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The Nonopaque, Detrital Heavy Mineralogy of the Morrison Formation near Crownpoint, San Juan Basin, New Mexico

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CONTENTS

ILLUSTRATIONS

TABLES

APPENDIXES

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ABSTRACT

Description and quantification of the nonopaque, detrital heavy mineralogy of the Upper Jurassic Morrison Formation in the southwestern part of the San Juan Basin have helped to identify stratigraphic trends, source-area lithologies, and zones of postdepositional alteration possibly related to uranium mineralization. A synthesis of stratigraphic variations in mineral species and diversity in Morrison sandstones reveals an increasing upward igneous component, characterized by euhedral zircon and subhedral apatite. Complementing this trend, the predominantly well-rounded assemblage of the Recapture Member changes to a mixed assemblage of rounded and angular grains in the Westwater Canyon Member. Overall, the low diversity in mineral species indicates a sedimentary, low- to medium-grade-metamorphic, and acid igneous parentage for Morrison sediments; however, postdepositional processes have played a significant role in determining the present mineralogy.

The roles that diagenesis and weathering have played in determining the present aspect of the assemblage, which is a mature garnet-zircon-apatite-tourmaline suite, cannot be overemphasized. For instance, the presence of authigenically etched to skeletal garnet and staurolite implies that entire grains have been destroyed. Comparison of cores with measured sections indicates that near-surface weathering has caused the destruction of some minerals, notably apatite, sensitive to acidic conditions. Therefore, in order to interpret the sedimentology, stratigraphic intervals in which postdepositional processes have affected the mineralogy were identified. These diagenetic zones may prove to be most useful in delineating the past movements and compositions of interstitial, possibly ore-forming, fluids.

INTRODUCTION

Problems inherent in heavy mineral studies should be considered before provenance interpretations and stratigraphic correlations are made. These problems result from modifications to the composition and appearance of detrital heavy mineral suites by weathering in the source area; mechanical abrasion during transport; selective sorting due to differences in shape, roundness, and density of the grains; and weathering and diagenesis after deposition (Van Andel, 1959; Dietz, 1973). In addition, human factors such as sampling techniques, analytical procedures, and operator bias influence the results. In this study, diagenesis was found to be the most critical factor and, as a consequence, data interpretation is difficult at best.

Despite these potential difficulties, the nonopaque, detrital heavy mineral suite of the Morrison Formation was studied to better understand the stratigraphy and provenance of this formation where it hosts sandstone-type uranium deposits of the Grants mineral belt near Crownpoint, New Mexico. Samples for heavy mineral analyses were taken from two measured sections and seven coreholes, which form a southwest-northeast line perpendicular to the trend of the Grants mineral belt and parallel to the dip of the Morrison Formation in the southwestern part of the San Juan Basin (fig. 1).

In the study area, the Morrison Formation is composed of (in ascending order) the Recapture, Westwater Canyon, and Brushy Basin Members. During the Late Jurassic, sandstones and mudstones of the Recapture and lower Westwater Canyon Members were deposited by meandering and braided streams flowing into the basin from source areas primarily to the west and southwest of the study area (A. C. Huffman, oral commun., 1982). Higher energy braided streams deposited the upper part of the Westwater Canyon Member, which interfingers with fluvial and lacustrine deposits of the Brushy Basin Member. A detailed discussion of the stratigraphy of the Morrison Formation in the San Juan Basin appears in Hilpert (1969), and stratigraphic correlation of the cores by geophysical logs is shown in Kirk and others (1983).

Sandstones in the Recapture Member are subarkoses, whereas those in the Westwater Canyon Member are lithic arkoses and arkoses; framework grains are primarily moderately well-sorted consisting of quartz, orthoclase, microcline, sodic plagioclase, and various rock fragments (B. A. Steele, oral commun., 1983). Although some rock fragments have been altered beyond recognition by diagenetic processes, many appear to be fine-grained volcanic (rhyolitic) fragments; others present include granite, quartzite (metamorphic), and sedimentary types. Heavy minerals constitute an average of 0.1 percent by weight of these sandstones; however, the nonopaque types represent only a fraction of this amount. Opaque, detrital heavy minerals are represented primarily by iron-titanium oxides (R. L. Reynolds, written commun., 1983), but these grains are not discussed in this report. In the following mineral descriptions, the total Morrison Formation is discussed as a unit, because the basic detrital mineral assemblage does not change substantially from member to member although there is an apparent increase in first-cycle material from bottom to top in the formation.

PREVIOUS STUDIES

Most petrologic studies of the Morrison Formation in the San Juan Basin do not describe the heavy mineralogy in detail, but rather focus on general stratigraphy and sedimentary petrology. Moreover, recent petrologic studies have been concerned primarily with the diagenesis of uranium-bearing parts of the Morrison Formation. In the most comprehensive description of Morrison heavy mineralogy, Cadigan (1967) used trend-surface analysis to show basin-wide variations in detrital heavy mineral populations. In a report on the heavy mineralogy of the Slick Rock uranium district of southwestern Colorado, Bowers and Shawe (1961) presented frequency distributions of various detrital heavy minerals. Martinez (1979) used heavy mineralogy to interpret the provenance of the upper part of the Morrison Formation between Gallup and Laguna, New Mexico. Other reports that discuss the provenance of the Morrison Formation in northwestern new Mexico include Craig and others (1955), Cooley and Davidson (1963), and Harshbarger and others (1957).

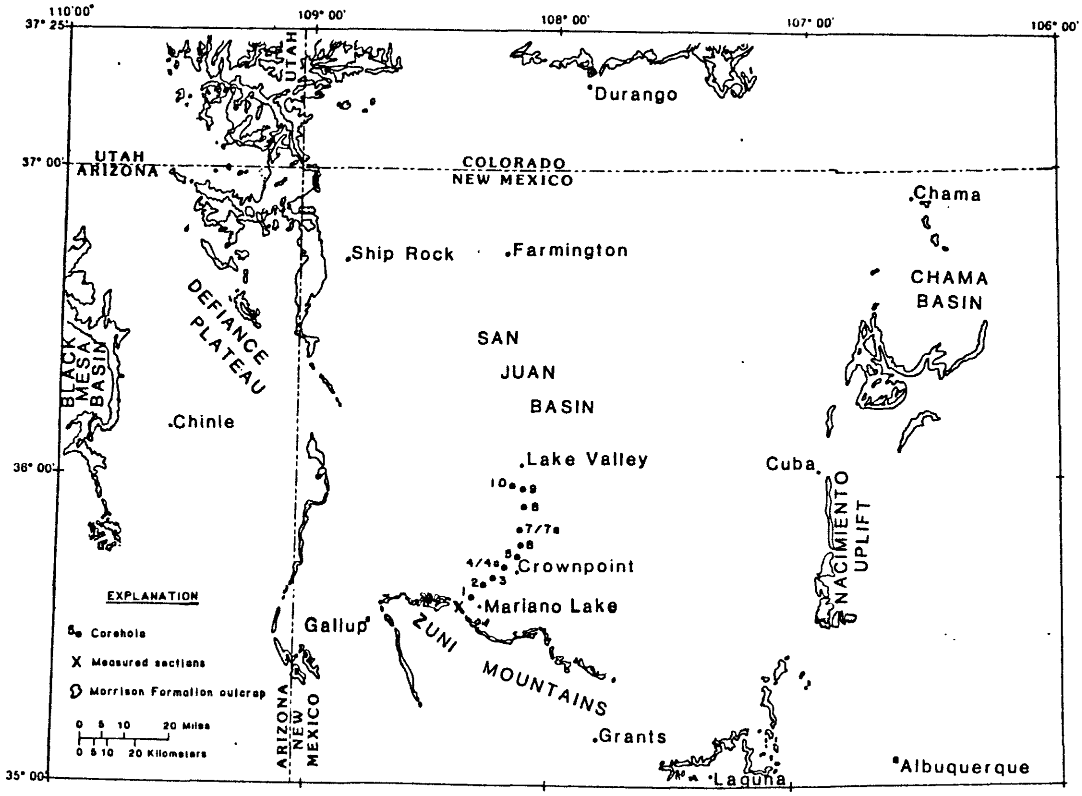

Figure 1.--Locations of measured sections and numbered coreholes, southwestern San Juan Basin, New Mexico.

METHODS

Separation Procedures

Fine- to medium-grained sandstone samples (158) were collected for heavy mineral analysis; however, finer and coarser grained sandstones were sampled in intervals where fine to medium grain sizes were unavailable. Because of the friable nature of many sandstones, pulverization was not required. When necessary, samples were disaggregated gently with a ceramic pestle on brown paper, and well-indurated sandstones were broken into pea-sized chunks with a mechanical jaw-crusher before disaggregation with a pestle.

The -60 to +230 size fraction (2 to 4 phi) was separated from the other grain sizes by sieving. At this point, heavily iron-stained samples, such as those from the surface sections and core 1, were treated with an aluminum-buffered oxalic acid solution to remove the iron-oxide coating (Leith, 1950). This mild solution does little damage to the heavy mineral grains. Next, each sample was elutriated to eliminate the finest clay particles, dried, and weighed. It was then placed in bromoform (specific gravity of 2.87) for separation of the heavy minerals from the light minerals. Because of the low percentage of heavy minerals in these rocks, the entire 2 to 4 phi fraction of many samples was frequently used in the separation procedure.

After separation, the heavy and the light fractions were dried and weighed. The magnetic portion of each sample was removed with a hand magnet and examined separately. Finally, all or a split portion of the nonmagnetic grains was mounted in canada balsam on a glass slide for petrographic study.

Petrographic Methods

About 200 nonopaque heavy, detrital mineral grains from each grain mount were recorded by counting all grains in the microscope field of view in evenly-spaced traverses. During each count, the number of opaque grains was also noted. Spindle-stage techniques (Wilcox, 1959) aided in the initial identification of some minerals. In addition, the scanning electron microscope (SEM) with an attached energy dispersive X-ray analyzer (EDX) was used to examine surface textures of grains and to obtain qualitative elemental analyses of selected grains.

MINERAL DESCRIPTIONS

Garnet, zircon, tourmaline, apatite, and staurolite constitute over 90 percent of the nonopaque, detrital heavy mineral suite (see appendixes 1-9). Minerals that occur in minor amounts include those of the epidote group, amphiboles, pyroxenes, rutile, sphene, andalusite, sillimanite, monazite, spinel, and topaz. Micaceous, heavy minerals, such as biotite and chlorite, are present sporadically.

Garnet

Almandine-spessartine garnet and minor grossular garnet constitute 9 to 60 percent (mean of 31.8 percent) of the assemblage. Almandine-spessartine types are colorless, light to dark pink, and occasionally salmon-pink or red; grossular varieties are yellow to yellow-green. Grains are subangular to rounded, and many display a mammillary or pebbly surface texture. Some colorless and pink garnets have sharp, angular faces that apparently follow crystallographic directions. These forms occur abundantly in a stratigraphic zone that extends from the Recapture Member to the upper part of the Westwater Canyon Member in cores 5, 6, 7, and 7a and appear less commonly in the same stratigraphic interval in the other cores and measured sections (fig. 2). Because breakage would have conformed to garnet's subconchoidal fracture, mechanical abrasion is an unlikely cause of these features. Furthermore, the smooth, lustrous nature of the angular surfaces indicates that they have not been exposed to surface weathering.

Laboratory studies have shown that these surfaces can result from chemical etching. In experiments on chemical etching of natural minerals, Honess (1927) demonstrated that at low temperatures using various reagents at either very basic or acidic pH's, etching will procede along regular crystallographic directions. Likewise, Bramlette (1929) created etch patterns on garnet with an HF solution, and McMullen (1959) found that a NaOH solution duplicated natural etch-features on garnet. Using various strengths of both acid (HF) and alkaline (NaOH) solutions, Gravenor and Leavitt (1981) found that garnets immersed in the 40 percent HF solution became etched within hours, whereas garnets in the NaOH solution became only slightly frosted after 22 days; however, it may be that more time is required for etching with alkaline solutions. Detailed electron microprobe analyses of many garnet grains indicated that the etched surfaces were not overgrowths (Gravenor and Leavitt, 1981) as some authors have asserted (Simpson, 1976). Rahmani (1973) theorized that because of the presence of fresh detrital apatite, etched garnets from Late Cretaceous-Paleocene sandstones were formed by the action of basic intrastratal solutions. This may be the case here; however, the geochemical situation is complex and requires knowledge of phosphate concentration in the intrastratal water in order to make a statement regarding water pH at the time of etching. In the present study, comparison of qualitative SEM-EDX analyses on rounded and etched grains showed less Mn in the latter, suggesting a loss during the etching process and preferential etching along crystallographic planes where Mn resides.

Reports on the natural occurrence of severely etched garnets are scarce. Bramlette (1929) described deeply etched garnets from Tertiary strata in Venezuela, and Smithson (1941) reported garnets from Mesozoic sedimentary rocks in Yorkshire that had been etched to form skeleton crystals with a "rhombic-dodecahedral" structure. While studying the Morrison Formation in southwestern Colorado, Bowers and Shawe (1961) described etched garnets as "building block forms"; Cadigan (1967) found similar forms in the Morrison from the San Juan Basin.

In the best description of this process, Smithson (1941, p. 100) portrayed the etching of garnet as one step in a series of steps toward complete dissolution: first, a mammillated surface develops; then, a minute rhombic etch pattern forms; and as etching proceeds, the garnet becomes severely etched--perhaps even a skeleton crystal; finally, it may totally dissolve. This sequence accurately portrays the change in appearance of detrital garnets of the present study on approaching the zone of intense garnet alteration from strata above or below (fig. 3a-d).

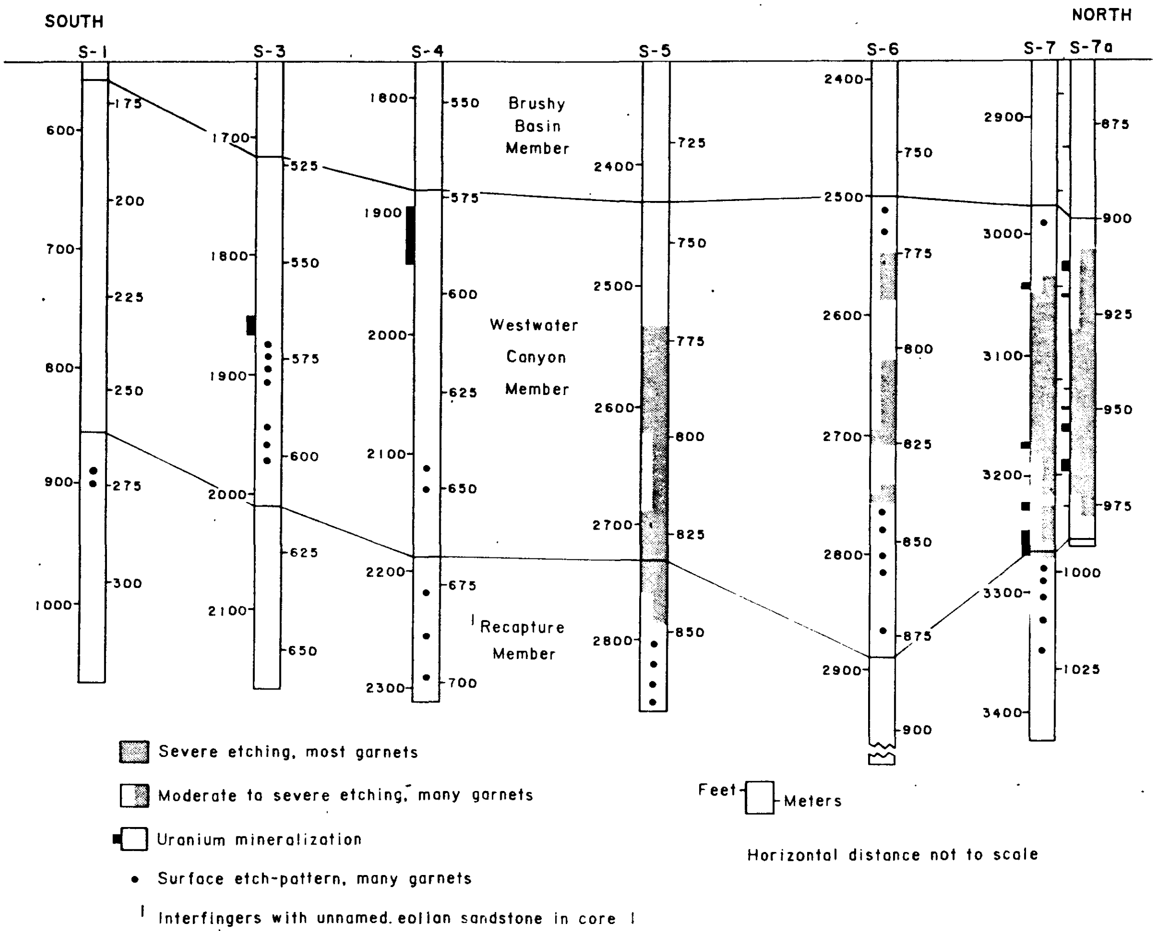

Figure 2.--Cross section of cores through the Morrison Formation showing the distribution of etched garnets.

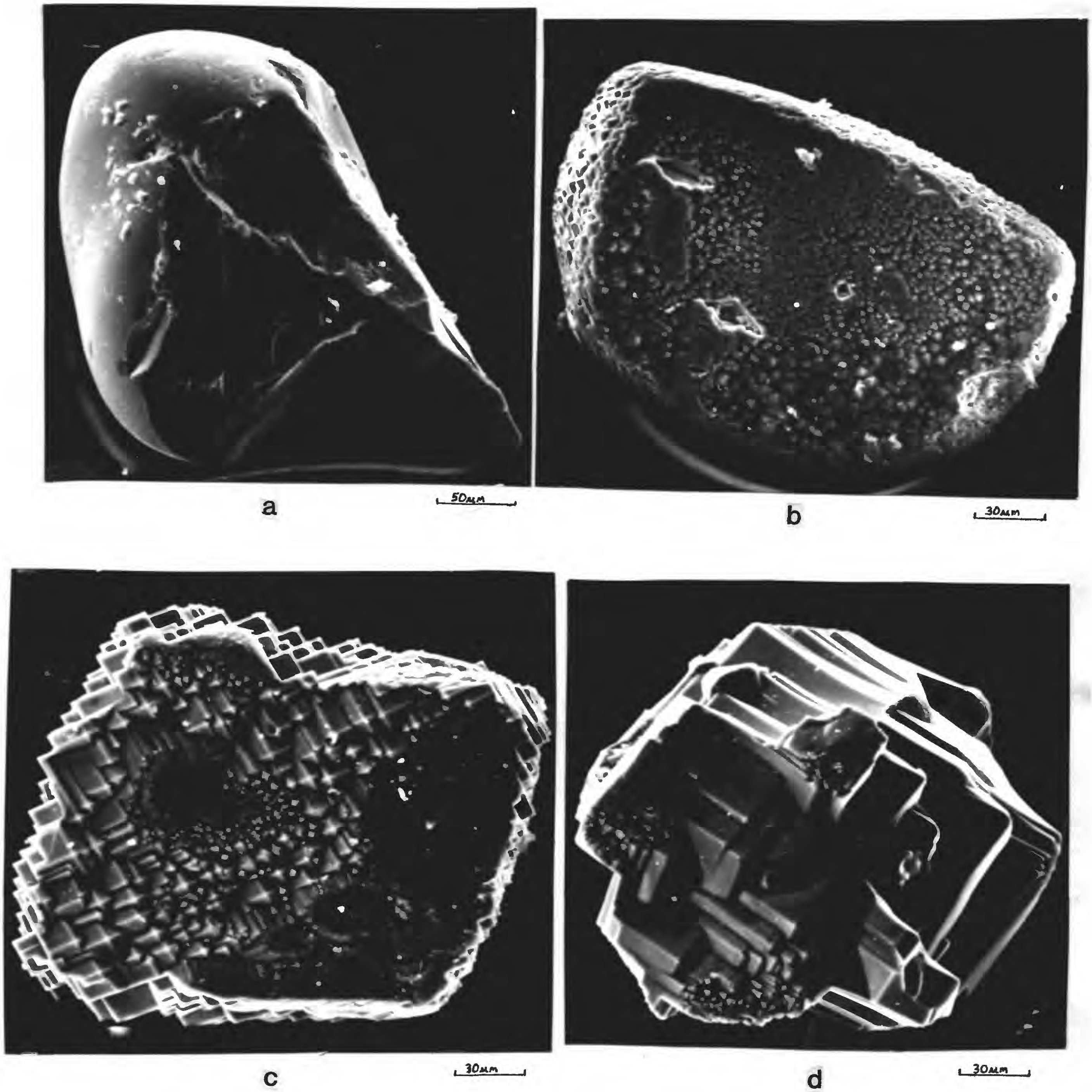

Figure 3.--Scanning electron micrographs of detrital garnet etch-stages from the Westwater Canyon Member of the Morrison Formation: (a) smooth, unetched garnet, (b) garnet with mammillary surface texture, (c) slightly etched garnet showing dodecahedral etch-surfaces, and (d) severely etched garnet.

In addition to etch-features, some garnets, such as those from the Recapture Member, have dull, pitted, uneven sufaces probably formed by prolonged exposure to surface weathering. The cloudy, opaque texture and slight birefringence of these grains suggests alteration to one or more unidentified authigenic minerals.

Zircon

Zircon constitutes 9 to 66 percent (mean of 30 percent) of the heavy mineral suite and is often the most abundant heavy mineral. Although many zircon morphological types occur, they can be divided into three groups: angular to rounded, subhedral, and euhedral grains.

Angular to rounded zircons are the most common and, of these, the rounded ones predominate occurring as colorless to light-pink, lozenge-shaped to spherical grains. In contrast, subhedral zircons are colorless or light pink and rarely pale yellow or dark brown and have sharp prism faces and rounded terminations. Some of the dark brown zircons with a lower birefringence may be metamict (fig. 4a). The euhedral grains are colorless, rarely light pink or pale yellow, and commonly have transparent and opaque inclusions. Characterizing these doubly terminated euhedra, complex and sharply defined faces occur that often include the first and second order prisms, the ditetragonal pyramid, and the pyramid (fig. 4b and 4c). Although they constitute less than 10 percent of the population, euhedral zircons may prove to be the most useful for stratigraphic intepretations.

Zircon is stable under most postdepositional conditions; however, corrosion pits and overgrowths occur on many grains. Some corrosion pits may be inherited from the source area (Agrawal, 1962; Roy, 1962); others may be diagenetic (Carroll, 1953; Poldervaart, 1955). In fact, zircons in and adjacent to ore zones show more corrosion that may be related to mineralizing solutions. Under the SEM, authigenic chlorite and potassium feldspar were found inside corrosion pits. Zircon overgrowths on detrital zircons are rare throughout the Morrison with no apparent pattern to their occurrence. These overgrowths are probably both recycled and authigenic and, occasionally, they include a rounded zircon core (fig. 5). In a few samples a specialized overgrowth occurs as a pointed projection perpendicular to a detrital zircon prism face; this type of authigenic zircon was termed an outgrowth by Butterfield (1936). Previous authors have suggested that this form of overgrowth may not be zircon, but rather a mineral isomorphous with zircon (Bond, 1948; Smithson, 1941); however, SEM-EDX examination has shown that at least in this study these outgrowths are zircon.

Tourmaline

Tourmaline constitutes one to 48 percent (mean of 13 percent) of the heavy mineral assemblage. Nearly all color varieties of the three main types of tourmaline occur: pale yellow to brown (dravite); green, gray-green, blue, and black (schorl); and colorless to pink (elbaite). In most samples, yellow-brown, strongly dichroic dravite is the most common variety. Tourmaline occurs as rounded to well-rounded spherical grains, and rarely as subhedral forms. Overgrowths on detrital tourmaline grains are uncommon; those that occur are rounded, suggesting that they were inherited from sedimentary rocks in the source area.

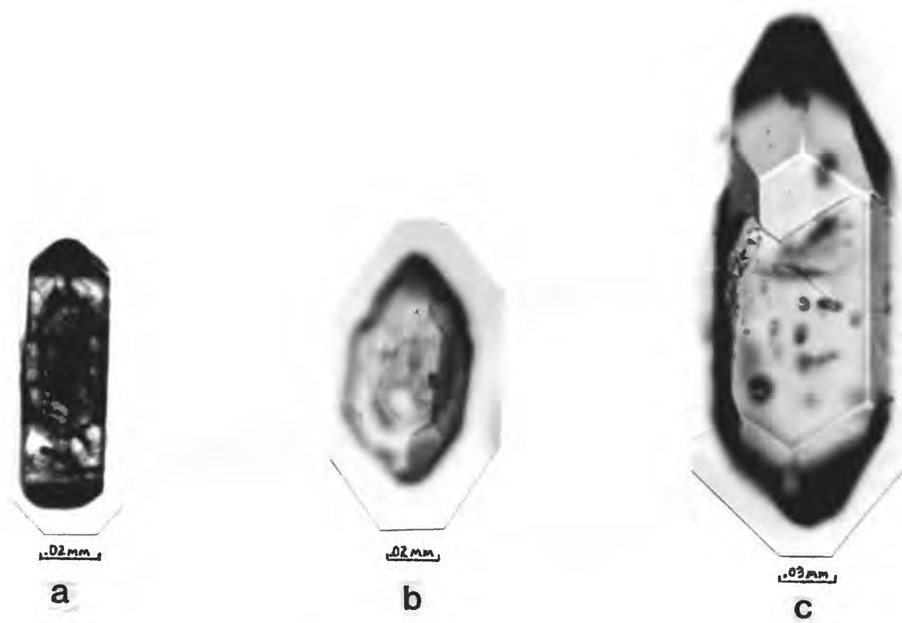

Figure 4.--Photomicrographs of euhedral, detrital zircons: (a) metamict(?), zoned Precambrian(?) zircon (core 7, sample 3259); (b) colorless, stubby zircon with (110) = (100) and (211) > (111) (core 7, sample 2903), and (c) colorless, inclusion-rich zircon with (110) and (211) (core 3, sample 1927).

Figure 5--Photomicrograph of euhedral zircon overgrowth with round core (Pinedale West, sample 19, Westwater Canyon Member).

Apatite

Apatite abundance varies from 0 to 54 percent of the heavy mineral population; however, this variation is due not to provenance changes, but rather to the instability of apatite under acidic conditions (Nickel, 1973). This is apparent when comparing the mean apatite percentage of 11.4 percent from the measured sections with that of the cores, 20.0 percent. Significantly more apatite was found in this study than in other petrologic studies of the Morrison Formation; however, most other studies have reported on surface samples and have used acid-leaching techniques in sample preparation.

Apatite occurs primarily as colorless, well-rounded, egg-shaped grains. Rarely, slightly pleochroic pink or brown, subhedral grains are present that have a pleochroic formula E>O: pink to pale yellow, black to dark red, or gray brown to pale yellow gray. Colorless, subhedral grains with sharp prism faces and, in some cases, sharp terminations, are considered to be a separate, distinctive population (fig. 6). Some of these apatite grains are characterized by an elongate tubular inclusion in the center of each grain parallel to the "c" axis.

Weathering has produced corroded, brown surfaces on many grains from surface samples; however, most apatite grains from subsurface samples show little or no alteration. Overgrowths on apatite grains are uncommon, and those that occur are rounded suggesting that they are recycled; however authigenic apatite is surprisingly common as a phase growing on titanium dioxide grains.

Staurolite

The occurrence of staurolite is quite variable from one sample to another; its abundance ranges from 0 to 33 percent. Pale-yellow to deep-golden-yellow, anhedral to sawtoothed grains (fig. 7) display a moderate pleochroism. In the uppermost part of the Westwater Canyon Member, deep golden-brown to reddish-brown, subrounded to subhedral staurolite with numerous inclusions occurs instead of the paler yellow variety.

Although some slightly etched grains may have been transported into the basin, the characteristic sawtooth shape of staurolite results primarily from deep, postdepositional chemical etching as described by Bond (1936) and Rahmani (1973). Other diagenetic effects that may be related to the etching process include replacement by calcite and unidentified clay(?) minerals.

Minor Nonopaque, Heavy Minerals

Epidote (group), amphiboles, pyroxenes, rutile, sphene, andalusite, monazite, sillimanite, spinel, and topaz constitute less than five percent of the nonopaque, heavy mineral assemblage. Pale-yellow to greenish-yellow, subrounded epidote is cloudy in transmitted light due to secondary alteration. Other epidote-group minerals--clinozoisite, zoisite, and allanite(?)--are rare in the Westwater Canyon Member. Blue-green to brown-green (γ to α) pleochroism characterizes hornblende, which is the most common

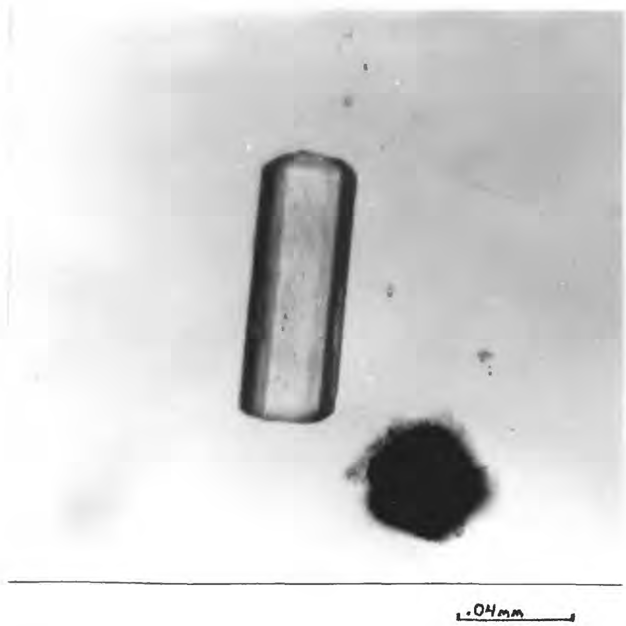

Figure 6.--Photomicrograph of subhedral, detrital apatite (core 7, sample 3375).

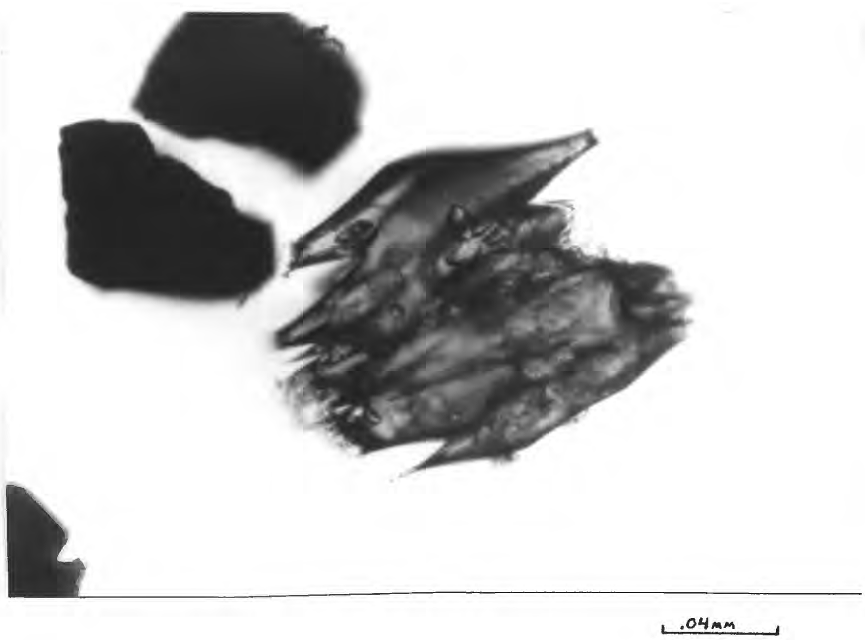

Figure 7.--Photomicrograph of etched, detrital staurolite (core 7, sample 3268).

amphibole, although some green to brown-green hornblende occurs. Other amphiboles noted rarely are pleochroic (γ to α), brown to black oxyhornblende, clove-brown to red-brown anthophyllite, and a few grains of cummingtonite and glaucophane. Although present in only a few samples, pale-yellow to pale-brown blocky augite is the most numerous pyroxene. Other pyroxenes, including colorless to pale-green diopside and an unidentified orthopyroxene, are rare. One or two deep-red to yellow-brown, well-rounded rutile grains were found regularly in the grain mounts of many samples. Pink-brown, irregular grains of sphene are sporadic in occurrence in the upper part of the Westwater Canyon Member. Andalusite occurs rarely as colorless, pink or brown, subhedral grains that display a moderate pleochroism and are often clouded by trains of inclusions parallel to the "c" axis. Completing the list of minor constituents are (1) pale-yellow, rounded monazite, (2) yellow to brown, fibrous sillimanite, (3) colorless to pink, euhedral spinel, and (4) colorless, prismatic topaz.

Micaceous Heavy Minerals

Because of their erratic, sink-float behavior in heavy liquids, biotite and chlorite were not included in the quantitative analysis. In addition, due to the hydraulic characteristics of these micaceous grains, the occurrences of these minerals may be closely related to depositional environment. Green to brown plates of biotite are present throughout the Morrison and are especially common in the upper part. Many plates are opaque as a result of diagenetic alteration. Red, and occasionally hexagonal, biotite (Ti-rich?) appears in the upper part of the Morrison. Light green chlorite occurs most frequently in the Westwater Canyon Member. Micrometer-sized chlorite is very common as an authigenic mineral, but it was seldom seen except under the SEM.

Authigenic, Nonopaque Heavy Minerals

Anhydrite, barite, titanium dioxides, ferroan carbonates, and minor dolomite occur abundantly as authigenic, interstitial cements (greater than 2.87 specific gravity) and as replacements of detrital framework grains. A fairly common and perhaps significant occurrence of authigenic apatite prisms on anatase was noted with the SEM. Recognition of which minerals are authigenic is important, but because these minerals have formed in place and, therefore, do not have a direct bearing on sedimentologic interpretations, they are not discussed in this report.

DISCUSSION OF TRENDS AND PROVENANCE

A strong overprint of diagenetic alterations makes the distinction between sedimentologic and postdepositional trends difficult. Due largely to diagenetic processes active from the Late Jurassic to the present, provenance interpretations based solely on the resultant refractory heavy mineral assemblage are limited. Nonetheless, the quantitative data reveal subtle depositional patterns in heavy mineral distributions. Overall, euhedral zircon and subhedral apatite, each of which at times comprises 10 percent of the heavy mineral population, are the most useful minerals for stratigraphic interpretation.

Previous literature on the use of zircon morphology as a provenance indicator is ambiguous and at times contradictory, but following the reasoning of Pupin and Turco (1972) and Poldervaart (1956), the morphologies of most euhedral, colorless zircons from the Westwater Canyon Member indicate that these zircons were derived from acid igneous rocks. According to Pupin and Turco's classification (1972, plate 1), which is based on the occurrence of certain prismatic and pyramidal crystal faces, most of these zircons would fall between the rhyolitic (S-12 field) and granitic (S-19 field) rock types. The morphological complexity of Morrison zircons--that is, the development of both the first and second order prisms and the predominance of the ditetragonal bipyramid over the pyramid--causes these zircons to plot outside the volcanic field. The reason for this is that acid volcanic zircons tend to have simple morphologies dominated by the first order prism and pyramid (Pupin, 1978; Hoppe, 1963). These simpler forms do occur in the upper Morrison of this study, but they are less common than the more complex morphologies. On the other hand according to Zimmerle (1979), the nearly ubiquitous presence of inclusions in Morrison euhedral zircons indicates that they came from a volcanic source, as inclusions are not common in granitic zircons (Poldervaart, 1956).

Evaluation of another morphological criterion, the elongation (length: width ratio) ratio, indicates increasing volcanic input upsection. In the Westwater Canyon Member, most euhedral and colorless zircons have an elongation ratio between 2 and 4 (average of 2.5) in the normal-prismatic range (table 1), but the majority of zircons from the Brushy Basin Member have elongations between 2.0 and 2.3 (average of 2.1). According to Poldervaart (1956), zircons from silicic volcanic rocks tend to have elongations less than 2. In addition, these stubby zircons have a much larger (110) prism face developed at the expense of the (100) prism face, putting them closer to Pupin and Turco's rhyolitic field (fig. 4c).

A summary of the morphological characteristics of euhedral, colorless zircons indicates that there was continuous input from silicic to intermediate, intrusive igneous rocks and a general increase in material derived from extrusive, rhyolitic rocks upsection in the Morrison Formation. Other petrographic features that include the presence of porphyritic rhyolite fragments, acid plutonic rock fragments, and abundant biotite in the Westwater Canyon Member tend to support this conclusion. Because the age of the zircons is unknown, this zircon population could either reflect the uncovering and erosion of older igneous material or indicate that there was Jurassic igneous activity in the source area. The occurrence of tuffs in the Brushy Basin Member and evidence for Jurassic volcanic activity in southern Arizona (Hayes, 1970; Marvin and others, 1973) suggest that some of these zircons are Jurassic in age. In addition, according to Silver (oral commun., 1981), an orogenic belt that existed in the region of southeastern California, southwestern Nevada, and western Arizona during the Mesozoic supplied some igneous detritus to the San Juan Basin.

Colored, subhedral zircons were probably derived from older, possibly Precambrian, rocks in the source area (Tomita, 1954; Tyler and others, 1940), because much of the color is the result of prolonged exposure to radioactive

Table 1.--Elongations[1] (length:width ratios) of colorless, euhedral zircons (in percent) from the Westwater Canyon Member of the Morrison Formation.

	Round (< 1)	Stubby (1>2)	Normal-prismatic (2-4)	Long-prismatic (>4)	Average elongation
Pinedale East	0	25	71	4	2.6
Core 3	0	23	76	1	2.8
Core 4	1	27	64	8	2.5
Core 6	0	19	75	6	2.7
Core 7	4	28	68	0	2.5

[1] Elongation categories after Poldervaart (1956).

elements in the zircon lattice. On the other hand, most well-rounded zircons have been recycled from sedimentary rocks, for experiments have shown that little rounding occurs during fluvial transport (Dietz, 1973); however, an unknown percentage of rounded zircons may have come from metamorphic or even extrusive rocks (Saxena, 1966).

The abundance of rounded and subhedral apatite grains is widely variable, although graphical representation of their occurrences shows a definite covariance (see appendices 1-9) that suggests this fluctuation and the lack of apatite in near-surface samples is due to a common factor, such as weathering. This is evident when comparing the low percentages of apatite from the Recapture Member with the higher numbers of the Westwater Canyon Member. Due to slower deposition and reworking by wind, sediments of the Recapture were probably exposed to surface weathering for a longer period of time than those of the more rapidly deposited Westwater Canyon. For this reason, trends in the Westwater Canyon Member such as the fact that colorless and subhedral apatite is more abundant upward probably reflect real depositional patterns. Furthermore, because these subhedral apatite prisms were found to occur in very fine grained volcanic rock fragments, an increase in their occurrence, like that of euhedral zircons, may correlate directly with an influx of volcanic detritus. Similarly, Callender and Folk (1958) studying lower Tertiary sands of central Texas, concluded that subhedral apatite prisms were derived primarily from volcanic source rocks. On the other hand, colored apatite prisms, which are present throughout in small numbers, probably originated in pegmatites (Deer and others, 1966, p. 507-508) in the Morrison source area.

Complementing the euhedral zircon and subhedral apatite trends, mineral diversity and angularity increase upward in the upper part of the Morrison Formation. This additional diversity is highlighted by the appearance of red-brown, in some cases euhedral, biotite implying a volcanic source.

Low garnet percentages correlate with low staurolite numbers in cores 4, 5, 6, and 7 within the Recapture and Westwater Canyon Members. The fact that many garnets are severely etched in this interval suggests that this decrease can be attributed, in part, to the complete loss of some garnets due to diagenesis. Similarly, diagenesis is probably responsible for the decrease in both the garnet abundance upsection and proceeding from the surface sections northward deeper into the basin. As a result, detrital garnet and staurolite percentages cannot be used in sedimentologic interpretations. Preliminary diagenetic interpretations indicate that the interstitial fluids responsible for the etching of these minerals may be related to uranium mineralization or redistribution.

Deep red garnets (Mn-rich) are more common in the measured sections than in the cores, but it is not known whether this is a depositional or postdepositional phenomenon. Yellow garnets (grossular?) occur sporadically at all localities, but comprise almost 50 percent of the garnet population in sample S1-810. Close stratigraphically to this yellow garnet occurrence, brown augite is present in small numbers. The horizon containing these minerals can be traced across the measured sections through cores 1 and 3 and may represent a syndepositional pulse of material.

Overall, the observed trends begin in the Westwater Canyon and continue into the Brushy Basin Member. Although the basic heavy mineralogy of the Recapture is similar to that of the Westwater Canyon Member, grains in the Recapture are more rounded reflecting the reworking of older sediments and inclusion of some eolian sediments.

INTERPRETATIONS AND CONCLUSIONS

The low diversity in mineral species in the Morrison Formation is due to two factors: (1) diagenetic attrition that has resulted from the dissolution of less stable minerals, and (2) the existence of primarily acid igneous, sedimentary, and low- to medium-grade metamorphic rocks in the source area. Unfortunately, silicic source rocks supply only a limited selection of heavy mineral species restricting the use of these minerals for stratigraphic purposes. Of course, one cannot entirely rule out the possibility that more mafic minerals existing at one time in the Morrison Formation have since been destroyed, but this is not considered to be likely, because in zones of little diagenetic alteration the mineralogy is not appreciably different from that in highly altered rock.

In summary, the detrital and nonopaque heavy minerals were derived from rocks of varied lithologies. Sedimentary rocks in the source areas and locally reworked material are represented primarily by well-rounded grains including zircon, apatite, tourmaline, and rutile. Metamorphic rocks are reflected by staurolite, epidote-group minerals, sillimanite, andalusite, some garnet, angular tourmaline, and chlorite. Minerals derived from intrusive igneous rocks include colored and subhedral zircon, colorless and euhedral zircon, hornblende, colored and subhedral apatite, and some biotite. Extrusive igneous rocks are represented by colorless and euhedral zircon, subhedral and colorless apatite, red and brown biotite, augite, oxyhornblende, and topaz.

Postulated source areas for the Morrison Formation have generally been central and southern Arizona where the Mogollon highlands and various other areas were positive features in Late Jurassic time (Cooley and Davidson, 1963; Martinez, 1979) and an orogenic belt in southeastern California (Silver, oral commun., 1981). Importantly, although these areas have diverse rock types, they also contain Jurassic rhyolitic volcanics and associated intrusives (Marvin and others, 1973; Hayes, 1970) that may have been the source of the acid igneous material in the Morrison Formation. Inferred paleostream directions of flow in the Crownpoint area show a strong west to east component in Westwater Canyon time (Galloway, 1978), further supporting the belief that Morrison source areas included central and possibly southern Arizona.

Because of the effects of postdepositional alteration, the nonopaque, detrital heavy mineral suite has limited value in stratigraphic correlation. For this reason, one of the most important contributions of the heavy mineral data has been to aid in identifying diagenetic trends-- trends that, otherwise, may have been attributed to depositional factors. Importantly, heavy mineral etch-zones in the Westwater Canyon Member may be indicative of the passage of fluids related to mineralization (Hansley, unpublished data).

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APPENDIXES

STRATIGRAPHY

Morrison Formation (Upper Jurassic)

Jmb Brushy Basin Member

Jmw Westwater Canyon Member

Jmr Recapture Member (interfingers with unnamed sandstone unit in measured sections)

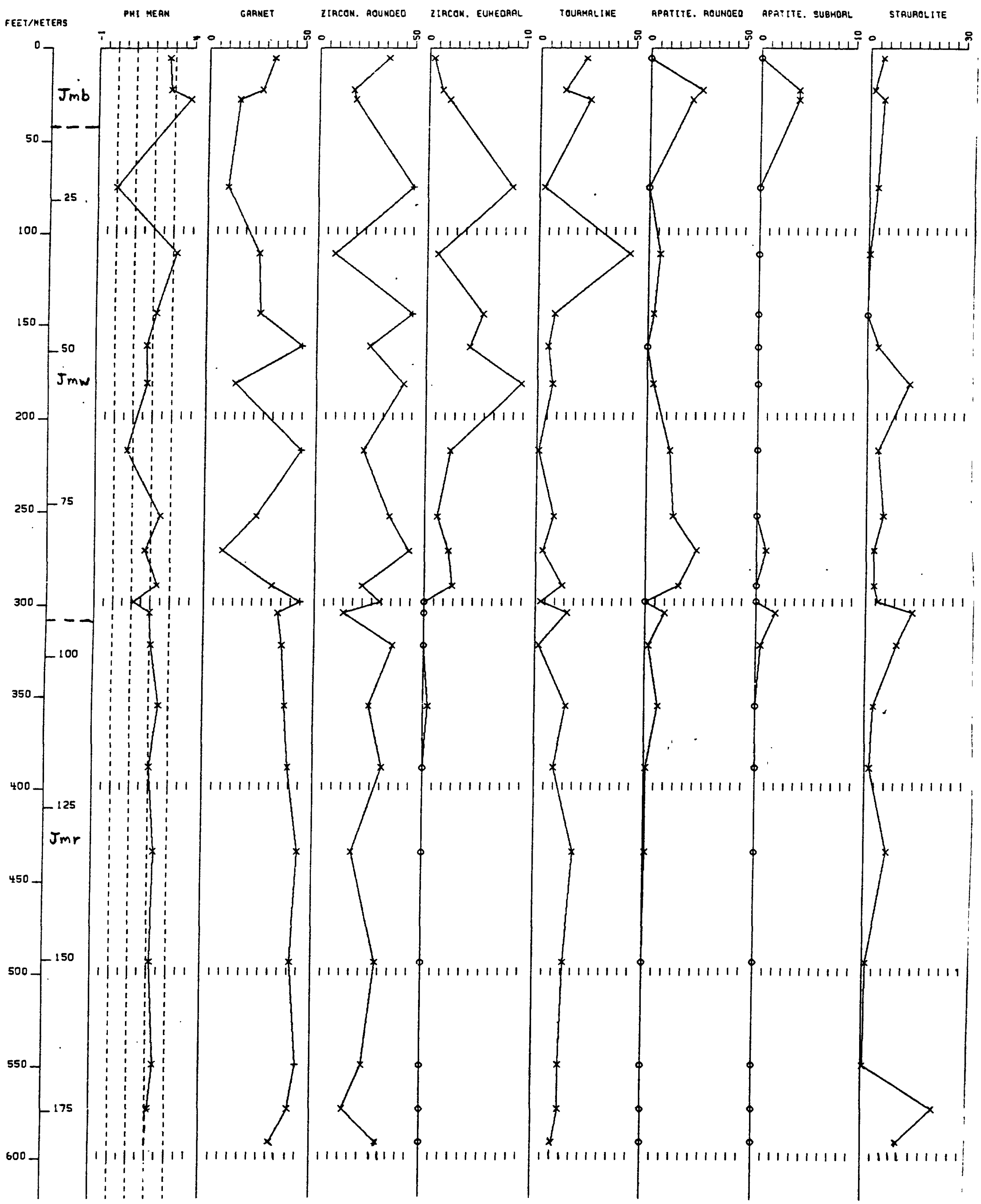
KEY

0 Not observed

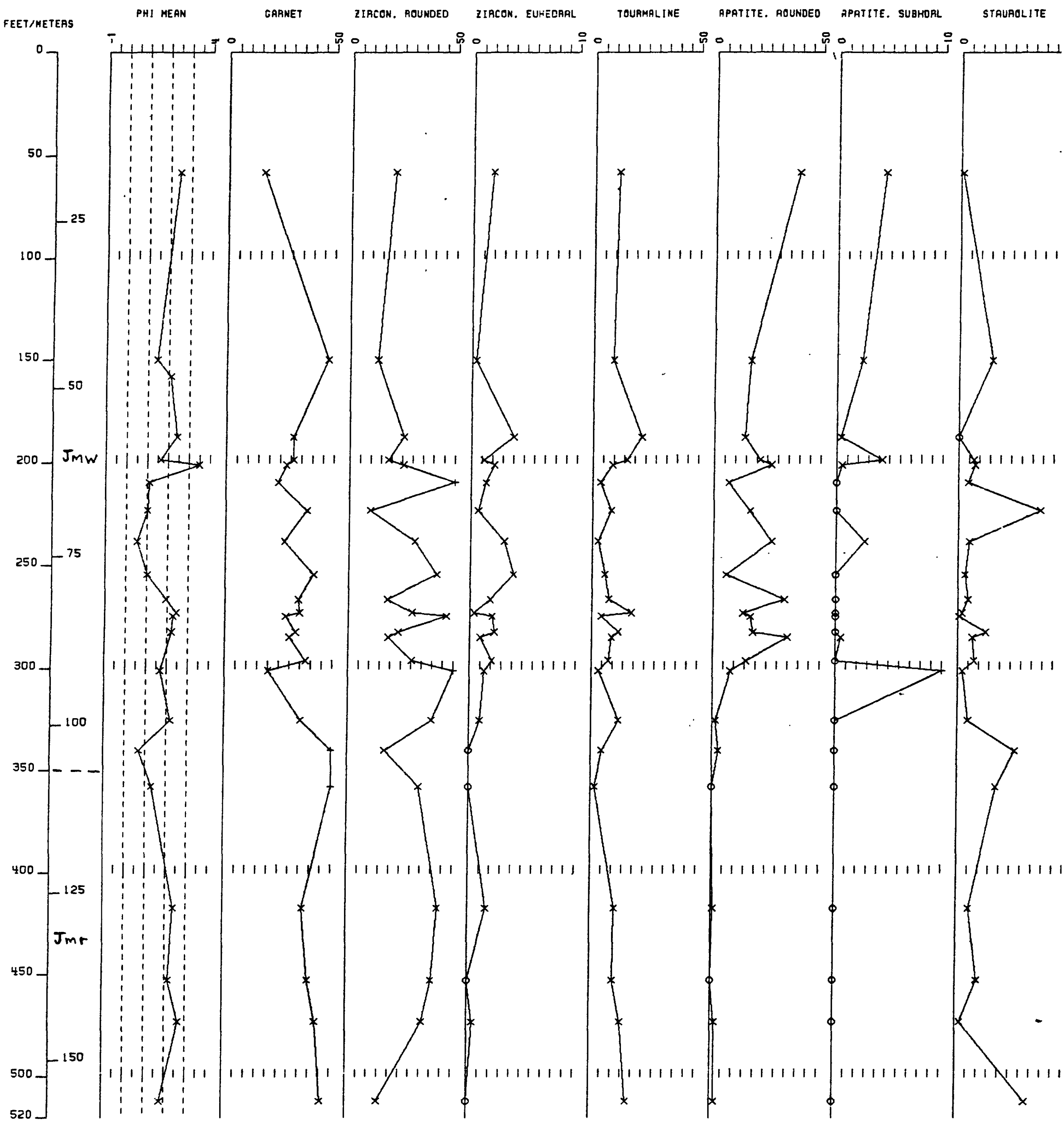
\+ Exceeds limits

x Present

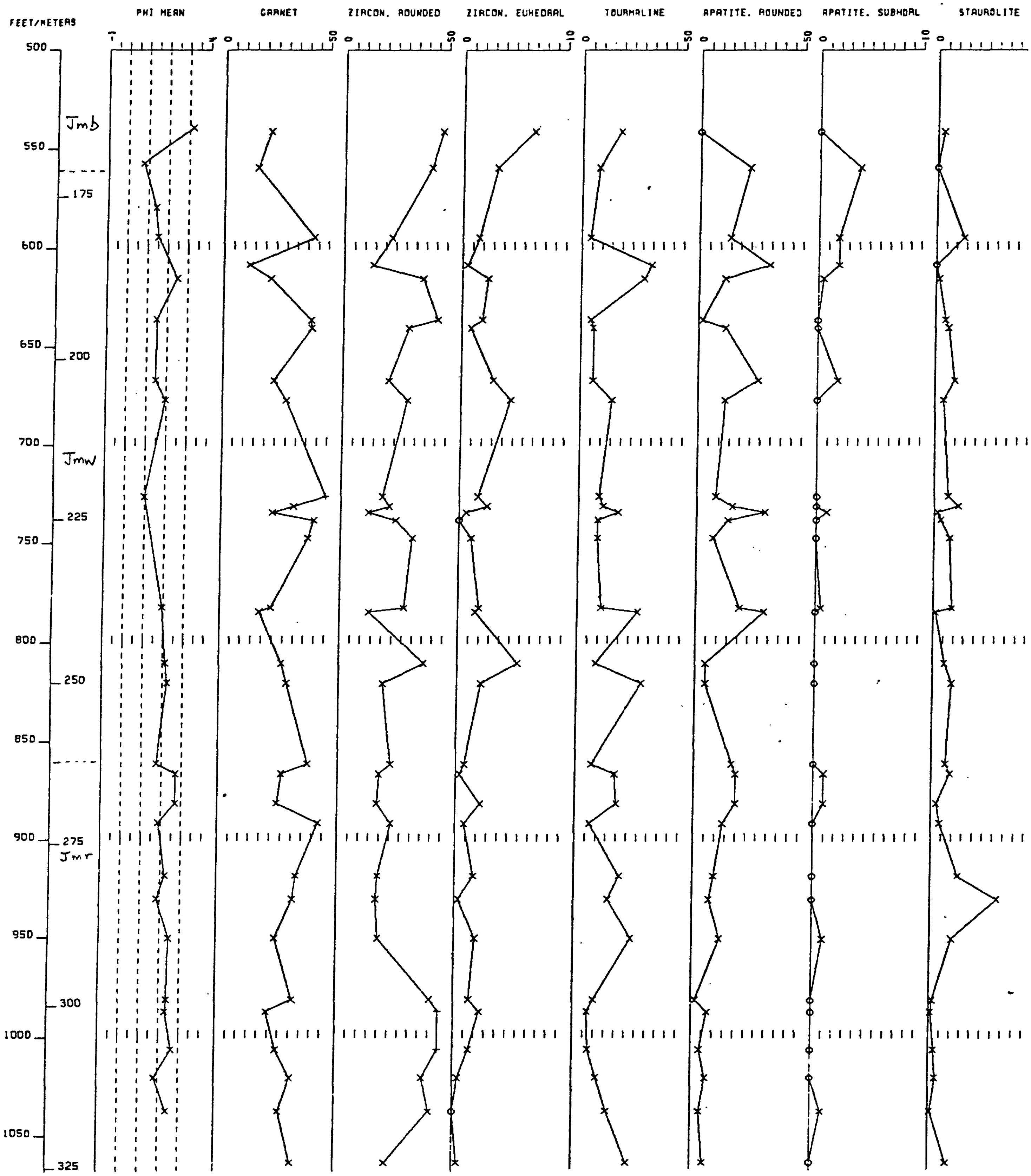
Appendix 1.--Plots of nonopaque, detrital heavy mineral data (in percent) for major minerals based on 200-point counts from Pinedale East measured section.



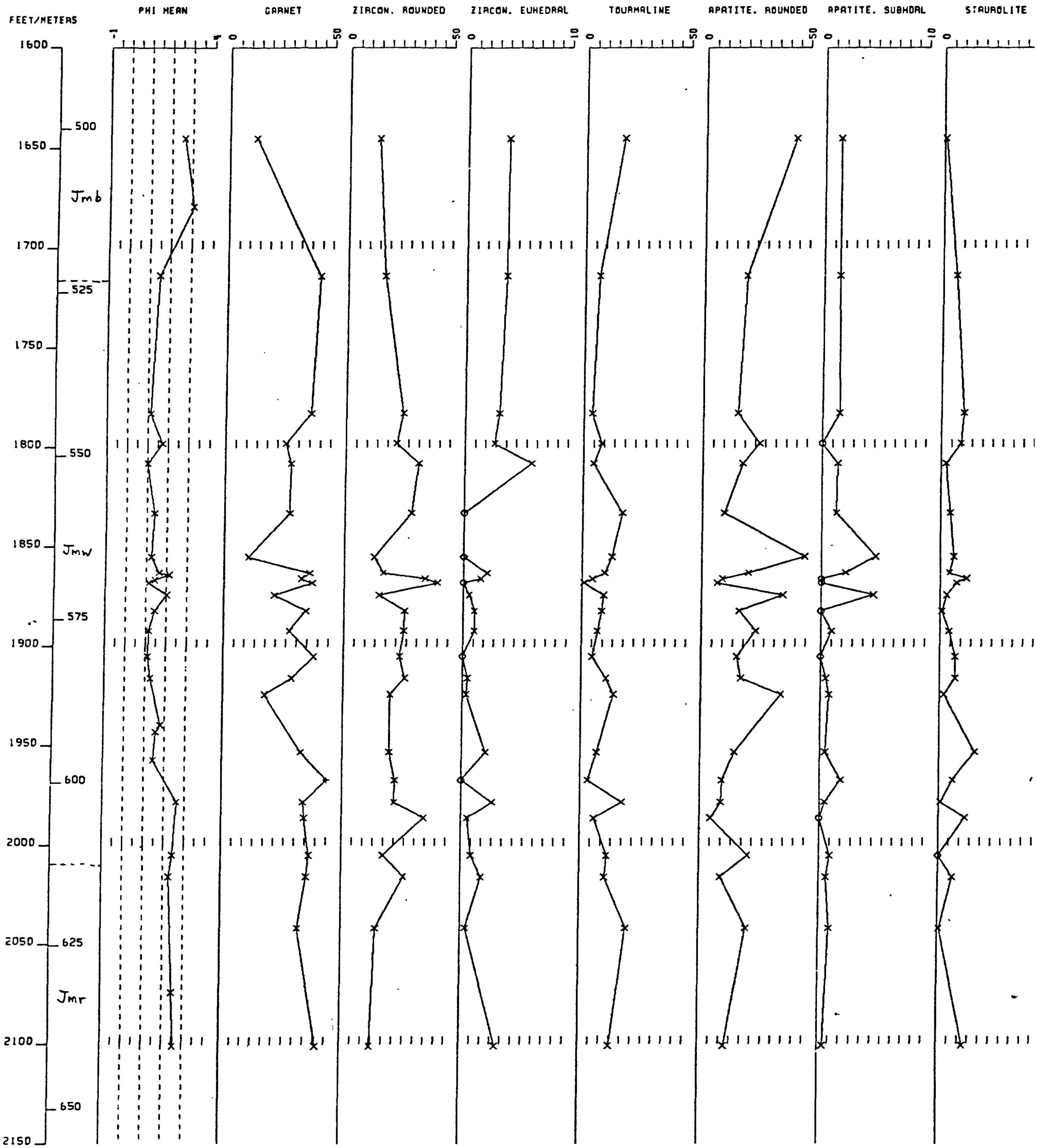
Appendix 2.--Plots of nonopaque, detrital heavy mineral data (in percent) for major minerals based on 200-point counts from Pinedale West measured section.



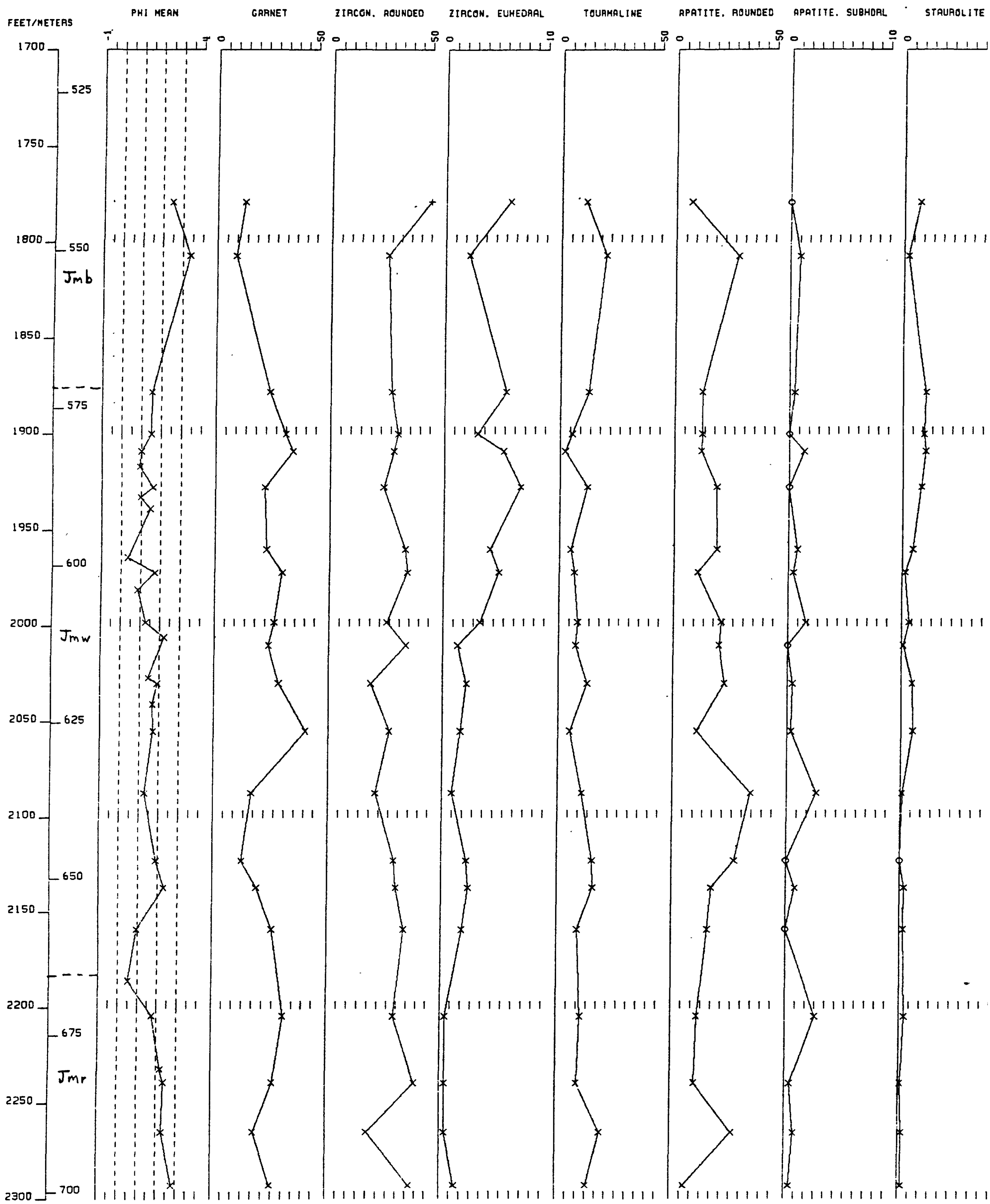
Appendix 3.--Downhole plots of nonopaque, detrital heavy mineral data (in percent) for major minerals based on 200-point counts, core 1.



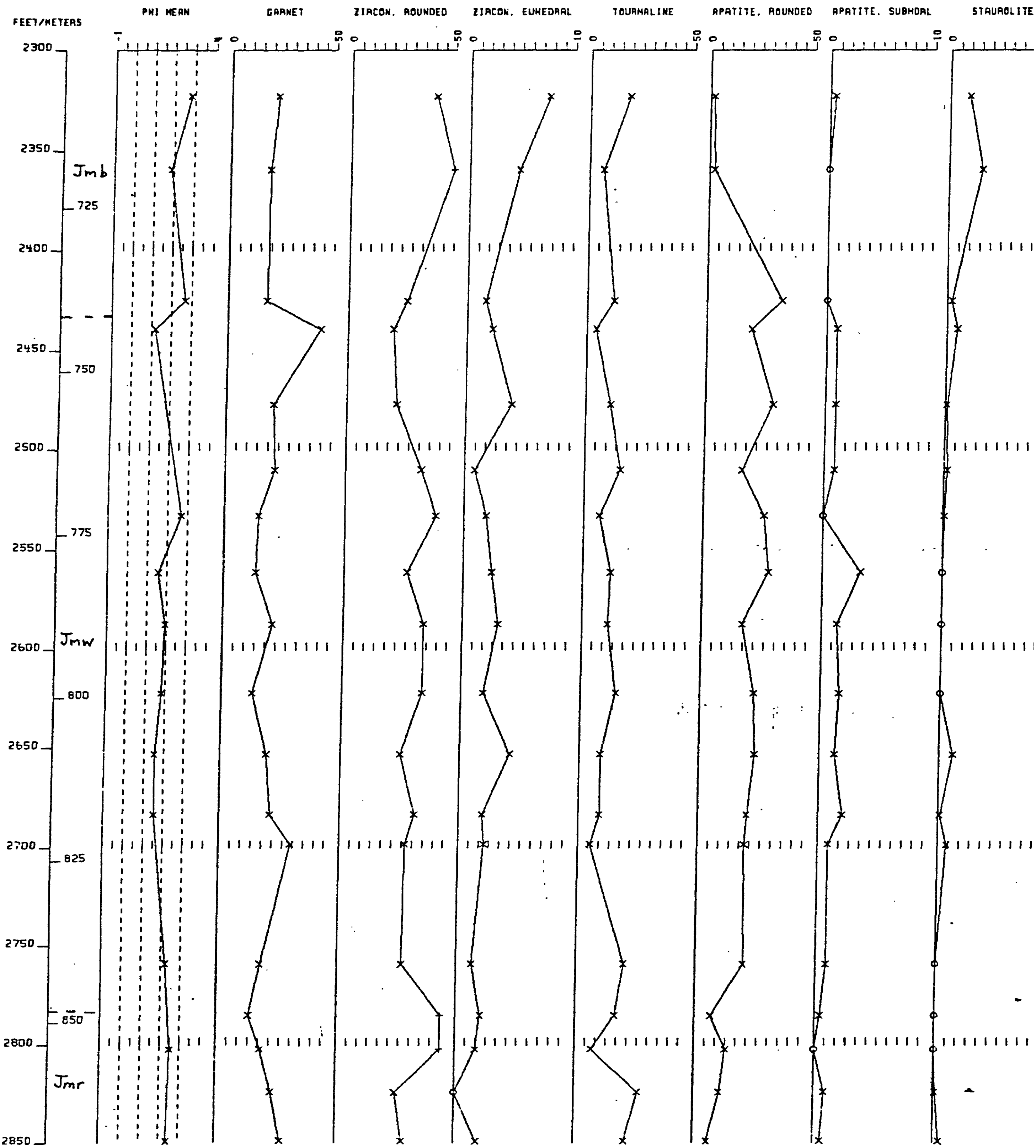
Appendix 4.--Downhole plots of nonopaque, detrital heavy mineral data (in percent) for major minerals based on 200-point counts, core 3.



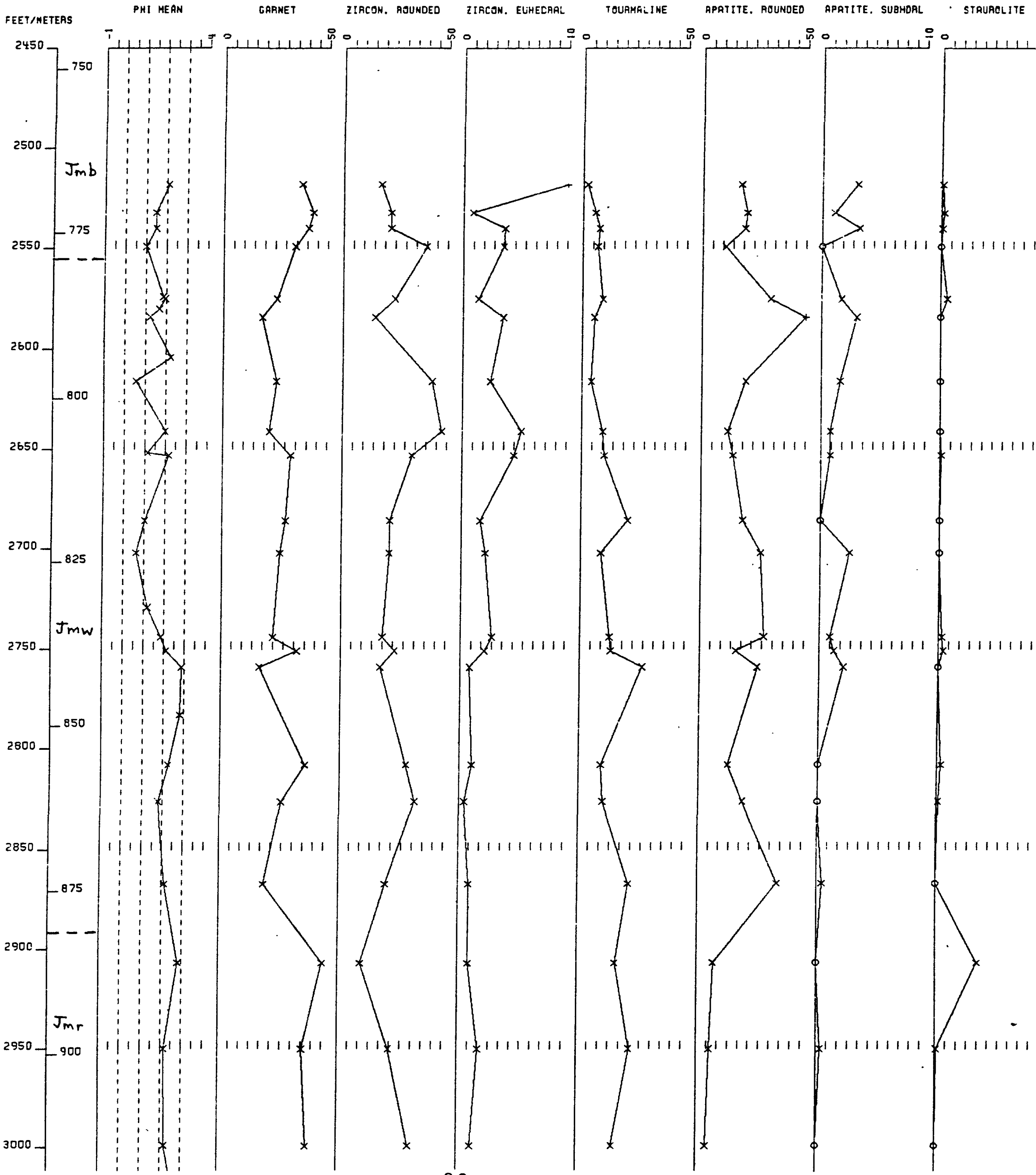
Appendix 5.--Downhole plots of nonopaque, detrital heavy mineral data (in percent) for major minerals based on 200-point counts, core 4.



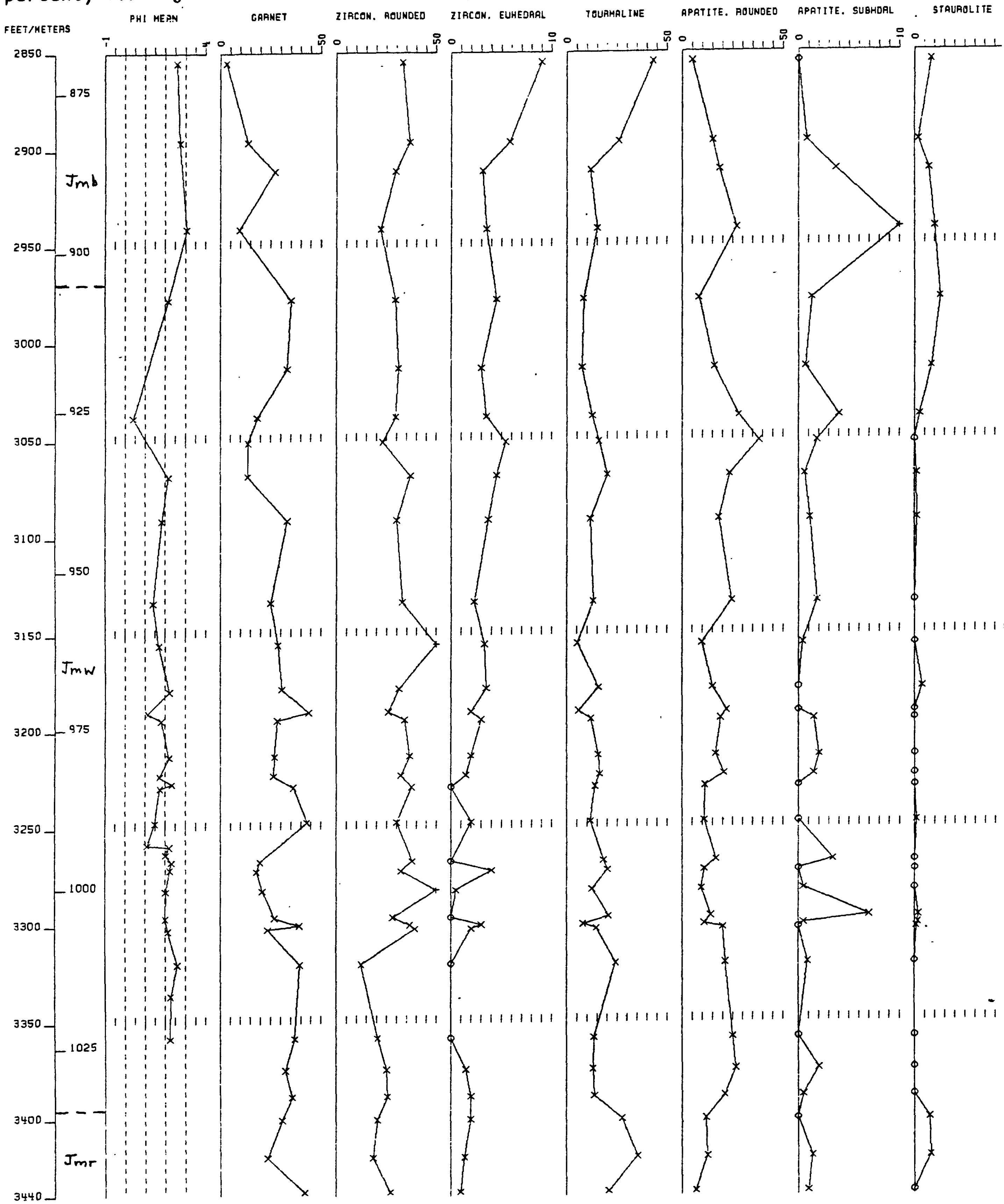
Appendix 6.--Downhole plots of nonopaque, detrital heavy mineral data (in percent) for major minerals based on 200-point counts, core 5.



Appendix 7.--Downhole plots of nonopaque, detrital heavy mineral data (in percent) for major minerals based on 200-point counts, core 6.



Appendix 8.--Downhole plots of nonopaque, detrital heavy mineral data (in percent) for major minerals based on 200-point counts, core 7.



Appendix 9.--Downhole plots of nonopaque, detrital heavy mineral data (in percent) for major minerals based on 200-point counts, core 7a.