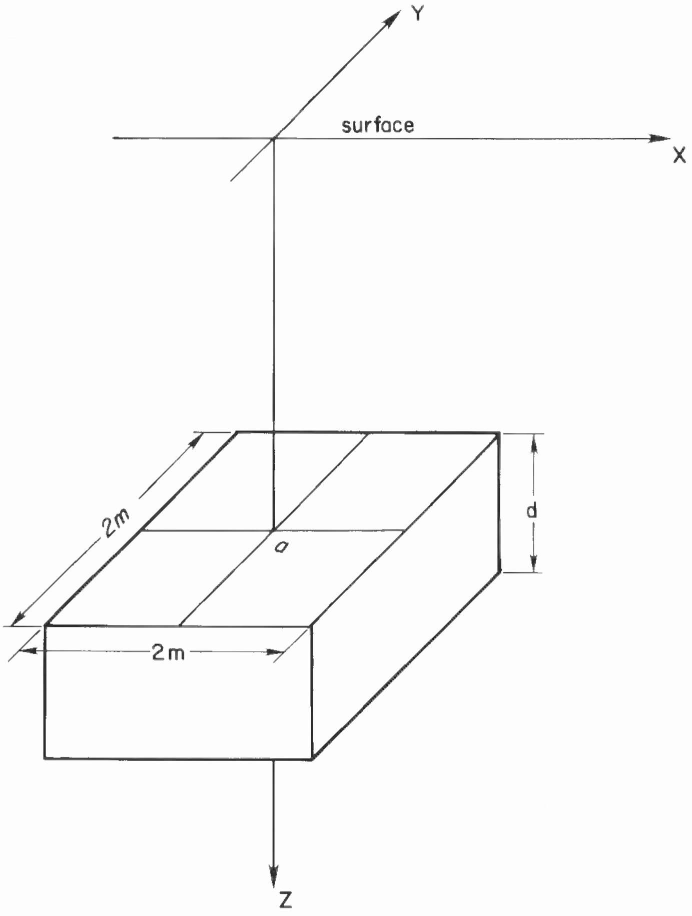

FIGURE 7. Illustration of rectangular prism buried at depth "a." Prism thickness is "d." Length and width of prism are "2m" (after Lachenbruch et al., 1976).

TABLE 6. Estimated levels of thermal maturation of coal over the center of a shallow rectangular intrusion (Figure 7). Values are in % vitrinite reflectance. Models A through E correspond to models A through E in Table 7 (for comparison between emplacement of an extensive sill and a rectangular prismatic intrusion, Figures 4 and 7, respectively).

Model	Width 2m (km)	Roof Thickness a (km)	Intrusion Thickness d (km)	% Vitrinite Reflectance Coal Burial Depth 1 km	2km
A1	1.0	3.0	1.0	0.40	0.55
A2	5.0	3.0	1.0	0.41	2.02
B1	1.0	5.0	1.0	0.40	0.55
B2	5.0	5.0	1.0	0.40	0.55
C1	1.0	3.0	0.2	0.40	0.55
C2	5.0	3.0	0.2	0.40	0.55
D1	1.0	5.0	0.2	0.40	0.55
D2	5.0	5.0	0.2	0.40	0.55
E1	1.0	2.0	0.2	0.40	NA
E2	5.0	2.0	0.2	0.41	NA
Without Intrusion				0.40	0.55

CONCLUSIONS

Coal-maturation data indicate relatively small spatial variations in thermal history across the study area. Such small variations may result from only slight differences in coal-burial histories across the study area. The slightly increased level of coal maturation observed in the Salt Lake coal field (along the Jemez lineament) might be anticipated if the volcanism has been associated with relatively small intrusions, as per the modeling discussion. However, it is also possible that the elevated maturation levels in the Salt Lake coal field reflect a deeper burial depth or higher background heat flow as compared to the adjacent coal groups. The observed level of regional maturation may be predicted by thermal models which assume a steady-state heat flow similar to that reported for the interior Colorado Plateau (59–65 mW/m^2) if the average coal burial depth is between 1 and 2 km. Shallower coal burial history models (about 1 km) require somewhat greater heat flows (67 to 75 mW/m^2) to predict coal-maturation levels. The lack of profound regional trends in coal maturation across the study area (i.e., increasing maturation toward the Basin and Range province) is consistent with heat-flow data. This observation suggests that any post-Cretaceous thermal events which may be associated with the southern Colorado Plateau boundary or Jemez zone have been initiated relatively recently and/or are occurring at relatively great depths. Alternatively, thermal events may be in the form of relatively small, widely spaced intrusions. If large-scale thermal processes are occurring in the crust and upper mantle, they may be doing so farther south of the study area beyond the range of thermal influence. It is quite possible that the hydrothermal regime in the present study area is such that heat is not being advected from the Datil-Mogollon volcanic field toward the Colorado Plateau. If such is the case, one may have to be appreciably closer to the thermal source to observe its thermal influence than is needed to observe the influence of the thermal source in the San Juan Basin-San Juan Mountains transition.

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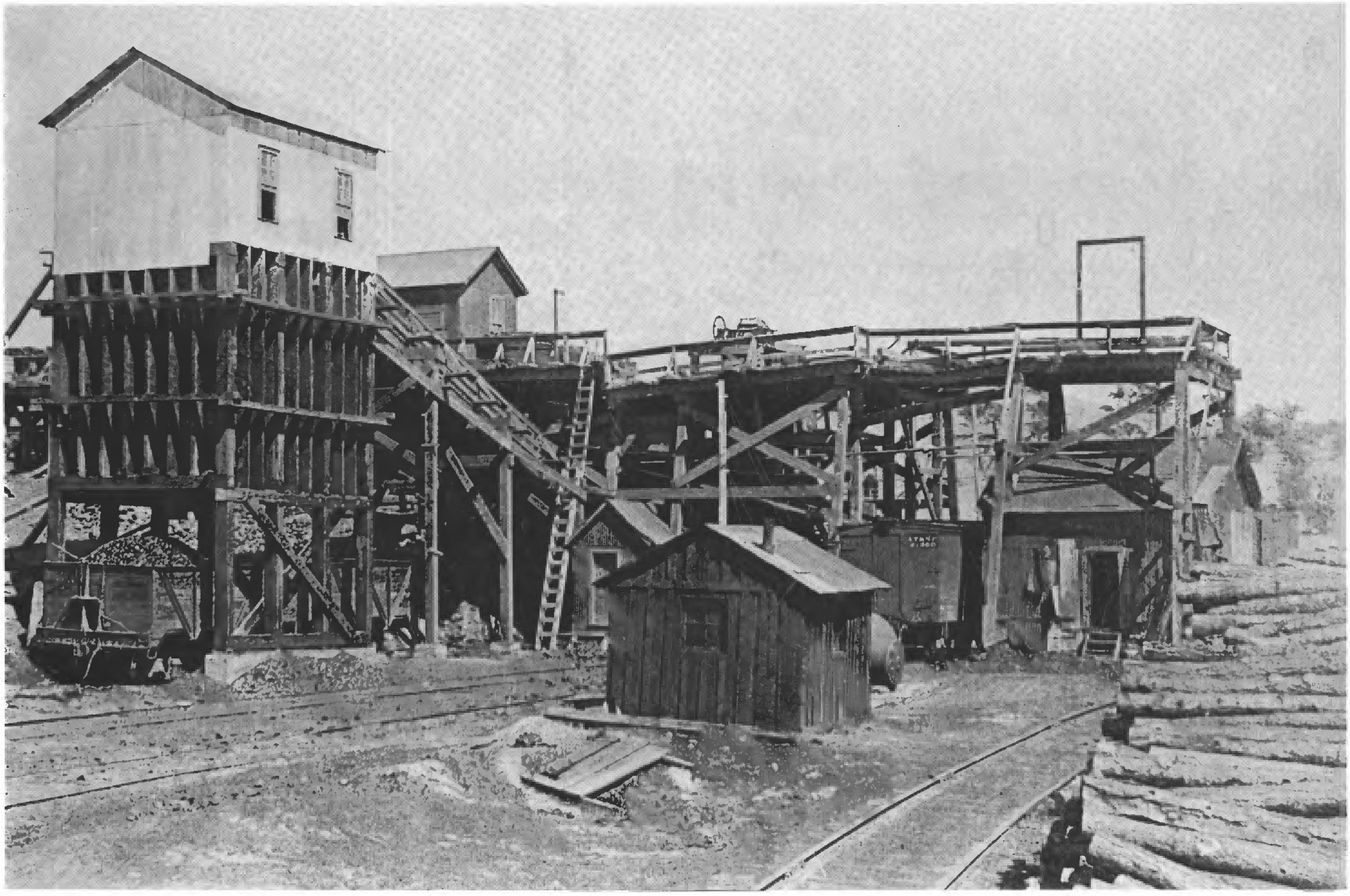

The Navajo coal mine loading facilities near Gallup, circa 1913 (courtesy Gallup Public Library photo archives).