UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

VITRINITE REFLECTANCE AND ILLITE CRYSTALLINITY, CAMBRIA SLAB AND FRANCISCAN COMPLEX, CENTRAL CALIFORNIA COAST

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Open-File Report 86-295

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ABSTRACT

This report concerns the thermal maturation of Upper Cretaceous strata of the Cambria slab, as well as the argillaceous matrix of surrounding Franciscan melange. These rocks are exposed along the coast of central California in San Luis Obispo County. Analyses were completed on 30 surface samples using the techniques of vitrinite reflectance and illite crystallinity. Values of mean reflectance (Rm) for the Cambria slab range from 0.46% to 1.34%, whereas Franciscan melange varies between 0.71% and 1.36%. Illite crystallinity confirms the elevated values of Rm.

ACKNOWLEDGMENTS

This study was supported by the U.S. Department of Energy, with funds administered to the University of Missouri through USGS Purchase Order 110178. We thank David Houseknecht and Joe Wood of the University of Missouri for their expert advice in matters of sample preparation and organic petrography. Chris Gillett, Pad Quinn, and Jack O'Leary assisted in the laboratory. The impetus for research on the Cambria slab was provided by David Howell. Keith Kvenvolden and Les Magoon made several helpful suggestions to improve the clarity of the report.

INTRODUCTION

The Cambria slab is a sequence of well-bedded and variably deformed sedimentary strata exposed along a limited stretch of the central California coast (Fig. 1). The Upper Cretaceous turbidites and shales are surrounded by highly deformed polymict melange of the Franciscan Complex. This report concerns the thermal maturity displayed by Cambria strata and matrix of the Franciscan melange. Analytical techniques include vitrinite reflectance and illite crystallinity. Interpretations of the data appear in a companion paper (Underwood and Howell, in review), and the primary intent of this report is to provide complete descriptions of laboratory techniques and resulting data sets.

GEOLOGIC BACKGROUND

The Cambria slab is best exposed along seacliffs which extend roughly 18 km south and 6 km north of the town of Cambria (Fig. 1). These strata were described by Hsu (1969) and later mapped in greater detail by Hall (1974). Dinoflagellates and palynomorphs indicate a Cenomanian through Campanian age (Smith, 1978).

Most strata of the Cambria slab are thick-bedded sandstone turbidites that have been subjected to polyphase deformation (Smith and others, 1979). Folds, flextures, faults, slumps, and local intervals of broken formation (with extensional, bedding-parallel shear fabrics) are superimposed upon a general east- to northeast-dipping homocline (Howell and others, 1977; Smith, 1978). Fold axes typically trend north and northeast (Fig. 2), and axial planes verge toward the west and northwest; most folds are tight and asymmetric.

Deformation within the surrounding Franciscan melange is much more extreme (Cowan, 1978, 1982). The melange matrix consists of scaly argillite; sandstone phacoids are aligned parallel to the scaly fabric and help define a crude foliation. Exotic blocks are dispersed throughout the melange; common lithologies include radiolarian chert, greenstone, greenschist, blueschist, and serpentinite. Structural analyses completed by Cowan (1978, 1982) demonstrate that multiple episodes of deformation have affected the melange, including an early phase of axially symmetric extension. Pumpellyite is present in many sandstone blocks (Ernst, 1980).

The contact between the Cambria slab and melange is undulatory in plan view (Fig. 2). Locally, the bedded turbidites clearly overlie melange (Smith, 1978; Becker and Cloos, 1985). The main bounding fault appears to dip steeply westward, with slab sediments resting above melange (Hall, 1974). Cataclasis, brecciation, and veining along the contact are minor, which led Luneau and Cloos (1986) to infer that faulting was syndepositional; if so, the present orientation of the fault must have changed considerably as subsequent phases of folding were superimposed upon the primary structural grain. Tertiary units deposited above Franciscan strata to the north and east have been folded into broad anticlines and synclines (Hall, 1974, 1976), and this phase of folding must have affected Cambria strata as well.

In addition to the complications associated with the main contact, there are two inferred intrusions of mud-matrix melange that crosscut the Cambria slab (Becker and Cloos, 1985). Slivers of melange are exposed in Abalone Cove and along a Highway 1 roadcut across from China Harbor (Fig. 2). Two interpretations have been offered for these occurrences. According to Becker

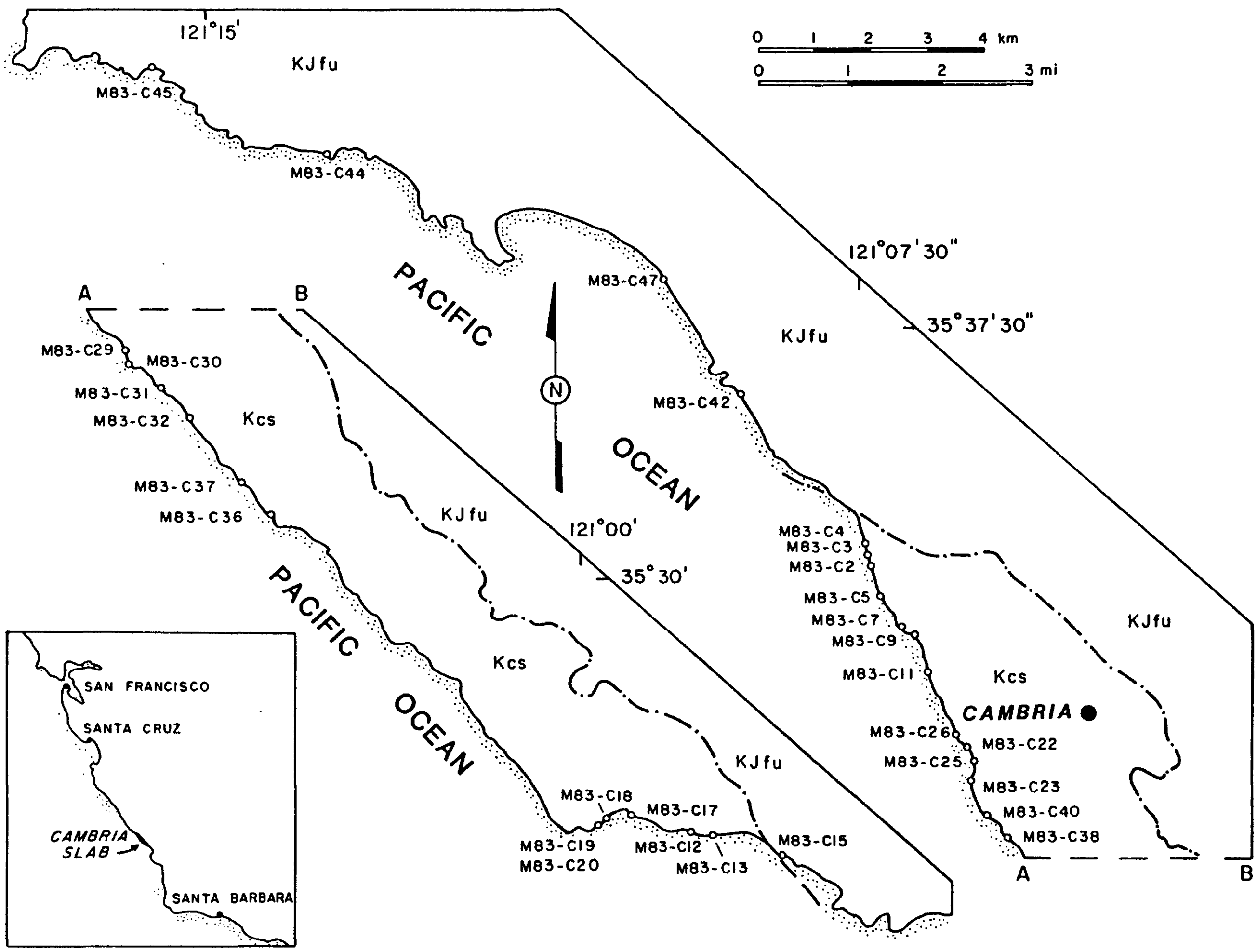


FIGURE 1. Map showing the location of Cambria, distribution of Cambria slab strata (Kcs) and Franciscan melange (KJfu), and all sample localities used for measurements of vitrinite reflectance and illite crystallinity. Contact (dashed line) was mapped by Smith (1978).

and Cloos (1985), diapirs of melange rose from considerable depth; the favored source is a zone of active deformation in a flow melange channel beneath the Franciscan accretionary wedge (see also Cloos, 1982). A less mobilistic interpretation places the melange within the cores of antiformal structures that have been truncated by high-angle faults (Howell and others, 1977; Smith, 1978).

METHODS

In order to test the various tectonic and structural hypotheses proposed for the Cambria slab, we measured levels of thermal maturity for 30 shales; samples were collected from fresh seacliff exposures of both Cambria turbidites and surrounding Franciscan melange (Fig. 1). Analytical techniques include measurements of vitrinite reflectance and illite crystallinity. The vitrinite reflectance method is based upon the empirical observation that reflectance values (Ro) in both coals and shales increase exponentially with burial depth and temperature (for example, Dow, 1977; Bostick, 1979). Similarly, the crystallinity of the clay mineral illite varies as a function of temperature; the degree of crystallinity is measured from the sharpness of the illite peak on X-ray diffractograms (Weaver, 1960; Kubler, 1968).

Measured values of vitrinite reflectance can be influenced by a number of variables including weathering and oxidation (Marchioni, 1983). Individual organic particles can be strongly anisotropic in their reflectance, although this anisotrophy is minimal over the range of maturity displayed by Cambria/Franciscan strata (Stach et al., 1975). Ro values can also be suppressed by concentrations of hydrogen-rich macerals and/or anaerobic conditions in the environment of deposition (Hutton and Cook, 1980; Newman and Newman, 1982; Price and Barker, 1985). Geochemical data from Franciscan terranes in northern California and the San Simeon region demonstrate that these circumstances should not pose a problem (Underwood, 1985; Strong, 1986; Larue, 1986). Because of the resistance of vitrinite to weathering, grains can be recycled from older sedimentary strata. If unrecognized recycled material is more mature than the present host rock, then mean reflectance values become erroneously high. The conventional practice is to plot data in histrogram form to help identify recycled grains; strongly bimodal trends signify the inclusion of both indigenous and recycled populations (for example, Dow and O'Connor, 1982). Procedures of sample preparation, optical measurements, and statistical analysis are discussed in greater detail in Appendix A and Underwood and Strong (1986). Ro histograms for Cambria/Franciscan data are included in Appendix C. Values of mean reflectance (Rm) are based upon measurements of approximately 50 individual particles per sample.

Several techniques have been proposed to model thermal maturation. For example, Hood and others (1975) developed a time-temperature model based upon the concepts of maximum temperature and effective heating time. Recent studies question the validity of this method, especially at lower levels of thermal maturation (Suggate, 1982). Other workers contend that Ro equilibration occurs within 10^4 to 10^6 years and that additional time has little or no influence (Barker, 1983; Price, 1983). Price (1983) plotted a direct correlation between Ro and borehole temperature based upon fourteen first-cycle sedimentary basins of differing age throughout the world. Because our study of the Cambria slab is concerned with relative changes in paleotemperature rather than absolute values, we have used the Price (1983) correlation for all of our paleotemperature estimates. Nevertheless, we stress that the role of heating time remains highly controversial (for example, Bostick, 1984; Kohsmann, 1985), and our temperature estimates should be viewed as maximum values.

Because of the potential problems associated with recycled vitrinite, Ro anisotropy, alginite-suppression, and so on, we have also employed the technique of illite crystallinity as an independent check on mean reflectance (Rm) values. The correlation between illite crystallinity and vitrinite reflectance is well established within several circum-Pacific subduction complexes (Underwood and others, in prep.) and elsewhere (Kisch, 1980; Duba and Williams-John, 1983; Guthrie and others, 1986). Our quantification of illite crystallinity follows the Kubler (1968) method; the width of the 10Å illite peak is measured at one-half the peak height. Slides were glycolated prior to X-ray scanning, and peak width is expressed in terms of $^{\circ}2\theta$. Additional descriptions of technique appear in Appendix A.

RESULTS

A complete tabulation of vitrinite-reflectance and illite-crystallinity data appears in Appendix B. Rm values for shale samples extracted from the Franciscan melange vary between 0.71% and 1.36%. According to the Price (1983) correlation, this corresponds to a range in peak paleotemperature of 142° to 228°C. Shales from the Cambria slab were collected from both well-bedded intervals and local zones of more intense stratal disruption ("broken formation"). No detectable differences in thermal maturity are noted between the two structural styles (Figs. 2 and 3). Rm values for the entire Cambria slab range from 0.46% to 1.34%; the inferred range in peak paleotemperature is 85°C to 226°C.

There are several significant spatial trends in thermal maturation parameters within the Cambria slab. The most prominent trend is the progressive increase in Rm values toward the melange exposure in Abalone Cove (Fig. 2). The highest Rm value of the entire study (1.36%) was obtained from melange matrix exposed within the cove. Significantly, well-bedded Cambria strata immediately southeast of the melange sliver yield an almost identical value of 1.34%. Mean reflectance gradually decreases to the southeast away from Abalone Cove, but Rm values drop off very abruptly to the northwest. No detectable Rm anomaly is evident in the vicinity of the China Harbor melange (Fig. 2). Interestingly, there are consistent contrasts between Cambria shales and melange matrix across both the northwestern and southeastern limits of the slab. At both sites, Rm values for the Cambria slab are lower than values within adjacent melange. Overall, however, there is considerable overlap between levels of maturity for the two tectonostratigraphic units.

Direct correlations have never been made between illite crystallinity and peak paleotemperature. Moreover, the technique is unreliable below maturity levels of around 0.80% Rm because of problems associated with contamination by detrital illite and diffuse peak expression. Consequently, we have used illite crystallinity only to confirm the elevated values of vitrinite reflectance. Most data from the Cambria region plot along or below the correlation line established for Franciscan rocks in northern California (Strong, 1986). The crystallinity index (peak width) decreases in samples with unusually high Rm values (Fig. 3), and the illite data confirm the reflectance anomalies associated with Abalone Cove locality.

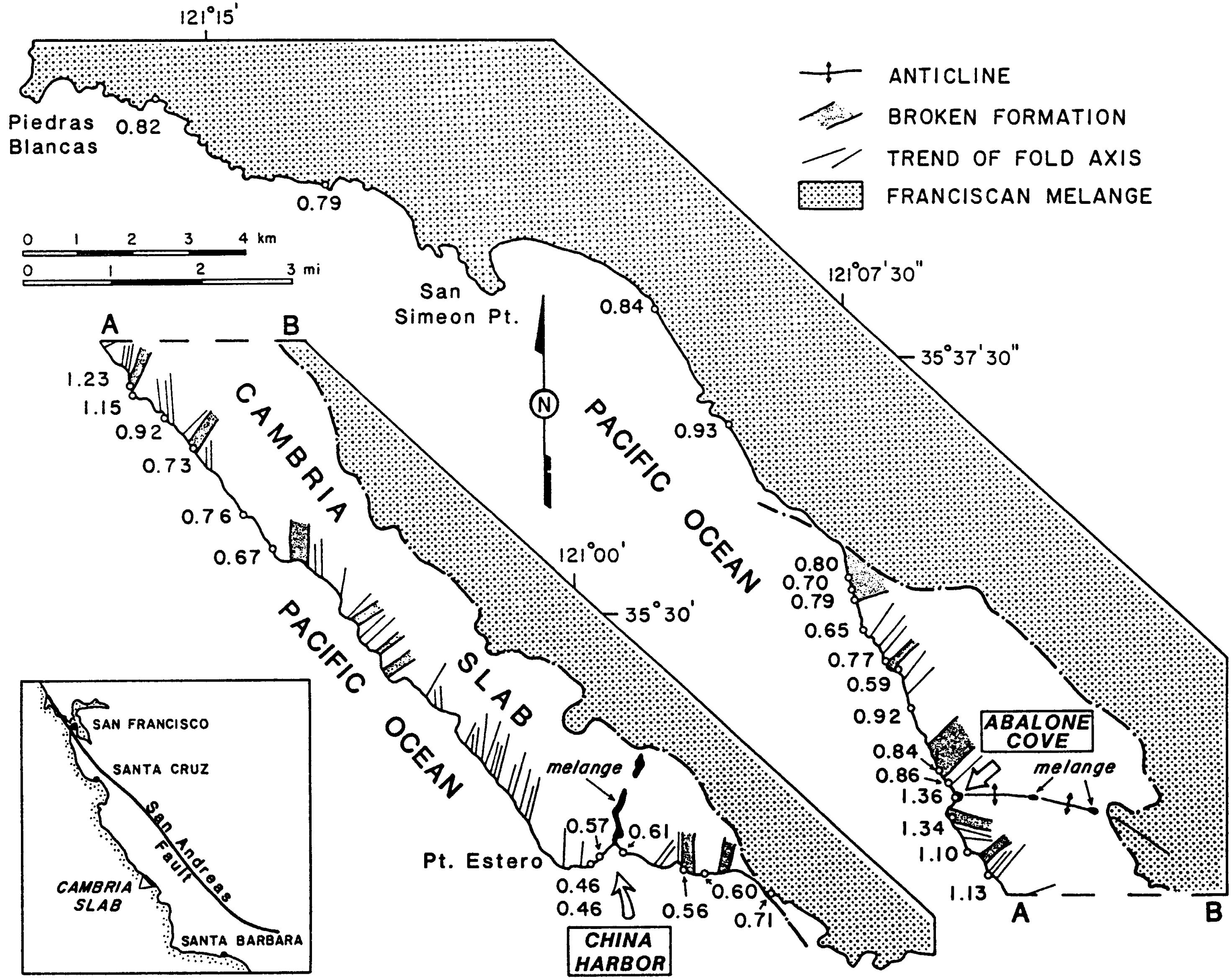


FIGURE 2. Principal structural elements and levels of thermal maturity for the Cambria slab and surrounding melange of the Franciscan Complex. Trends of folds and zones of broken formation were mapped by Howell and others (1977) and Smith (1978). Numbers refer to values of mean vitrinite reflectance.

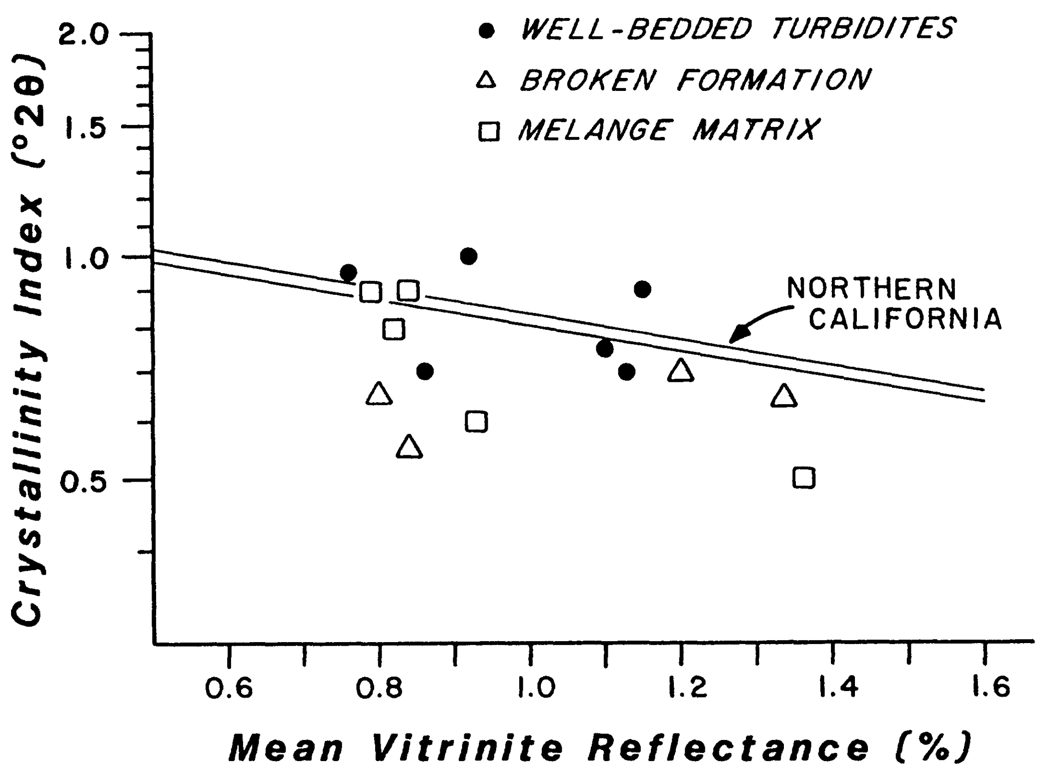


FIGURE 3. Correlation between values of mean vitrinite reflectance (Rm) and illite crystallinity index (CI). Correlation line is based upon analyses of 32 Franciscan shales from northern California (Strong, 1986). Regression equation is log CI = 0.085 - 0.174Rm, and the correlation coefficient is r = 0.706. Data points are from Cambria strata (both zones of broken formation and well-bedded turbidites) and matrix samples from the Franciscan melange surrounding the Cambria slab. See Appendix B for tabulation of data and Figure 1 for sample localities.

APPENDIX A. TECHNIQUES OF SAMPLE SELECTION, PREPARATION, MEASUREMENT, AND STATISTICAL EVALUATION

Sample Selection

One problem with the technique of vitrinite reflectance is the potential alteration of vitrinite particles by weathering and oxidation at or near the surface. Surface weathering can produce multimodal patterns on histograms depicting random reflectance (Marchioni, 1983), and the weathering effect can extend as deep as 10 meters below the surface. In order to minimize this effect, pains were taken to select the freshest possible samples from beachcliff exposures. It also should be noted that actual measurements made from oxidation halos yielded lower reflectance values than similar measurements made on unaltered cores.

Kerogen Concentration

Measurements of organic-carbon content demonstrate that most Franciscan shales from northern California are depleted in organic matter, with values typically ranging between 0.35 and 0.65 wt-% carbon (Underwood, 1985; unpublished data). Consequently, organic matter had to be extracted and concentrated before measurements of vitrinite reflectance could be completed. The laboratory methods are outlined in Underwood and Strong (1986).

Data Collection

Observations in reflected light were made using a 50x oil-immersion lens and a 16x ocular mounted on a Leitz Ortholux research microscope set up in the reflected light mode. A Keithly 244 high-voltage power supply and a Hewlett-Packard direct-current power supply provided stable power to the photometer and the light source, respectively. Reflected light was directed to a Leitz MPV-1 photometer through a 70-micron diameter diaphragm (constricted to a 4-micron opening during calibration), and the Ro value was read on a Keithly 177 Microvolt digital voltmeter. Calibration of the photometer for a linear response was performed weekly using polished reflectance standards (0.299, 0.506, 0.940, 1.025, and 1.672%).

The criteria for selection of particles to measure are described in Dow and O'Connor (1982) and Underwood and Strong (1986). Briefly, vitrinite particles were recognized on the basis of morphology, color, and texture of the polished surface. At the levels of maturation documented in our study, vitrinite can be identified on the basis of relative reflectivity or a "lowest gray" scale. Such methods require abundant kerogen, however, so that direct comparisons of macerals can be made within a single field of view. To avoid bias toward a "correct" reflectance value in lean samples, we depended strongly on morphologic criteria to select vitrinite particles (see Stach et al., 1975). About 50 data points were gathered from each sample to assure statistically valid results.

Data Reduction and Interpretation

It is a common practice to plot reflectance data in histogram form to help identify recycled vitrinite (Dow and O'Connor, 1982). Given a Gaussian distribution of Ro values, calculations of mean and standard deviation are completed using all available data points. Populations of vitrinite can be distinctly bimodal or multimodal, however. By convention, the mode showing the lowest reflectance is viewed as the indigenous population; higher values are labeled "reworked" and eliminated from calculations of mean reflectance.

If a few isolated values are much higher than the majority, "recycled" grains are routinely eliminated. However, some Cambria samples produced complicated multimodal patterns, which inhibits objective identification of the "recycled" population (Appendix C). Multimodal distributions can be caused by surface weathering (Marchioni, 1983), and turbiditic shales commonly are bimodal or multimodal (Castano and Sparks, 1974). Moreover, we believe the inference of recycling should be consistent with independent geologic information linking the depositional environment to a suitable source terrane with elevated thermal maturity. Such a link is difficult to establish because of displacements of the Cambria slab along the San Andreas and Nacimiento fault zones (Howell et al., 1977). To avoid data bias and increase the degree of reproducibility in the Cambria study, higher Ro values were eliminated from calculations of mean reflectance only when a data gap of at least 0.10% Ro (one sampling interval) is present.

Illite Crystallinity

Another measure of thermal maturity is the degree of crystallinity of the clay mineral illite (Weaver, 1960; Kubler, 1968). The conversion of smectite to illite involves the progressive expulsion of interlayer water and incorporation of cations (primarily K^+ and Na^+) within the clay lattice. This process is transitional, and the intermediate product is a mixed-layer/ smectite clay. The final phase of illitization requires the dehydration of the last layers of water from between the clay layers and the inclusion of additional K^+ ions into the illite structure. As this reaction proceeds the degree of illite crystallinity increases (Dunoyer de Segonzac, 1970).

Perry and Hower (1970) concluded that the transformation of smectite to illite is controlled largely by temperature rather than pressure, so illite crystallinity can be correlated with thermal maturity. Crystallinity is quantified from the morphology of the characteristic 10Å illite peak on an X-ray diffractogram. Higher crystallinity is indicated by a sharper or narrower peak, and lower crystallinity is indicated by a diffuse or broader peak (Weaver, 1960, Kubler, 1968).

As with vitrinite reflectance, there are several factors that can bias the results of crystallinity measurements. Disordering of the illite is increased by the presence of interlayer smectite (Gaudette et al., 1966), and degradation may result from weathering (Dunoyer de Segonzac, 1970). These factors reduce the degree of crystallinity. An increase in crystallinity can be caused by interstitial solutions in more permeable sediments, the presence of larger detrital illite particles, or the incorporation of K^+ or Na^+ into the structures of alkali deficient illites (Dunoyer de Segonzac, 1970).

Two X-ray diffraction methods are available to measure illite crystallinity. Weaver's (1960) method, called the sharpness ratio, is the ratio of the total height of the 10Å reflection to the height of the same peak at 10.5Å (Fig. 4). Higher degrees of illite crystallinity are illustrated by increasing sharpness ratios.

Kubler's (1968) method was used in our study; the so-called crystallinity index (CI) uses the width of the 10Å illite reflection at half the peak height on the X-ray diffractogram (Fig. 4). Kubler's original values were defined in terms of millimeters, and comparisons of values could be made only if laboratory instruments were calibrated according to the same analytical conditions. Subsequent workers (e.g., Kisch, 1980; Duba and Williams-Jones, 1983) expressed their measurements in terms of degrees 2θ, which normalizes

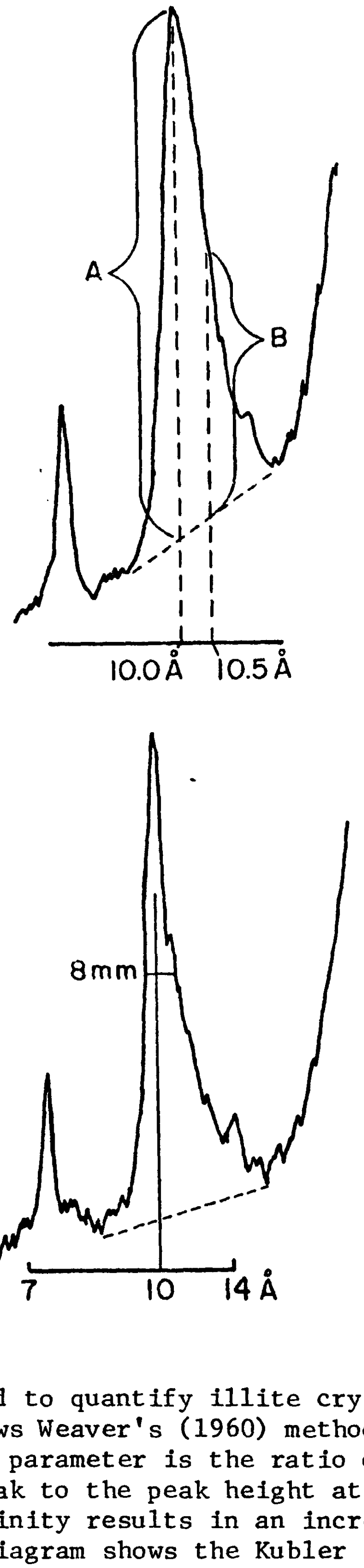


FIGURE 4. Methods used to quantify illite crystallinity. Upper diagram shows Weaver's (1960) method, termed the sharpness ratio; this parameter is the ratio of the total height of the 10 Å peak to the peak height at 10.5Å. A higher degree of crystallinity results in an increasing sharpness ratio. The lower diagram shows the Kubler (1968) method; the so-called crystallinity index uses the width of the 10Å reflection at one-half the peak height. Values (expressed in terms of °2θ) decrease with increasing crystallinity. All values reported in this study use the Kubler method.

the differences between instruments. The crystallinity index data presented in this report, therefore, are expressed in degrees 2θ.

Sample Preparation

Approximately forty grams of shale were crushed in a cast iron mortar and then sifted in a 105 micron sieve. The finer fraction was dispersed in 400 milliliters of distilled water, using an ultrasonicator for four minutes. A pinch of Calgon was added prior to sonication to facilitate dispersal of floccules. Samples were allowed to settle, and after eight hours the 2-micron fraction was sampled from the uppermost 10 cm of water using a pipette. This size fraction was sampled to reduce contamination by detrital illite, which is usually larger. The clay suspension was then pipetted onto a glass slide and allowed to air dry at room temperature. Three oriented slides were prepared in this manner for each sample. One slide was left untreated, one was glycolated, and the other heated at 100°C for two hours.

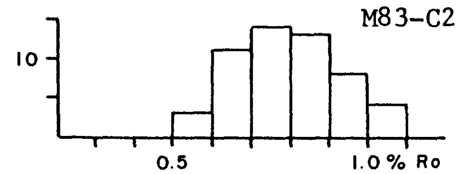
All samples were analyzed by X-ray diffraction using a Phillips X-ray diffractometer. CuK_α radiation was generated by a graphite monochromator. Samples were run at a rate of 1° per minute from 3° to 35° 2θ. The voltage was set at 35 kilovolts and 20 milliamps. The same rate and meter settings were used for all slides. All three slides (untreated, glycolated, heated) were examined to better define the 10Å illite peak and segregate the effects of any mixed-layer clays present. Only glycolated samples were used to measure the illite crystallinity, however, because this treatment eliminates the influence of mixed-layer clay minerals on the diffractogram response of illite.

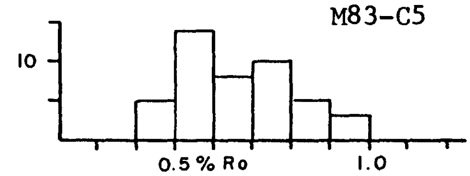
APPENDIX B. TABULATION OF VITRINITE-REFLECTANCE AND ILLITE-CRYSTALLINITY DATA

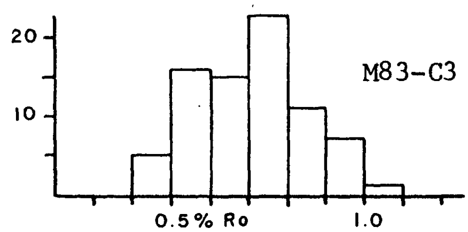
Sample No.	Points	Range Ro (%)	Mean Ro (%)	Stan.Dev.	Temp (^oC)	IC ($^o2\theta$)
M83-C2#	53	0.53-1.03	0.79	0.13	156	
M83-C3#	80	0.43-1.04	0.70	0.14	140	
M83-C4#	50	0.37-1.24	0.80	0.19	158	0.65
M83-C5	50	0.45-0.97	0.65	0.14	131	
M83-C7	43	0.39-1.19	0.77	0.20	153	
M83-C9	37	0.38-0.81	0.59	0.11	118	
M83-C11	50	0.47-1.34	0.92	0.20	176	1.00
M83-C12#	46	0.35-0.73	0.56	0.11	111	
M83-C13	50	0.35-0.92	0.60	0.14	120	
M83-C15*	63	0.44-0.95	0.71	0.12	142	
M83-C17	50	0.35-0.95	0.61	0.15	122	
M83-C18	50	0.42-0.81	0.57	0.10	113	
M83-C19	50	0.33-0.65	0.46	0.07	85	
M83-C20	44	0.32-0.66	0.46	0.08	85	
M83-C22	50	0.51-1.21	0.86	0.17	167	0.70
M83-C23#	40	1.05-1.70	1.34	0.16	226	0.65
M83-C25*	49	1.04-1.69	1.36	0.16	228	0.50
M83-C26#	50	0.50-1.28	0.84	0.19	164	0.55
M83-C29#	50	0.87-1.53	1.23	0.15	215	0.75
M83-C30	50	0.69-1.65	1.15	0.25	206	0.90
M83-C31	50	0.51-1.32	0.92	0.19	176	
M83-C32#	40	0.50-1.00	0.73	0.13	146	
M83-C36	76	0.47-1.04	0.67	0.13	135	
M83-C37	48	0.44-1.11	0.76	0.17	151	0.95
M83-C38	50	0.65-1.53	1.13	0.22	203	0.70
M83-C40	50	0.64-1.44	1.10	0.18	200	0.75
M83-C42*	49	0.60-1.17	0.93	0.14	178	0.60
M83-C43*	50	0.45-1.17	0.79	0.18	156	0.90
M83-C45*	46	0.56-1.10	0.82	0.13	161	0.80
M83-C47*	50	0.51-1.30	0.84	0.18	164	0.90

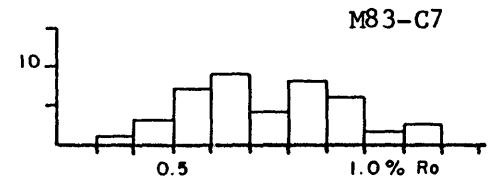
= broken formation; * = melange
Temperature based upon Price (1983) correlation.

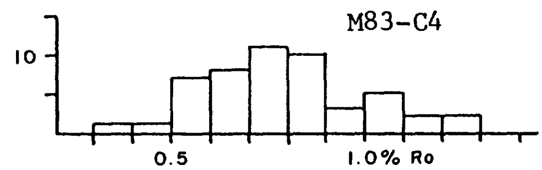
APPENDIX C. HISTOGRAM PLOTS OF VITRINITE REFLECTANCE DATA

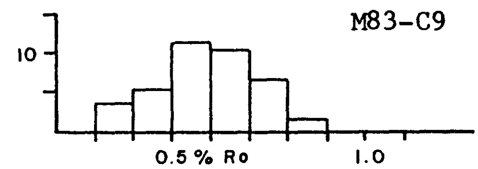


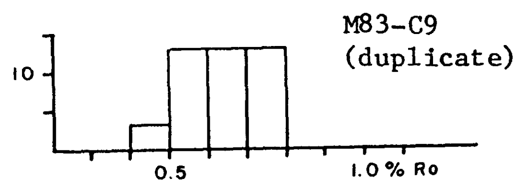


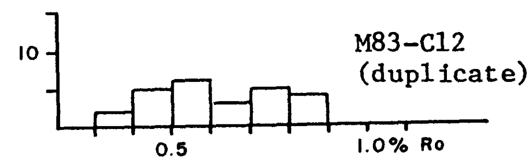


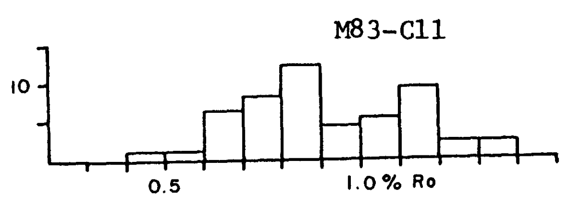


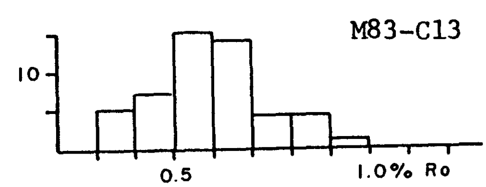


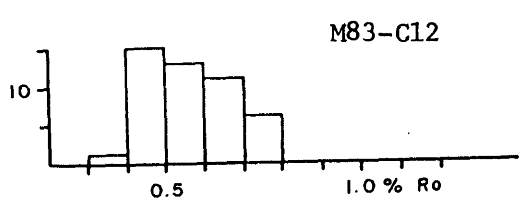


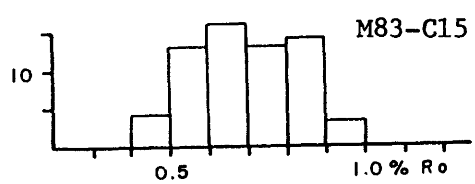


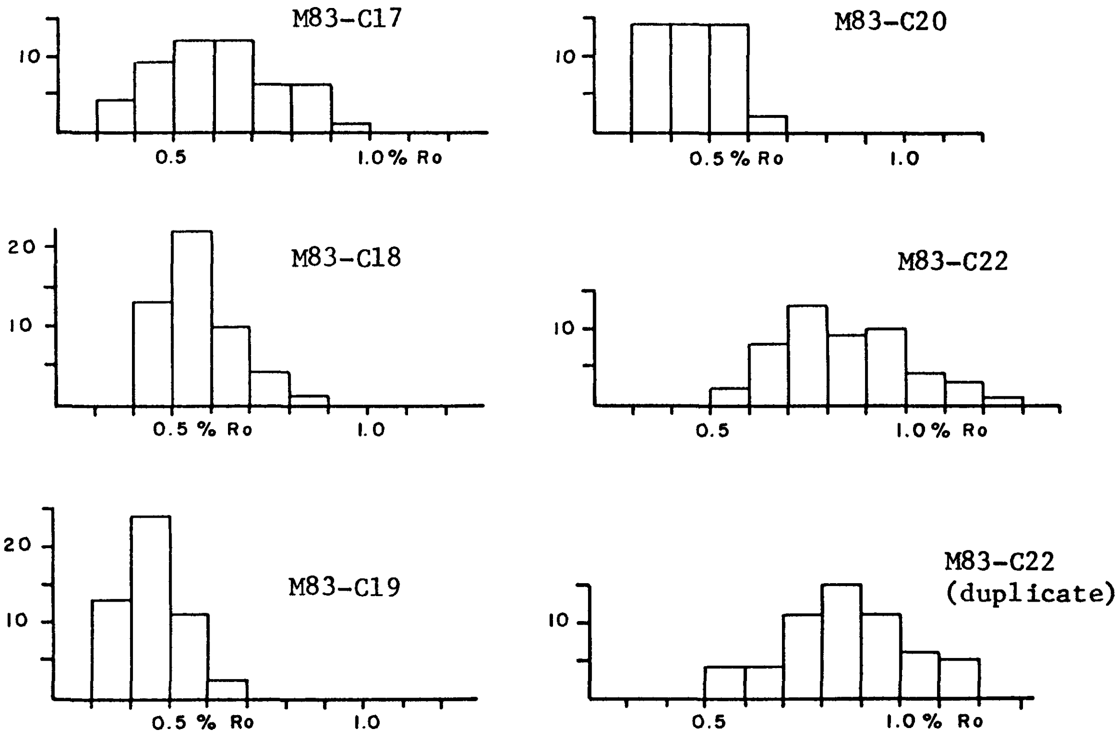











M83-C17
10
0.5
1.0% Ro
M83-C20
10
0.5 % Ro
1.0
M83-C18
20
10
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1.0
M83-C22
10
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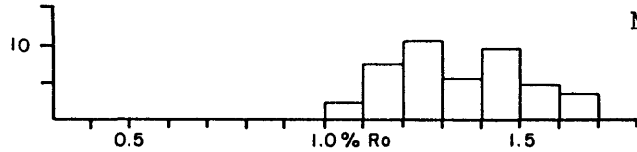
M83-C23



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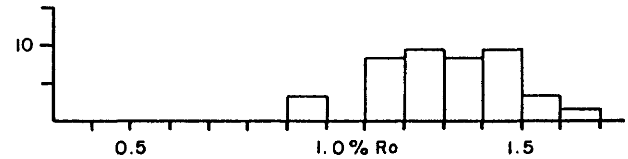
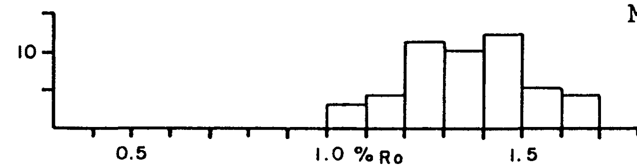
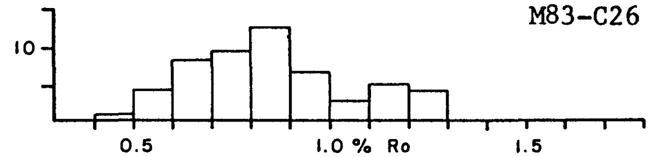


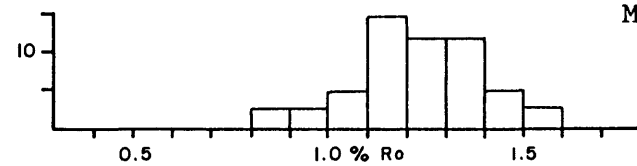
M83-C25



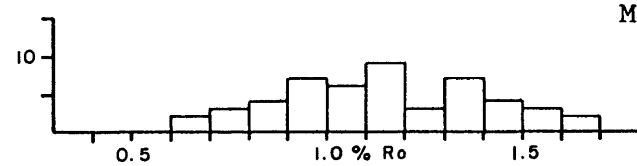
M83-C26

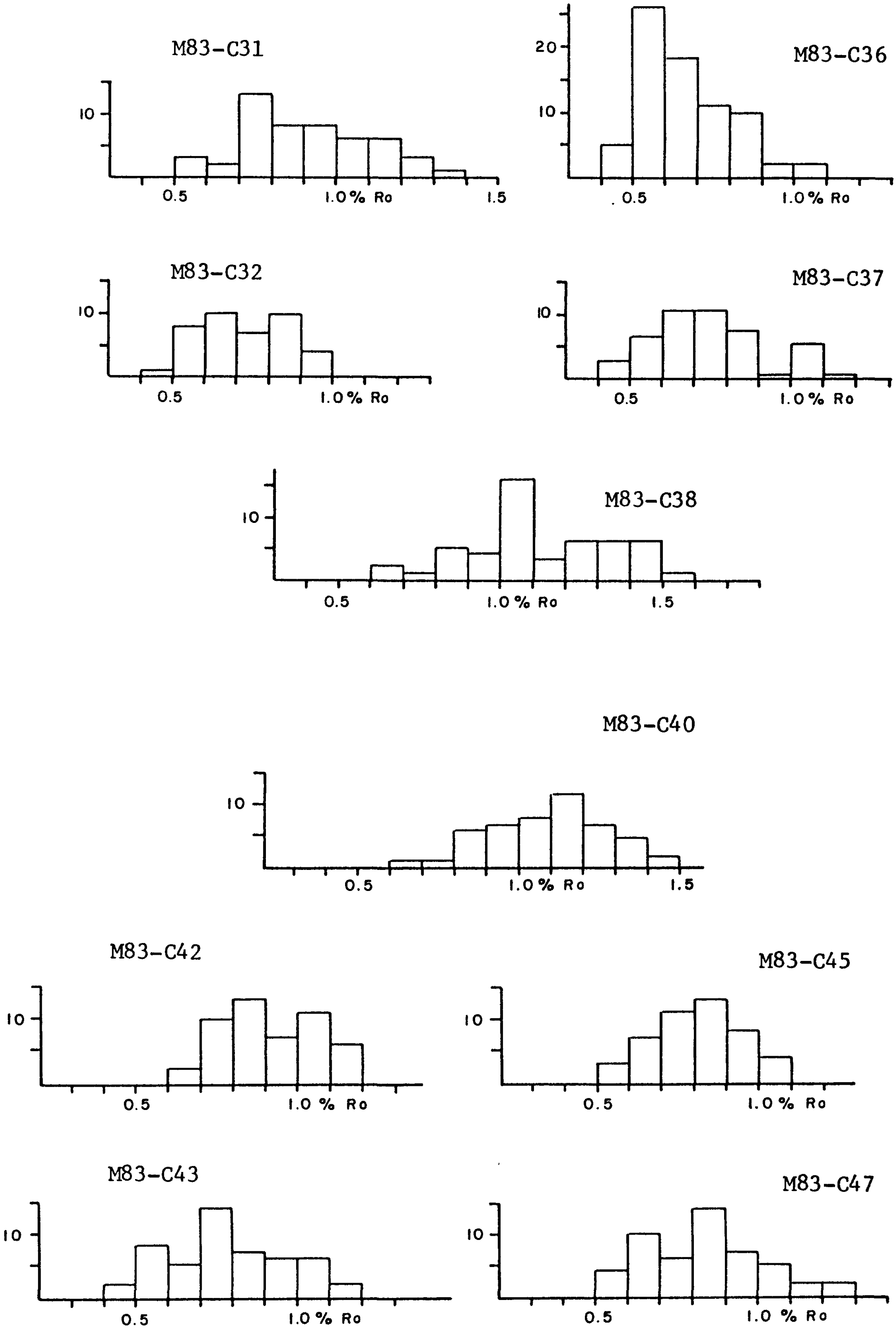


M83-C29



M83-C30




M83-C31
10
0.5
1.0% Ro
1.5
M83-C36
20
10
. 0.5
1.0% Ro
M83-C32
10
0.5
1.0% Ro
M83-C37
10
0.5
1.0% Ro
M83-C38
10
0.5
1.0% Ro
1.5
M83-C40
10
0.5
1.0% Ro
1.5
M83-C42
10
0.5
1.0 % Ro
M83-C45
10
0.5
1.0 % Ro
M83-C43
10
0.5
1.0 % Ro
M83-C47
10
0.5
1.0 % Ro

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