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Stratigraphy and sedimentology of Baicalia-Conophyton cycles Helena Formation (Middle Proterozoic Belt Supergroup) northwest Montana

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STRATIGRAPHY AND SEDIMENTOLOGY OF BAICALIA-CONOPHYTON CYCLES, HELENA FORMATION, (MIDDLE PROTEROZOIC BELT SUPERGROUP) NORTHWEST MONTANA

by

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Stratigraphy and Sedimentology of **Baicalia-Conophyton** Cycles, Helena Formation, (Middle Proterozoic Belt Supergroup) northwest Montana (103 pp.)

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An analysis of sediment dynamics at three scales combined with an analysis of stromatolite morphology results in several interpretations regarding the **Baicalia-Conophyton** cycles of the Middle Proterozoic Helena Formation.

Nine different sediment types comprise the **Baicalia-Conophyton** cycles and reflect a range of environments from turbulent debris, tabular and hummocky silt and **Baicalia** sediment types to less turbulent domed stromatolite, pinch-and-swell couple, and even couple sediment types, to low turbulence carbonate mud, microlamina and **Conophyton** sediment types. Vertical sequences of these sediment types form fining- and thinning-upward cycles, one of which coincides with the lower **Baicalia** to **Conophyton** cycle described by Horodyski (1989). This coincidence provides a basis for comparison between siliciclastic-to-dolomite cycles and stromatolite cycles.

Information from sediment types and their vertical sequences confirms Horodyski's (1989; 1983) paleoenvironmental interpretations that 1) **Baicalia** lived in a more turbulent environment and **Conophyton** lived in a less turbulent environment, 2) the sequence from the base of the lower **Baicalia** unit up through the inclined **Conophyton** unit represents a sequence of decreasing turbulence, and 3) changing environmental conditions probably contributed to the morphologic change from **Baicalia** to **Conophyton**, perhaps in addition to a change in the microbe community or a change in the activity of the microbe community.

Lateral and vertical variability in sediment type succession may represent small scale transgressions and regressions or may reflect basinwide changes in environment supportive of expansions and contractions in a restricted environment. This study did not identify cycles with **Conophyton** or quiet water sediments at cycle bases.

The **Baicalia-Conophyton** cycles are a useful chronostratigraphic unit. **Baicalia-Conophyton** cycles may overprint a larger regressive or contractive sequence during which a greater amount of calcite was deposited. The cyclic interval identified by O'Connor (1967) and Eby (1977) in the Swan and Mission Ranges appears to migrate stratigraphically across the **Baicalia-Conophyton** cycles. Siliciclastic-to-dolomitic cycles may thin substantially in the sediments overlying the **Baicalia-Conophyton** cycles in Glacier Park.

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INTRODUCTION

After nearly one hundred years of scrutiny, the depositional processes, environments and dynamics of the Middle Proterozoic Belt basin sedimentation (1.5-1.2 Ga) are still controversial. This study combines an analysis of sedimentary processes with an analysis of stromatolitic growth forms to interpret the **Baicalia-Conophyton** cycles in the northeastern Belt basin. These analyses include sedimentologic descriptions and interpretations at three stratigraphic scales. Sediment types (Winston, 1986, 1989b), including stromatolites, are described and interpreted to determine depositional dynamics. Sediment type sequences are described and interpreted to determine facies dynamics. And basin fill patterns are described and interpreted to reconstruct dynamics of stromatolite and sedimentary cycle accumulation in the Helena Formation.

The Belt

The Middle Proterozoic Belt Supergroup is a very thick sequence of argillaceous, arenaceous and calcareous rocks. Belt rocks cover much of northwest Montana, northern Idaho and eastern Washington and also extend north into Canada where they are called the Purcell Supergroup (Figure 1).

Belt rocks were thrust eastward more than 100 km during the Late-Cretaceous-Paleocene Cordilleran Orogeny (Winston, 1989b); consequently the original shape of the Belt basin has been severely distorted. The modern Belt basin trends

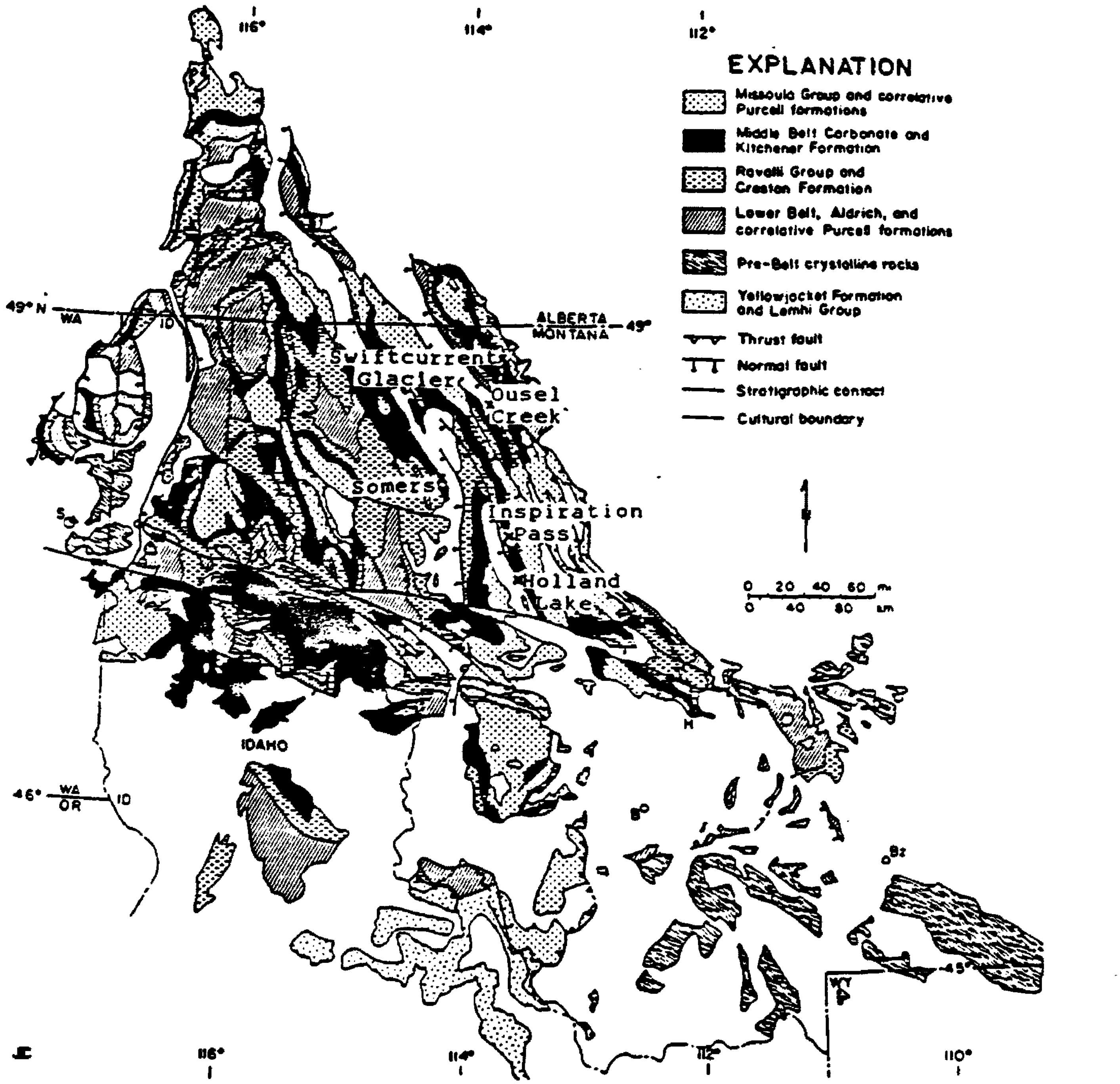


Figure 1. Generalized geologic map of the Belt and Purcell Supergroups. Locations of measured sections are marked (after Winston, 1989).

approximately northwest-southeast, mimicking the trends of the Middle Proterozoic basin axis and northeastern margin of the craton. The large Helena embayment extended eastward into central Montana as an autochthonous graben (Winston, 1989a), bounded on the south by uplift of the Archean crystalline Dillon block (Winston, 1989). To the southwest the Belt basin extended into eastern Idaho depositing the Lemhi Group and Yellowjacket Formations (Winston, personal communication). The original western part of the Belt Basin is unknown because the western portion of the basin was removed by latest Proterozoic rifting (Devlin and Bond, 1988).

Although the tectonic setting under which the Belt basin formed remains elusive, two contrasting theories dominate interpretations of Belt tectonics. One theory proposes that the Belt basin was an epicratonic reentrant which formed on the passive continental margin of the North American craton (Harrison, Griggs, and Wells, 1974). The other theory proposes that the Belt was an intracratonic basin (Winston, 1986; Hoffman, 1988). Most recent plate reconstructions (Moores, 1991; Hoffman, 1991; Dalziel, 1991) place the Belt in the center of a Proterozoic supercontinent. The information from this study and additional detailed stratigraphic and sedimentologic work in the Belt basin may further illuminate this issue.

Belt Stratigraphy

Geologists now recognize four major stratigraphic subdivisions in the Belt (Smith and Barnes, 1966; Harrison, 1972): the lower Belt, the Ravalli Group, the middle Belt carbonate and the Missoula Group (Fig. 1a). The middle Belt carbonate, the focus of this study, includes the Helena Formation and the Wallace Formation. Although the four units have group taxonomic level, only the Ravalli and Missoula are formal groups (Winston, 1989a). The lower Belt and middle Belt carbonate have informal status.

The middle Belt carbonate in the west is represented by the Wallace Formation, consisting of a lower green argillite unit overlain by a thick unit of thin layers of dark grey carbonaceous argillite interstratified with thin to thick gray carbonate and arenite beds (Winston, 1986). The Wallace Formation is characterized by pinch-and-swell couple and couplet sediment types (Winston, 1986) which generally coarsen and thicken to the west (Grotzinger, 1981). These sediments represent the most proximal siliciclastic deposits of the middle Belt carbonate (Winston, 1989a). Coarse pinch-and-swell couples of the Wallace Formation thin and fine eastward and interfinger with pinch-and-swell couplets of the central Wallace and western cycles of the Helena Formation (Grotzinger, 1981, 1986).

Across the eastern part of the basin the middle Belt carbonate is represented by the Helena Formation (Fig. 1).

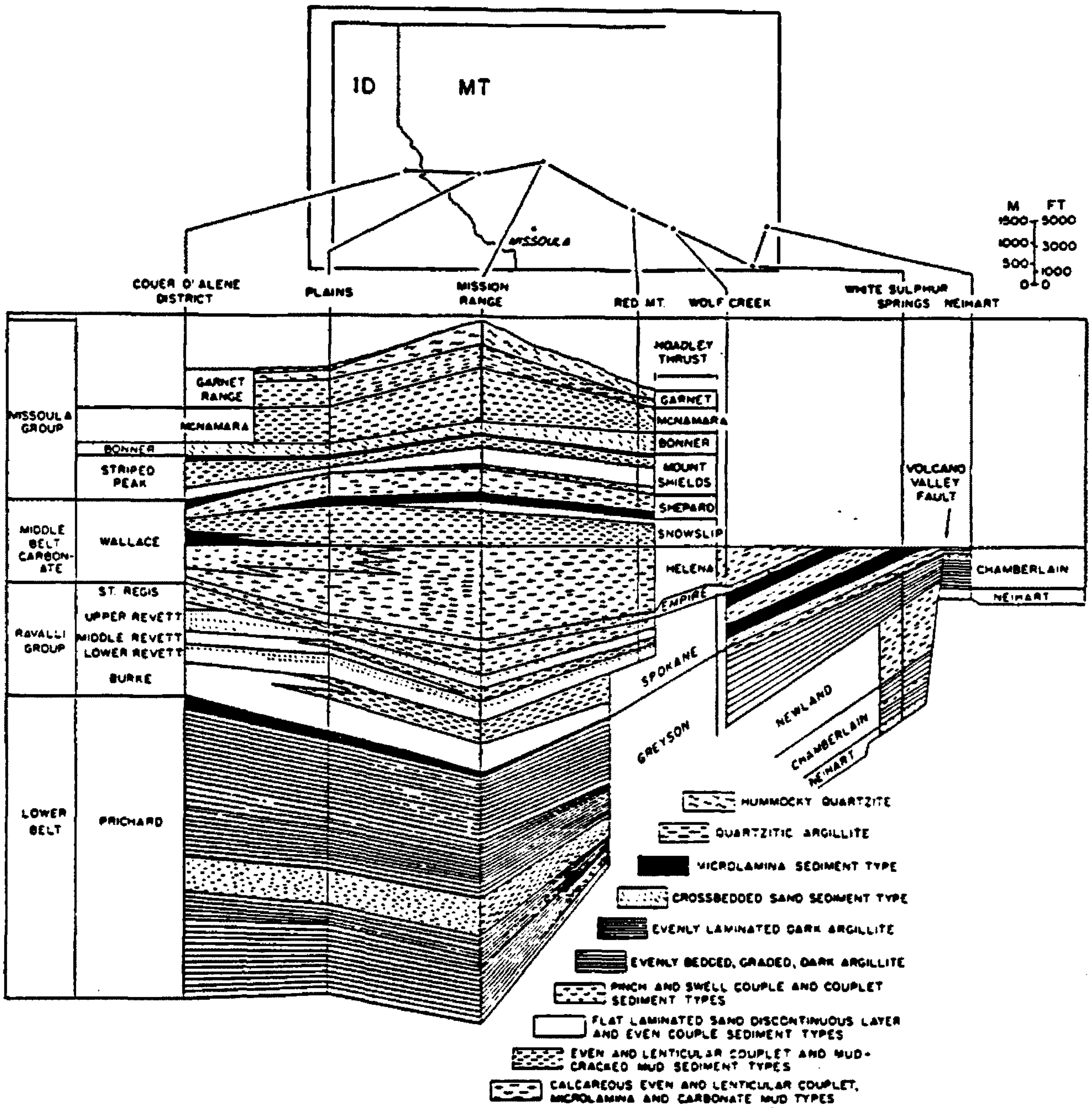


Figure 1a. Stratigraphic cross section of the Belt Supergroup from the Coeur d'Alene district, Idaho to the Little Belt Mountains, Montana, showing inferred pre-Middle Cambrian relationships (from Winston, 1989).

The Helena is characterized by siliciclastic-to-dolomitic fining-upward cycles (O'Connor, 1967; Eby, 1977). Sediment types generally fine eastward from pinch-and-swell couplets to uncracked even couplets, to lenticular couplets and microlamina (Grotzinger, 1981, 1986; Winston, 1989a, 1989b). The Helena Formation includes a very distinctive unit of alternating **Baicalia** and **Conophyton** stromatolite cycles (Horodyski, 1989). In Canada the Kitchener Formation of the Purcell Supergroup correlates with the Helena and Wallace formations (Smith & Barnes, 1966).

Belt Stromatolites

Stromatolites in the Helena Formation in Glacier National Park include a very prominent and distinctive zone of alternating layers of branched (**Baicalia**) and columnar (**Conophyton**) stromatolites called the **Baicalia-Conophyton** cycles by Horodyski (1983). Fenton and Fenton (1933) first described this unusual sequence of stromatolites calling them the bioherms of the Granite Park member of the Siyeh Formation. With considerable insight, Fenton and Fenton suggested that stromatolite morphologies in the Belt may reflect the depositional environments in which they formed.

This Study

Five stratigraphic sections through the Helena Formation stromatolite cycles were measured in and southwest of Glacier National Park. Horodyski (1989) measured, described and interpreted sections at Swiftcurrent Glacier, Ousel Creek and Somers, focusing on stromatolite morphology. I remeasured and redescribed the same sections and added detailed descriptions of the rocks enclosing the stromatolite layers. Figures 3, 4, and 5 are generalized stratigraphic sections from Swiftcurrent Glacier, Ousel Creek and Somers. Detailed stratigraphic sections are located in Appendix A. This information provides a basis for comparing sedimentary aspects of cycles with cycles of stromatolite form genera described by Horodyski, and for testing and reinterpreting Horodyski's paleoenvironmental interpretations of stromatolite sequences.

Sections at Holland Lake and Inspiration Pass (Figures 6, 7) were measured and correlated with other sections. The **Baicalia-Conophyton** cycles extend south and west from Glacier National Park to Holland Lake in the Swan Range, to the southwest Mission Mountains (Winston, personal communication) and comprise an important marker bed for intrabasinal correlation.

Analysis of sediment type sequences in these five sections resulted in the identification of six fining-upward sequences of sediment types (Figures 8, 9, 10) which include Horodyski's (1989) **Baicalia-Conophyton** cycles and which generally confirm Horodyski's (1989) lateral correlations based on stromatolite morphologies.

Siliciclastic-to-dolomitic cycles described by O'Connor (1967) and Eby (1977) also fine upward. The calcareous

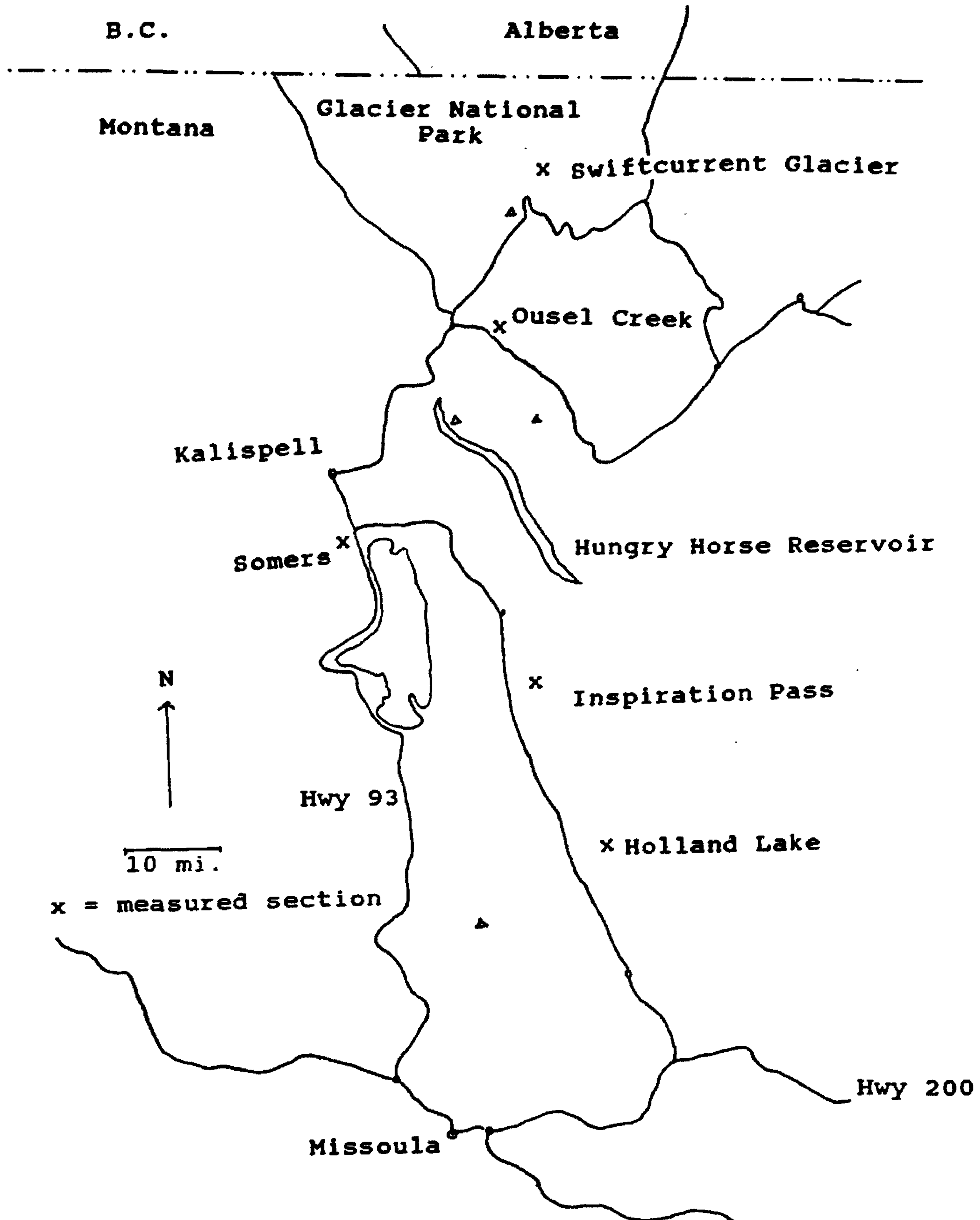


Figure 2. Location of measured sections on political map.

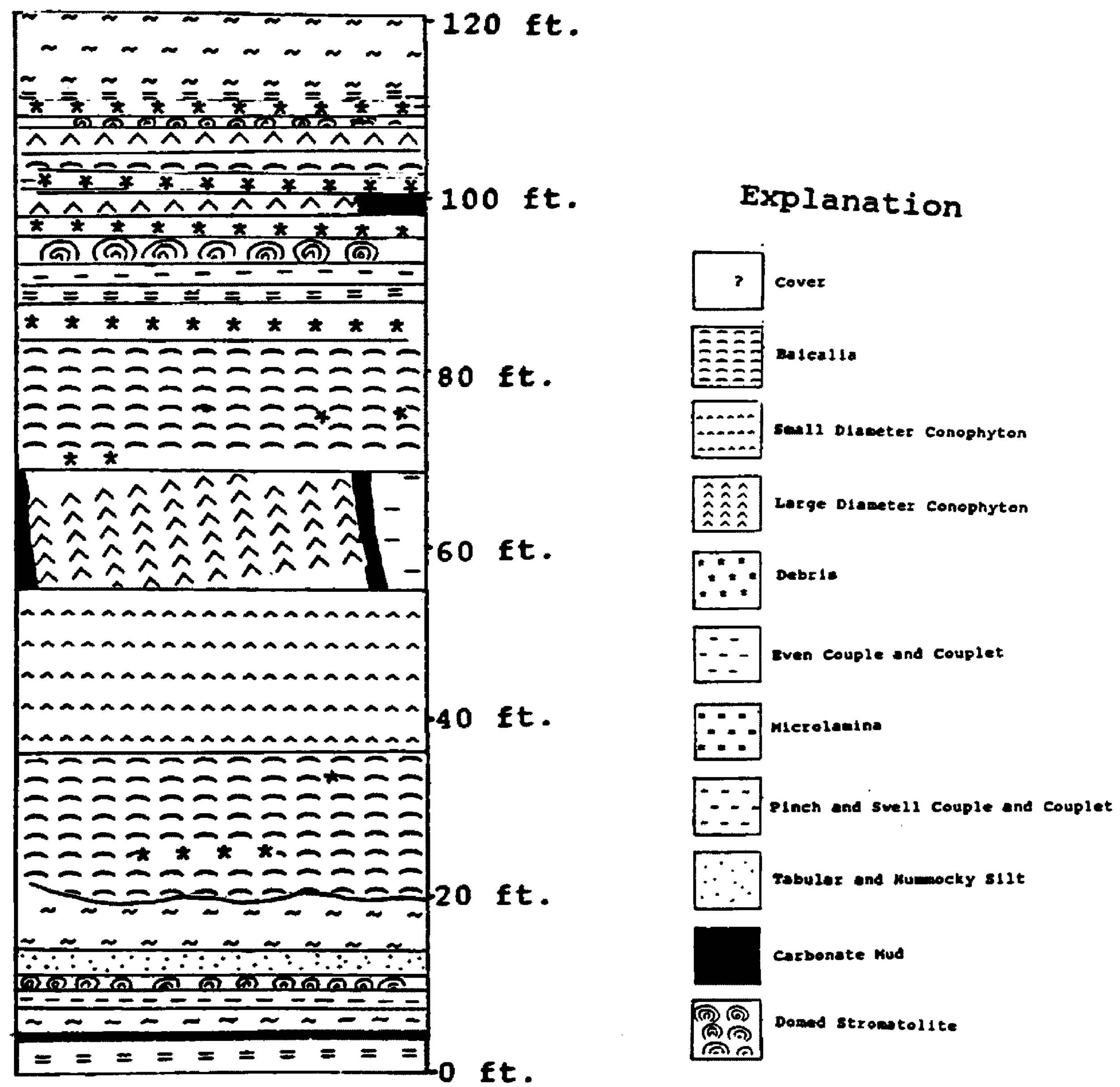


Figure 3. Generalized Section from Swiftcurrent Glacier.

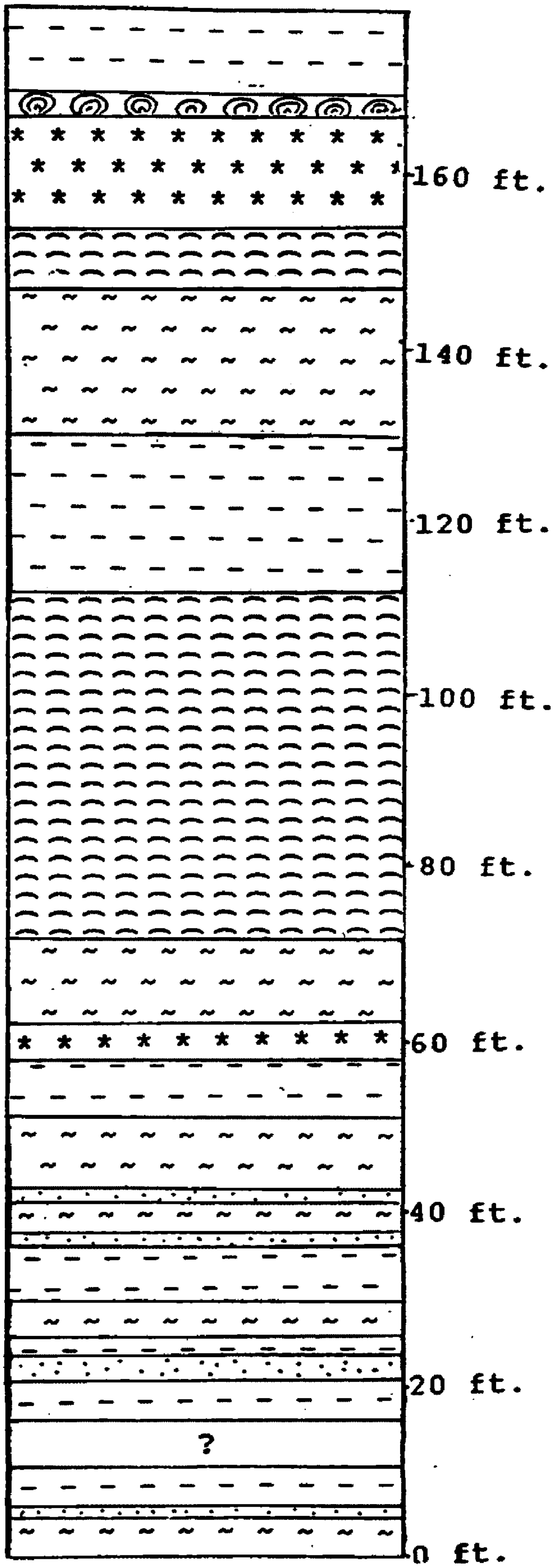


Figure 4. Generalized Section from Ousel Creek.

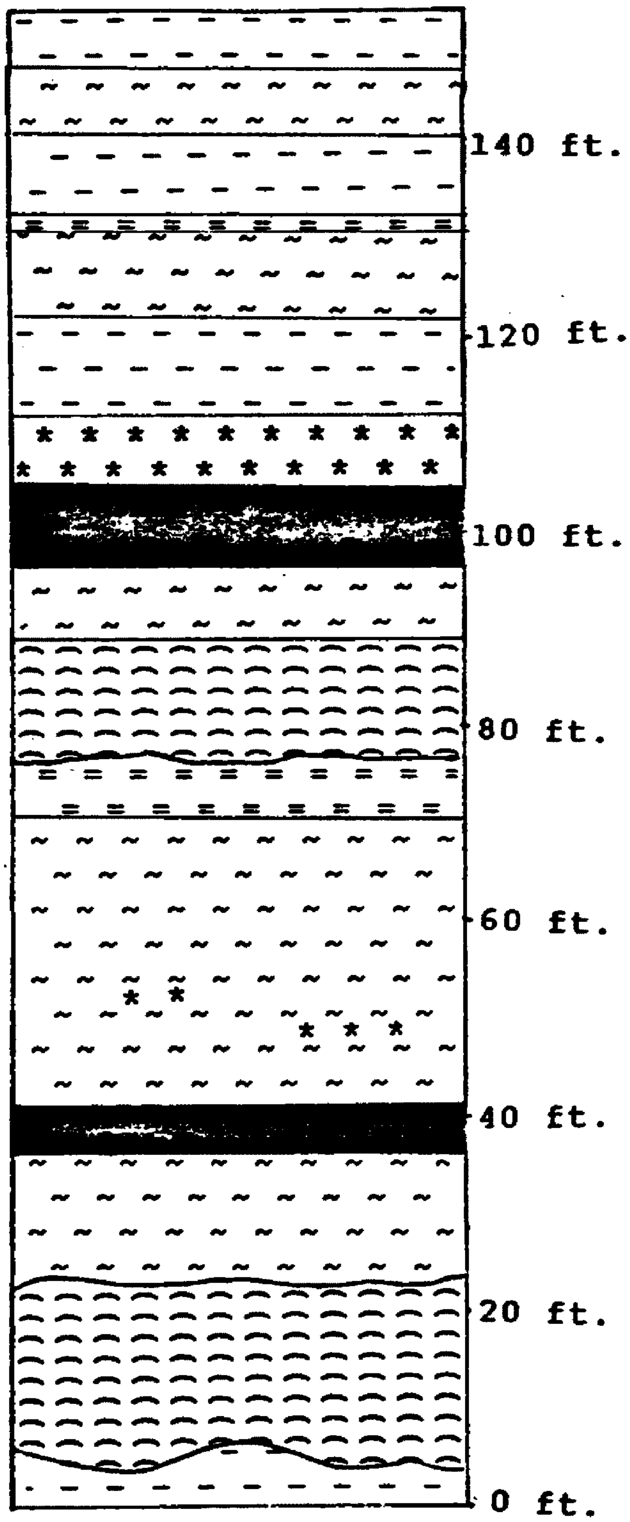


Figure 5. Generalized Section from Somers.

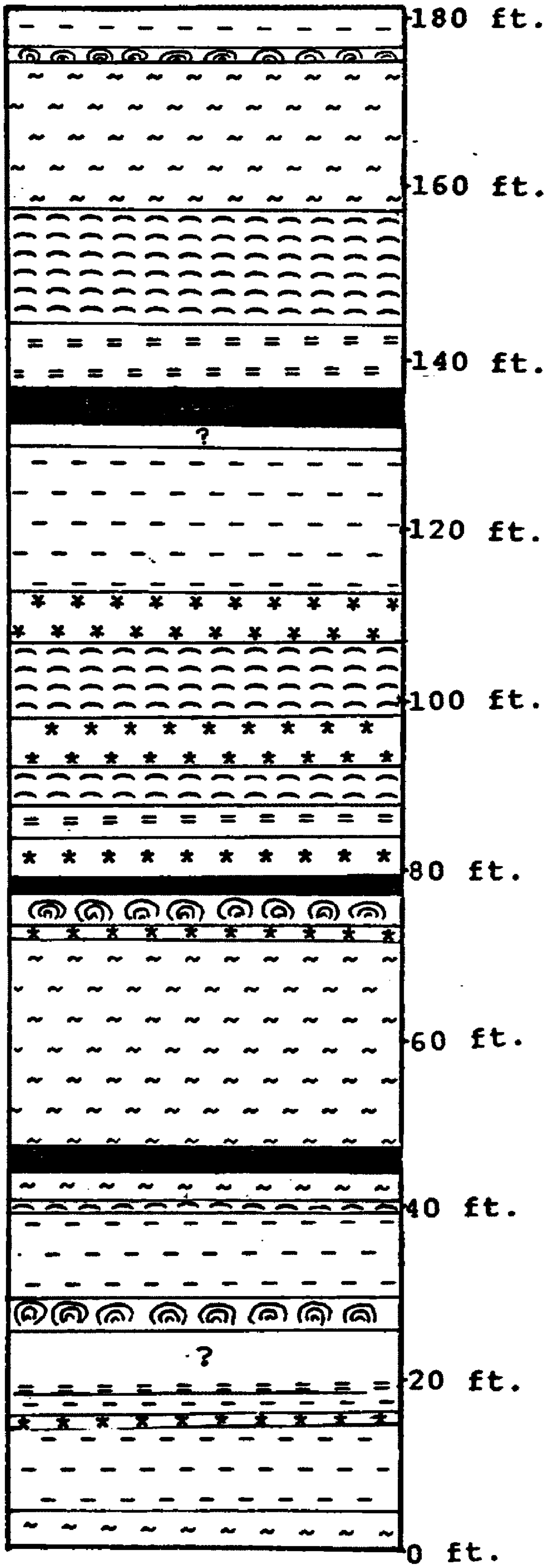


Figure 6. Generalized Section from Holland Lake.

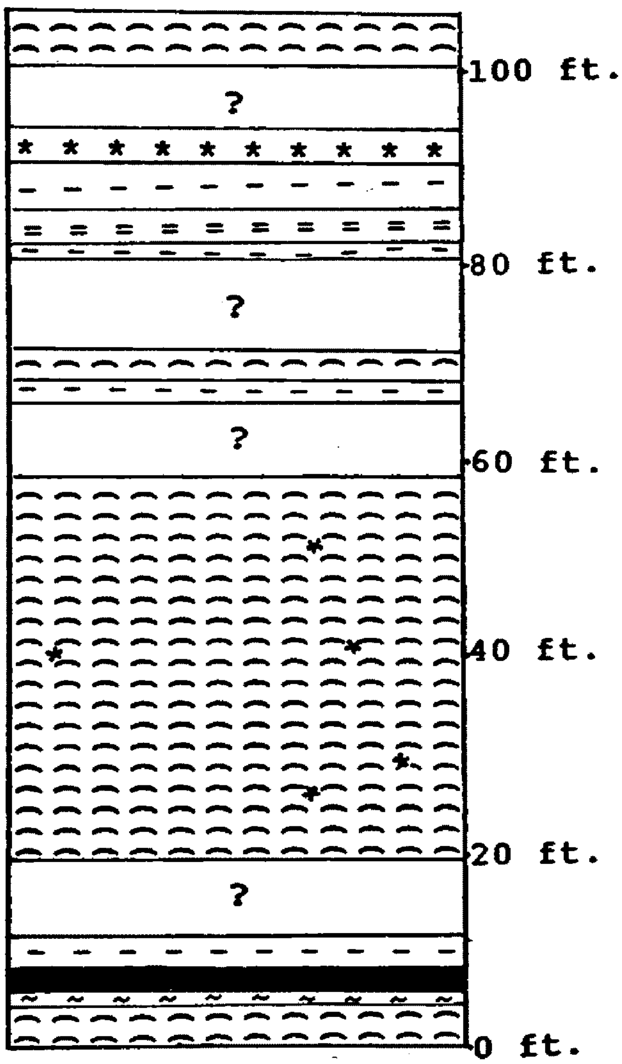


Figure 7. Generalized Section from Inspiration Pass.

Baicalia-Conophyton cycles appear to be a variation of fining-upward cycles in the Helena Formation. Therefore an analysis of stromatolite cycles integrated with siliciclastic-to-dolomitic cycles may provide a basis for testing existing environmental interpretations of all kinds of cycles in the Helena Formation.

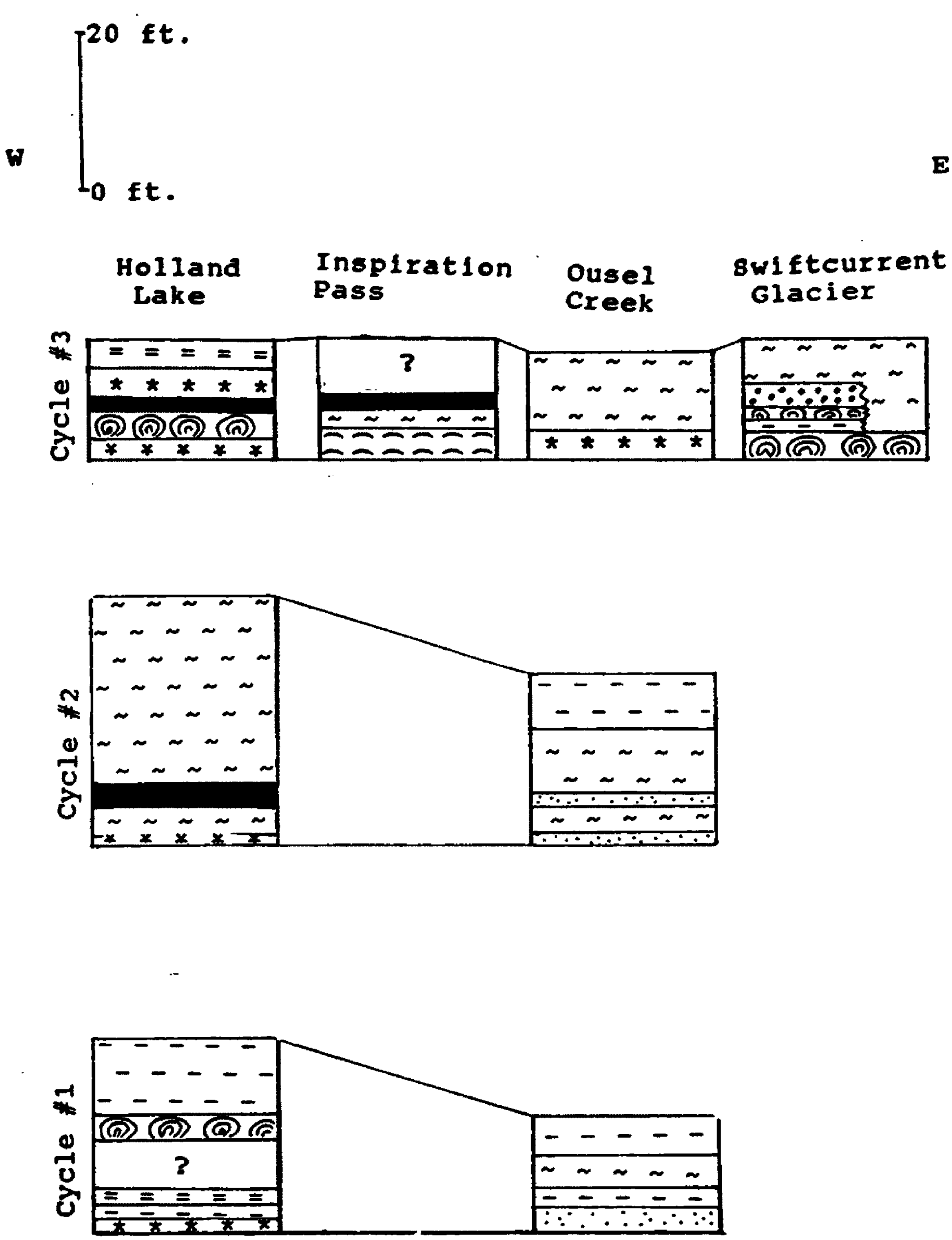


Figure 8. Siliciclastic fining-upward cycles below Baicalia-Conophyton cycles with proposed correlations. Breaks indicate cycle boundaries.

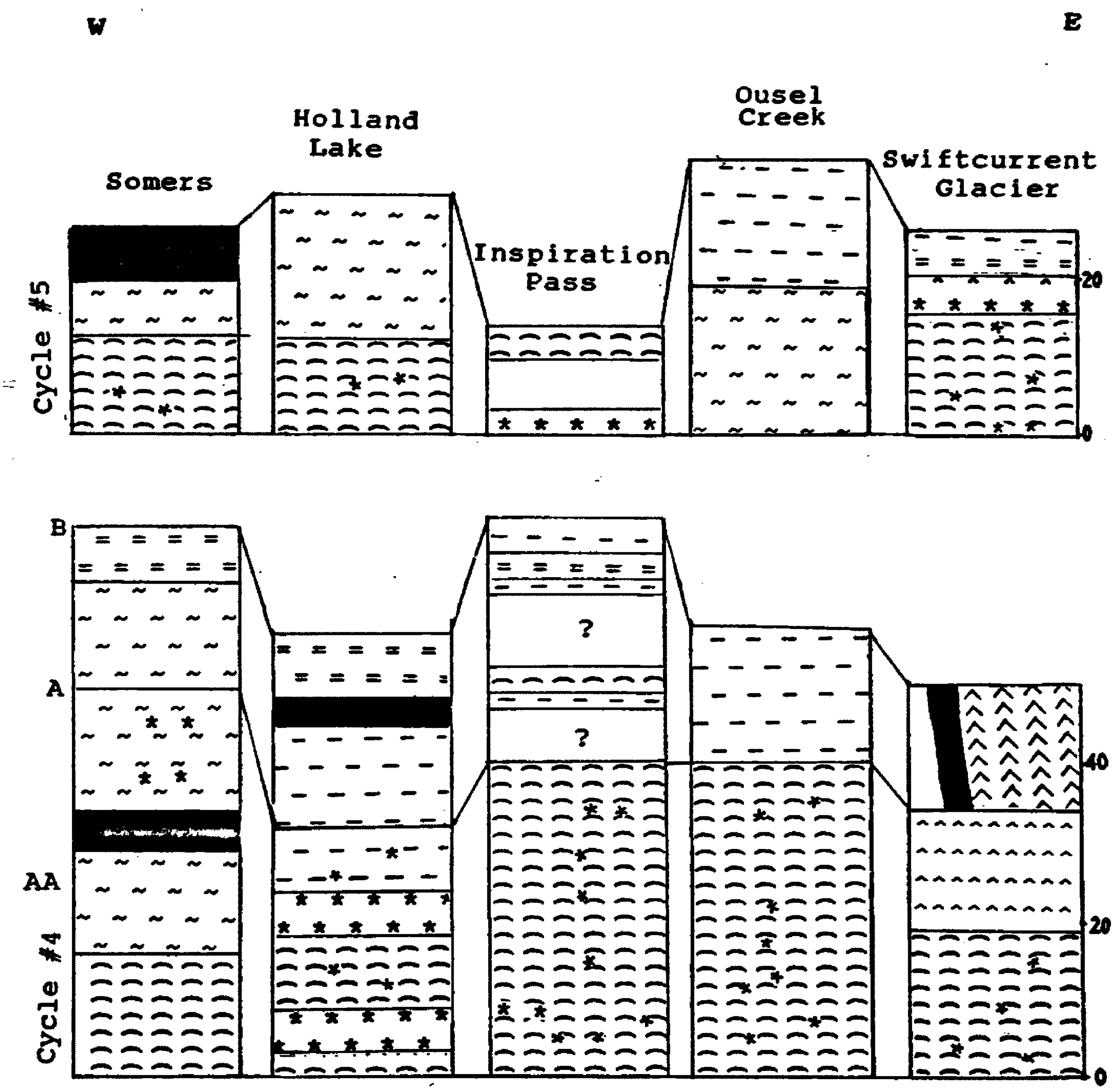


Figure 9. Baicalia-Conophyton fining-upward cycles with proposed correlations. Breaks indicate cycle boundaries.

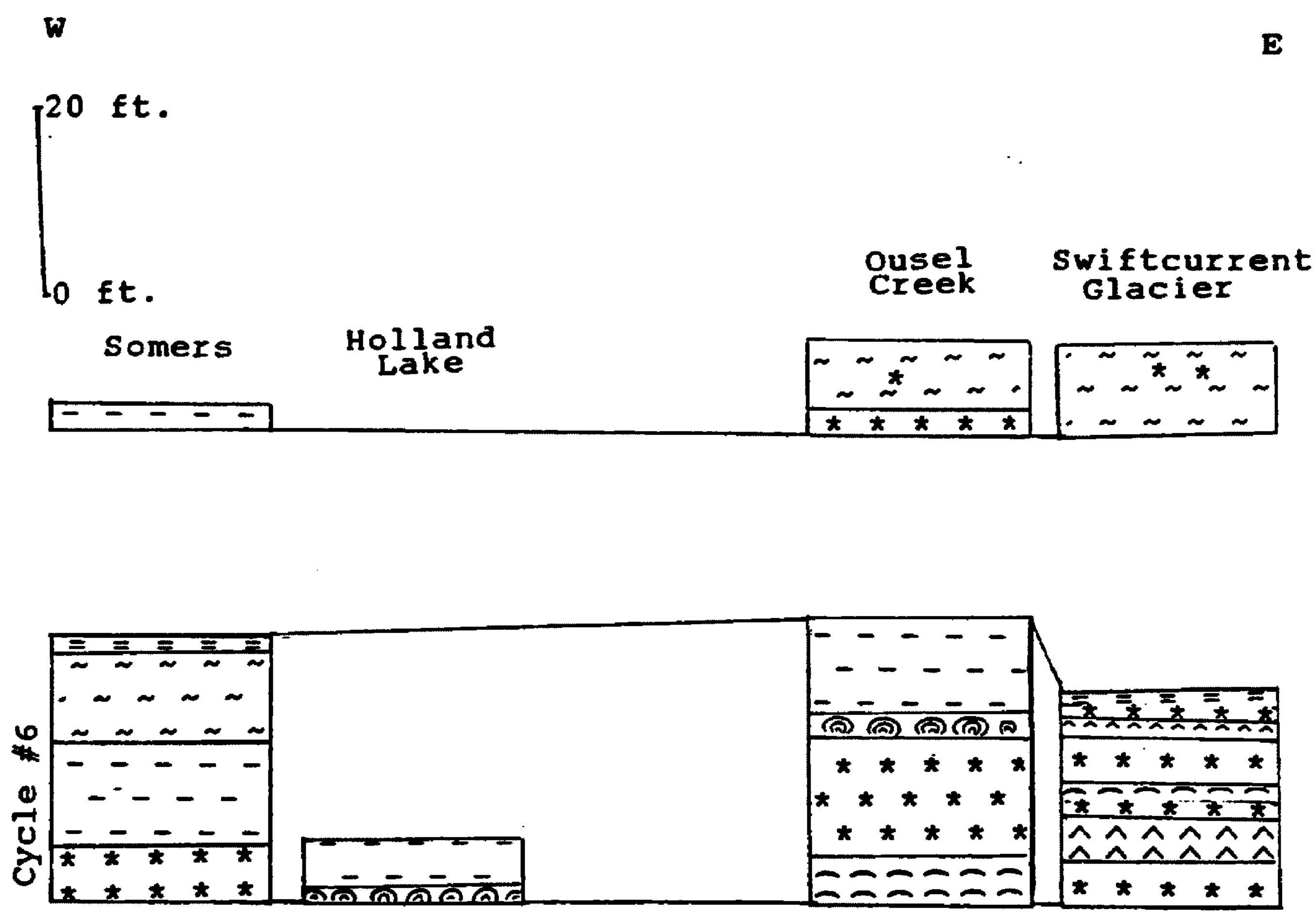


Figure 10. **Baicalia-Conophyton** fining-upward cycles and siliciclastic fining-upward cycle above **Baicalia-Conophyton** cycles. Breaks indicate cycle boundaries.

STROMATOLITES

As discussed in the introduction, analysis of the stromatolitic sedimentary cycles in the Helena Formation adds a biologic basis for reinterpreting existing environmental interpretations of sedimentary cycles in the Helena Formation. The general discussion of stromatolites which follows provides backround information for addressing specific problems in interpreting the sediments of the Helena Formation.

Stromatolites are organosedimentary structures generally produced by cyanophytes which trap and bind, or precipitate sediment through their growth and metabolic activity (Walter, 1976, based on Awramik and Margulis, 1974). Many interpretations of ancient stromatolites are based on information from modern stromatolites. Modern cyanophytes are prokaryotic, photosynthetic organisms with cells resembling those of bacteria (Sze, 1986). In modern ecologic systems cyanophytes photosynthesize both oxygenically and anoxygenically.

Modern stromatolites occur in a wide variety of environments including carbonate and noncarbonate, shallow and deep water, marine and nonmarine (Hoffman, 1976). Stromatolites require an aquatic environment suitable for the growth of the component microorganisms (Walter, 1976), a microbial rate of growth and accretion exceeding the rate of consumption or destruction (Walter,1976), and a rate of sedimentation sufficient to create preservable structure, but not so great as to prevent microbial growth (Walter, 1976).

Many researchers warn that modern stromatolites are not true analogues for fossil stromatolites (Serebryakov and Semikhatov, 1974; Banerjee, 1978; Serebryakov, 1976). Although modern environments differ substantially from Middle Proterozoic environments, many of the principles developed from the study of Recent stromatolites can apply to the analysis of fossil stromatolites (Gebelein, 1976). However, the application of Recent data to fossil stromatolites relies on a full understanding of the state of evolution of the hydrosphere, atmosphere and biosphere at the time the fossil stromatolites formed (Gebelein, 1976). By the Mid to Late Proterozoic the atmosphere was similar to the modern atmosphere (Walker, Klein, Schidlowski, Schopf, Stevenson, and Walter, 1983) although other aspects of the physical environment may have been quite different.

Stromatolite Classification

Although stromatolites are the products of organisms and therefore not true fossils (Logan, Rezak and Ginsburg, 1964) many researchers formally classify and name them according to the Linnean method, keeping with all the nomenclatural rules and codes (Preiss, 1976; Krylov, 1976). Krylov (1976) cautions that although Linnean binomial nomenclature provides a framework for naming stromatolites which all the international scientific community understands, only the strictest use of Linnean nomenclature will result in meaningful classification of stromatolites.

The Linnean method of classification can complicate stromatolite interpretation because morphologically different stromatolites from different parts of the same bioherm can be given different Linnean names (Krylov, 1976). Furthermore, diagnostic features of some stromatolites may change vertically within a single column and further complicate classification (Krylov, 1976).

Pointing out that some stromatolite morphologies may depend on the environment of deposition and may not be true biologic taxa, many researchers prefer to use Linnean-type binomial Latin names but distinguish those names from formal paleontological names with highlights instead of underlining them (Hoffman, 1969). Logan et. al. (1964) suggested replacing Linnean names with an informal classification based on overall form and using abbreviated names of several letters. For example, LLH refers to Laterally Linked Hemispheroids.

Researchers use at least twelve independent parallel stromatolite classification methods, each of which focuses on different aspects of stromatolite morphology (Krylov, 1976). For example, Rezak (1957) separated stromatolites into groups in which constituents share a single common feature, such as an axial zone (Rezak, 1957; Krylov, 1976).

Another method divides stromatolites into groups according to the shape of the laminations (Krylov, 1976). Yet another classification scheme divides stromatolites into types and subtypes in which the following five groups can be identified (Krylov, 1976): columnar, stratiform, nodular, columnar-stratiform, and columnar-nodular. These classification schemes are all equally valid but they cannot be united into a single general scheme (Krylov, 1976). Consequently the same stromatolite may be classified very differently depending on the scheme the researcher uses, and stromatolite supergroups and subtypes remain arbitrary although convenient subdivisions. In this paper I use Linnean-type names with highlights.

Stromatolite Morphogenesis

Researchers agree that both environmental factors (Logan, Hoffman, and Gebelein, 1974; Logan, Rezak, and Ginsburg, 1964) and biologic constituents or communities (Serebryakov, 1976; Fenton and Fenton, 1933) influence stromatolite morphology. Nevertheless, some researchers use stromatolites for biostratigraphic correlation emphasizing the biologic integrity and evolution of stromatolite forms; others use stromatolites for paleoecologic interpretation, emphasizing the response stromatolite forms have to their environments of deposition.

Environmental Control

Environmental controls on stromatolite morphogenesis may include currents and water flow patterns (Dill, Kendall, and Shinn, 1989; Dill, Shinn, Jones, Kelly and Steinen, 1986; Horodyski, 1989; Hoffman, 1967), water chemistry and clarity, nutrient content (Dill et al, 1989) and light intensity (Brock, 1976). However, determining exactly which environmental factors contribute to different morphologies is usually difficult (Semikhatov, 1976). For example, modern studies indicate that long axes of elongate stromatolites orient parallel to the direction of oncoming currents (Cecile and Campbell, 1978; Hoffman, 1967). Analysis of paleocurrents and fossil stromatolites reveals that this is also true of some fossil stromatolites (Hoffman, 1969; Horodyski, 1989). On the other hand, studies of modern stromatolites indicate that some stromatolites orient themselves toward the sun (Awramik and Vanyo, 1986) in a variety of environments. In this case stromatolite orientation reflects direction of light incidence instead of current direction.

Paleoenvironmental interpretations based on stromatolite morphology are more convincing if sedimentary structures around stromatolites change vertically as the stromatolite morphology changes vertically (Serebryakov, 1976; Semikhatov, 1976). For example, Cecile and Campbell (1978) demonstrate that Lower Proterozoic stromatolites from the

Kilihigok Basin in the Northwest Territories show consistent changes in gross morphology, lateral associations and elongation with vertical changes in environmental facies. Sheets of coalescing biscuit-shaped stromatolites with moderate elongation in the direction of oncoming currents in association with intraclast-rich sediments formed in a zone of relatively strong currents (Cecile and Campbell, 1978). This interpretation integrates analysis of sedimentary structures with an analysis of simple stromatolite morphology.

Environmental response may not apply to all Riphean stromatolites. For example: 1) in some places stromatolites change while laterally associated sedimentary structures do not appear to change (Serebryakov, 1976a, 1976b), 2) in other places the composition of stromatolite assemblages remains the same regardless of vertical changes in the composition and characteristics of the surrounding sediments (Serebryakov, 1976b). These phenomena show biological control of stromatolite morphology regardless of environment.

Fuxing (1989) suggests that environments of deposition determine whether stromatolite morphologies are environmentally or biologically controlled. For example, subtidal and lower subtidal environments are typically stable, quiet water environments which have little influence on stromatolite morphology. In these environments stromatolite forms are mostly controlled by their biologic composition. Higher energy, upper intertidal zone stromatolites may appear similar to subtidal stromatolites but their morphology may depend on high turbulence. Thus stromatolite morphologies are determined by environment, in some cases, and by biologic composition in others.

Biological Controls

Many researchers contend that biological factors, such as the genetic make-up of the community of microbes, control stromatolite morphology and, with limited success (Hoffman, 1976; Gebelein, 1976), use stromatolite groups as index fossils and stratigraphic marker beds (Bertrand-Sarfati and Trompette, 1976; Donaldson, 1976; Gowda et al, 1978; Hoffman, 1976). Biostratigraphic correlations using stromatolites are more convincing if they are used over a small area (Bertrand-Sarfati and Trompette, 1976), if the occurrence of stromatolites is cyclic (Semikhatov and Serebryakov, 1976), or if surrounding lithologies also correlate (Semikhatov and Serebryakov, 1976).

Soviet geologists use assemblages or groups of stromatolites to divide the late Precambrian into four chronostratigraphic intervals: Early, Middle and Late Riphean and Vendian (Semikhatov, 1976; Preiss, 1976). For example, the Russian middle Riphean contains groups such as **Anabaria** Komar, **Baicalia** Krylov, **Svetliella** Shaplova and many varieties of **Conophyton** and **Jacutophyton** (Preiss, 1976;

Semikhatov, 1976). As an assemblage of groups these stromatolites can be identified as Middle Riphean in age, although no single individual stromatolite group is exclusive to the Middle Riphean.

This Riphean biostratigraphic scheme is apparently valid throughout the Soviet Union (Semikhatov, 1976; Preiss, 1976). Where groups and forms have limited biostratigraphic ranges, tentative correlations can be made between Precambrian rocks on other continents and Precambrian rocks in the Soviet Union (Preiss, 1976).

Therefore, neither an environmental approach nor a biostratigraphical approach to stromatolite morphogenesis is entirely satisfactory (Serebryakov, 1976). Ecological controls on stromatolite morphology do not explain worldwide temporal succession of Riphean stromatolite morphologies. However, nor do researchers understand the mechanism of biologic control over stromatolite morphology. Therefore a firm grasp of both possible biologic controls and possible environmental controls is crucial in order to frame a context within which to interpret stromatolites (Dill et al, 1989; Semikhatov, 1976).

Stromatolites of this Study

This study focuses on stromatolite cycles of **Baicalia** and **Conophyton** in the Helena Formation of Glacier National Park and to the south and west. As reviewed by Cloud and Semikhatov (1969) the group of stromatolites attributable to

Baicalia typically have subcylindrical branching columns with a diameter up to 17 cm. Where columns split the two branched columns tend to widen upward from the base. Surfaces of columns are generally uneven to ragged. Laminations are gently convex to flattened.

Baicalia occurs in turbulent environments (Horodyski, 1989; Aitken, 1989). Bertrand-Sarfati and Trompette (1976) comment that **Baicalia** occurs with **Conophyton** at the edges of the Taoudenni Basin in Africa. In the Canadian Little Dal Group **Baicalia**-formed reefs are surrounded by reef debris. Aitken (1989) interprets **Baicalia** to have ranged from below storm wave base to the shallow subtidal zone.

Stromatolites in the **Conophyton** group are characterized by thin, conical laminae which bend up sharply into a distinct axial zone or are interrupted by an axial zone. Columns are generally subcylindrical with a diameter from 10 to 70 cm. Internal laminae commonly continue from one column to the next. The horizontal profile is subcircular to ovate, spheroidal or irregular.

The earliest reported occurrence of **Conophyton** is from the Early Proterozoic of the Soviet Union (Semikhatov, 1976). **Conophyton** occurred worldwide during the Riphean. North American locations include the Mescal Limestone, Apache Group (Preiss, 1976), and the Rae Group of Canada (Donaldson, 1976). Modern examples of **Conophyton** occur in hot springs in Yellowstone National Park (Walter, Bauld and Brock, 1976).

Depositional settings in which **Conophyton** formed are numerous and varied. This variation is illustrated in the following: 1) **Conophyton** occurs with fine-grained sediments that lack obvious stratification and clastic detrital material (Donaldson, 1976; Horodyski, 1983, 1989), 2) coarse-grained **Conophyton** debris occurs between **Conophyton** columns in the Rae Group of Canada (Donaldson, 1976), 3) **Conophyton** occurs at the edges of sedimentary basins (Bertrand-Sarfati and Trompette, 1976), 4) **Conophyton** beds extend across basins in the Soviet Union (Serebryakov, 1976), and 5) **Conophyton** occurs in hot springs in modern environments (Walter et al, 1976).

Interpretations arising from the above observations include: 1) **Conophyton** was subaqueous (Banerjee and Basu, 1978), 2) **Conophyton** grew on an intertidal flat (Banerjee and Basu, 1978), 3) **Conophyton** columns were bafflers (Donaldson, 1976), 4) **Conophyton** were quiet water, back reef stromatolites (Horodyski, 1989), 5) some **Conophyton** colonies lived in a subtidal environment with low turbulence (Donaldson, 1976), and 6) other **Conophyton** colonies lived in turbulent conditions with strong currents (Donaldson, 1976).

Helena Formation Stromatolites

Stromatolites are abundant in the Helena Formation, especially in Glacier National Park (Walcott, 1914; Fenton and Fenton, 1931, 1933; Horodyski, 1983, 1989), although the number of typical Middle Riphean stromatolite groups in the Helena is unusually sparse (Eby, 1977). Silicified dome-shaped stromatolites in the lower portion of the formation occur in thin, but laterally extensive chert layers (Horodyski, 1983). Mound and dome-shaped calcitic and calcitic-dolomitic stromatolites occur in the middle and upper portions of the Helena Formation (Horodyski, 1989, 1983).

The most striking stromatolites occur in the upper part of the Helena Formation in Glacier National Park and extend to the south and west, forming a very prominent zone of cyclically alternating layers of **Baicalia** and **Conophyton** (Rezak, 1957; Horodyski, 1989, 1985, 1983, 1977), called the **Conophyton** Zone by Rezak (1957). Horodyski (1983) more accurately called this unit the **Baicalia-Conophyton** cycles because both stromatolite groups are prominent in the zone and because **Baicalia** persists significantly farther south and west in the basin than does **Conophyton**. The **Baicalia-Conophyton** cycles in Glacier National Park form a 24-32 meter thick unit approximately 200 meters below the top of the Helena Formation (Horodyski, 1989).

Cycles of **Conophyton** and **Baicalia** like those in the Helena are typical of Middle Riphean bioherms (Krylov,1976; Serebryakov, 1976). Other occurrences of this kind of cycle include bioherms in Canada, Africa, and Russia. Serebryakov

(1976) summarized a general pattern common to all reported stromatolite cycles which also applies to the Helena Formation stromatolites: each cyclic bioherm sequence begins at the base with **Baicalia** beds passing up to **Jacutophyton**, a branched conical stromatolite, and then **Conophyton**. **Baicalia** generally caps the complete cycles. Scour surfaces typically separate the cycles.

In some places **Baicalia-Conophyton** cycles can be used for stratigraphic correlation over tens of kilometers in spite of minor changes in morphology (Serebryakov, 1976; Bertrand-Sarfati, 1972).

Previous Interpretations of Helena Formation Stromatolites

Horodyski (1989, 1985, 1983, 1977, 1976) asserts that in the Belt basin environmental conditions controlled stromatolite morphologies, including the alternation of **Baicalia** and **Conophyton** morphologies. According to Horodyski (1977), four physical factors influenced the column and branching pattern of stromatolites in the Belt basin. Horodyski (1977) infers that: 1) accumulation of detritus on stromatolite growth surfaces inhibited column formation by smoothing over surfaces, 2) close spacing of stromatolite columns inhibited divergence in columns, 3) a planar growth profile of stromatolite bioherms discouraged column divergence, and 4) variable environmental conditions encouraged variable column diameters.

Noting that **Baicalia** bioherms and surrounding debris beds probably formed in a more turbulent environment than **Conophyton** and surrounding micrite mud, and noting that in places in the **Baicalia-Conophyton** cycles a possible erosion surface separates **Baicalia** from **Conophyton**, Horodyski (1989) suggested that the columnar and branching **Baicalia** formed in a high turbulence reef front environment and that elongate and inclined **Conophyton** formed in low turbulence conditions, perhaps a back reef environment. According to Horodyski (1989) the upward transition from **Baicalia** to **Conophyton** to inclined **Conophyton** may represent a shallowing upward sequence that prograded to the west accompanied by subsidence or eustatic sea level rise (Horodyski, 1983).

Microstructural similarities between some samples of **Conophyton** and **Baicalia** suggest that similar microbial communities responding to varying environmental conditions produced the different morphologies (Horodyski, 1989, 1983). The conical morphology of modern **Conophyton** in Yellowstone Park springs is primarily due to the presence of actively motile elements in the microbial community (Walter, et al, 1976). The change in the morphology of Riphean stromatolites may reflect the addition of these actively motile elements to the microbial community, a change in the activity of the microbial community, or changing environmental conditions (Horodyski, 1983). Evidence from sediment types, discussed below, supports the interpretation that changing environmental conditions contributed to changes in stromatolite morphology.

SEDIMENT TYPE DESCRIPTIONS

In order to sedimentologically analyze Belt lithologies Winston (1986; 1989b) proposed a sediment type classification system of Belt rocks based on sedimentary structures, grain size and inferred original mineralogic composition. This system provides for easy identification and correlation of Belt lithofacies.

The **Baicalia-Conophyton** cycles contain several sediment types described by Winston (1986; 1989b) including pinch-and-swell couple and pinch-and-swell couplet, even couple and even couplet, microlamina, carbonate mud, and tabular and hummocky silt sediment types. Four new sediment types in the **Baicalia-Conophyton** cycles are described here and include the debris sediment type, **Baicalia** sediment type, **Conophyton** sediment type, and domed stromatolite sediment type (Figure 11).

Pinch-and-Swell Couple and Couplet

Description: As developed in the **Baicalia-Conophyton** cycles, the pinch-and-swell couple sediment type consists of 3-10 cm thick beds with lower layers of tan or grey-weathering wavy silt and clay that fine up to dark, locally clay rich, calcitic microsparite forming a graded couple (Winston, 1986). Pinch-and-swell couplets are thinner variations: 0.3 to 3 cm thick graded beds with silt and clay bases which fine up to dark, locally clay-rich

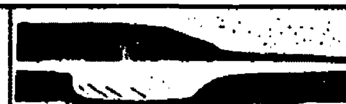
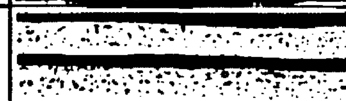
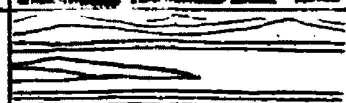
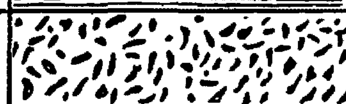
Sediment type		Sediment Type Descriptions
Pinch-and-swell couple and couplet		Lower tan or grey-weathering wavy silt and clay fining up to dark calcitic, locally clay rich, microsparite.
Even couple and couplet		Even tabular layers of tan or grey-weathering silt fining up to uncracked clay-rick carbonate mud drapes.
Microlamina		Thin alternating laminae of three varieties: siliciclastic, carbonaceous, and calcareous.
Carbonate Mud		Thick beds of massive, uniform, fine-grained micrite, now inverted to microspar and dolomicrospar.
Tabular and Hummocky Silt		Tabular beds of flat-laminated and low-angle hummocky and climbing-ripple crosslaminated silt and clay.
Debris		Randomly oriented silt, clay, molar-tooth and stromatolite intraclasts, locally interbedded with micrite.
Baicalia		Massive bioherms, 1-2 m across with branching stromatolites. Laminae are fine to medium crystalline microsparite, clotty to extremely fine microsparite.
Conophyton		Massive bioherms 3-20 meters across with cone-shaped stromatolites. In thin section similar to Baicalia.
Domed Stromatolite		Calcitic stromatolites with gently domed, flat or pseudocolumnar laminae.

Figure 11. Sediment types developed in the Baicalia-Conophyton cycles (after Winston, 1989).

carbonate mud, now inverted to microsparite. Because most outcrops in my measured sections include interlayered pinch-and-swell couples and couplets, this study treats them as a single sediment type.

Some the silty layers in the pinch-and-swell couples contain flat laminae or low angle hummocky crosslaminae; others appear massive. The lower layers of some couples incorporate stromatolite and intraclast debris. The bases of most silty layers bow down into load casts (Winston, 1989b). Other bases appear to be scoured.

Some microsparite couple tops consist of alternating fine and extremely fine microsparite laminae. Other tops consist of uniform microsparite. Capping many microspar layers are carbonaceous and hematitic organic layers containing clay and some scattered silt grains.

On the whole, pinch-and-swell couples in the **Baicalia-Conophyton** cycles are finer grained than those in the main body of the Wallace Formation farther west (Winston, 1989b).

Although molar-tooth ribbons are not very common in this sediment type (Winston, 1989b), many beds in the **Baicalia-Conophyton** cycles contain vertical and horizontal molar-tooth ribbons (O'Connor, 1972). These may have formed as gas expansion cracks filled with fine-grained and blocky calcite (Furniss, 1990). Decomposition of organic material in the pinch-and-swell interlayers could have produced methane and carbon dioxide gases that formed bubbles, cracked the sediments, and induced calcite precipitation in the cracks.

Together with debris beds surrounding **Baicalia** bioherms, pinch-and-swell couples typically comprise the coarser lower parts of thick, fining upward sequences. Beds of the pinch-and-swell couple sediment type generally pass up into finer-grained sediment types including the even couple and couplet, microlamina, and micrite mud sediment types. At Somers the pinch-and-swell sediment type passes vertically into **Baicalia** bioherms with a sharp and undulose boundary which may be a 30 to 90 cm deep scoured channel bottom.

Pinch-and-swell couples pass laterally on the outcrop scale to even couples and couplets at Inspiration Pass (Fig. 7) and to bioherms of **Baicalia** at Somers and at outcrops below the loop in Glacier Park. At Somers the pinch-and-swell sediment type also overlaps **Baicalia** bioherms.

Regional correlations of sections indicate that the pinch-and-swell couple sediment type is more developed in the western portion of the basin and passes eastward into **Baicalia** bioherms and debris beds. Winston (personal communication) reports thick sequences of pinch-and-swell couples passing up into the lower **Baicalia** beds at the south end of the Mission Mountains. The westward increase in more siliciclastic pinch-and-swell couples represents Wallace lithologies interfingering with the more calcite rich beds of the Helena Formation (Winston, personal communication; Grotzinger, 1981; O'Connor, 1967).

Interpretation: Graded layers reflect episodic transport of silt, clay and carbonate mud in standing water. Grotzinger (1981) and Winston (1989) proposed that the silt and clay was introduced into the basin by episodic floods from the western side of the basin. Hummocky stratification indicates that some pinch-and-swell couples probably record sediment reworking by storms (Johnson, 1990; Winston, 1989b). The deep load casts probably reflect rapid accumulation of silt on water saturated mud (Winston, 1989b). The carbonaceous seams in the upper fine calcitic capping layers of the couples may reflect the growth of organic films on the muddy surfaces, separating episodes of sediment influx. Organic films may have produced irregular undulose surfaces on which the succeeding layers of silt were deposited.

Even Couple and Couplet

Description: As developed in the **Baicalia-Conophyton** cycles, the even couple sediment type consists of 3-10 cm thick even tabular layers of tan or grey-weathering silt with occasional climbing ripple crosslaminae capped with uncracked clay-rich carbonate mud drapes. Even couplets in the study area are Winston's (1989b) uncracked even couplet variety, generally .3 to 3 cm thick. Because most examples in measured sections included occasional interlayered couples and couplets this study treats them as a single sediment type.

The lower flat silt laminae have sharp flat bases and consist of microspar, clay and quartz silt which fine up to microspar and clay with only scattered quartz silt. Clay comprises up to 20% of the sediment. Many even couples and couplets contain horizontal and vertical molar-tooth ribbons.

On the outcrop scale even couples and couplets pass vertically to microlamina and occasionally to debris or the pinch-and-swell couple sediment type. Regionally, units of even couples and couplets pass eastward to **Conophyton**, and westward to the pinch-and-swell couple and couplet and microlamina, and in some levels to the carbonate mud sediment type (Figures 8, 9, 10).

Interpretation: The flat tabular beds of even couples and couplets represent episodic influxes of suspended silt, clay and carbonate mud and subsequent suspension settle out. Ripple crosslaminae indicate gentle current transport and deposition.

Microlamina

Description: As manifested in the **Baicalia-Conophyton** cycles, the microlamina sediment type consists of .03 mm or thinner alternating laminae of three varieties: siliciclastic, carbonaceous, and calcareous. The siliciclastic variety contains sharply bounded silt and clay interlaminations and weathers black. The carbonaceous variety contains silty carbonaceous and carbonate mud interlaminations and weathers black. And the calcareous variety contains admixture of dolomitic and calcitic microspar (Winston, 1989b; Grotzinger, 1981; O'Connor 1967) in silty and carbonaceous interlaminae. Occasional laminae truncate one another. In one thin section of the carbonaceous variety, silt had filled small pits where carbonaceous clasts had been ripped out, indicating traction transport (Thin Section SG 3). Occasional intervals contain molar-tooth blobs.

Where this sediment type occurs in the **Baicalia-Conophyton** cycles it tends to overlie the pinch-and-swell couple and couplet and even couple and couplet sediment types or debris beds and tends to cap fining-upward sequences (Fig.8,9,10). Undulatory surfaces at the tops of fining-upward sequences typically separate microlaminae from overlying **Baicalia** bioherms. In some instances laminae are bowed down beneath **Baicalia** bioherms suggesting that the bioherm weight loaded the microlaminae below. Elsewhere microlamina beds interstratify with couples and couplets. In other cases laminae are truncated by the undulatory surfaces suggesting that the surfaces were scoured and eroded, perhaps by channels.

The microlamina sediment type is most fully developed in the Holland Lake and Somers Sections. Laterally the microlamina sediment type passes to the even couple and couplet sediment type, the **Conophyton** sediment type, the carbonate mud sediment type, and occasionally to the pinch-and-swell couple sediment type (Figures 8, 9) to the east and the north.

Interpretation: The microlamina sediment type reflects alternate silt and clay settleout in relatively quiet water with slow currents and with relatively little siliciclastic input. Silt deposition was probably episodic in the carbonaceous and calcareous varieties with enough time between silt influxes events to allow organic layers to form on the sediment surfaces. Influxes of silt were probably accompanied by currents strong enough to rip up organic clasts; however, turbulence was too weak to transport coarse debris.

Carbonate Mud

Description: As developed in the **Baicalia-Conophyton** cycles the carbonate mud sediment type consists of thick beds of massive, uniform, apparently non-layered, fine-grained micrite, now inverted to microspar and dolomicrospar. Numerous vertical and horizontal molar-tooth ribbons and blobs typically cut the carbonate mud sediment type.

Although this sediment type tends to form the upper parts of siliciclastic-to-dolomitic cycles in the Helena Formation (O'Connor, 1967; Winston, 1989b), carbonate mud is not common in the **Baicalia-Conophyton** cycles. Carbonate mud overlies pinch-and-swell couples, interstratifies with the even couple and couplet sediment type or fills the space between **Conophyton** bioherms and columns. Where associated with **Conophyton**, the carbonate mud sediment type consisted of dolomitic microspar.

Regionally the carbonate mud sediment type passes laterally to even couples and couplets and pinch-and-swell couples and couplets.

Interpretation: The carbonate mud sediment type reflects periods of inorganic or organically induced carbonate precipitation with very little siliciclastic influx (Winston, 1989b). O'Connor (1967) interpreted this sediment type as a quiet water deposit formed near the eastern margin of the Belt basin.

Tabular and Hummocky Silt

Description: As developed in the **Baicalia-Conophyton** cycles, the tabular and hummocky silt sediment type contains tabular beds of flat-laminated and low-angle hummocky and climbing-ripple crosslaminated silt and clay with up to 15 % dolomite rhombs. Silt sized siliciclastic grains include quartz, feldspar, and muscovite. Clay comprises up to 20% of the sediment.

This dolomitic sediment type typically interlayers with pinch-and-swell couples and even couples and couplets below the **Baicalia-Conophyton** cycles. Some fining-upward cycles below the stromatolite cycles begin with this sediment type.

Interpretation: Winston (1989b) interprets this sediment type as silt concentrated by storms that reworked pinch-and-swell, microlaminae and even and lenticular couplet sediment types.

Debris

Description: The debris sediment type consists of 5-20 cm thick beds of randomly oriented silt, clay, molar-tooth intraclasts, and, near **Baicalia** bioherms, stromatolite intraclasts in a fine- to coarse-crystalline sparry matrix. This sediment type can be separated into two general varieties: a thinner-bedded (5-8 cm) variety and a thicker more massive-bedded (9-20 cm) variety. The thin bedded variety typically comprises the coarser lower portions of some pinch-and-swell couples, and alternates with silt-lenses, carbonaceous mud and microspar, mostly in fining-upward sequences from debris to microspar (5-10 cm). In one thin section a micritic stromatolite fragment is only partially ripped off a stromatolite demonstrating the origin on the micritic fragments. Vertical molar-tooth ribbons cut through carbonaceous carbonate mud interlayered with thin bedded debris beds. The massive-bedded variety of the debris sediment type consists of 5-25 cm thick beds of intraclast debris in a microspar matrix.

On the outcrop scale the massive variety of the debris sediment type typically surrounds and overlies **Baicalia** bioherms and fills the space between **Baicalia** columns. Vertically the debris sediment type passes to pinch-and-swell couples and even couples and couplets. Regionally the debris sediment type passes laterally to pinch-and-swell couples, **Baicalia**, even couples and couplets, domed stromatolites and even **Conophyton** (Fig. 8,9,10).

Interpretation: Debris deposits indicate strong turbulence with much bedload transport. Currents were strong enough to rip up clasts of silt, clay and stromatolites and to concentrate those clasts in beds.

Both thin- and massive-bedded varieties suggest that turbulence levels and deposition were episodic, and perhaps record storms. Sudden decreases in turbulence deposited the debris quickly in random orientations. Those with organic films reflect cessation of sediment transport and deposition between debris-depositing events.

Baicalia Sediment Type

Description: This sediment type consists of beds up to 4 meters thick and bioherms 1-2 meters across and up to 4 meters high of branched stromatolites attributable to the group **Baicalia**. The stromatolites have subcylindrical branching columns up to 25 cm across with gently convex laminations. The stromatolites typically form bioherms 1-2 meters across (Horodyski, 1989) and up to 4 meters high.

In thin section, laminae of **Baicalia** consist of alternating layers of fine to medium crystalline microsparite and extremely fine irregular microsparite up to 1 mm thick. Tops and bottoms of laminae are undulatory and indistinct. Some laminae consist of very fine, clotty-looking microspar with up to 15% clay. Other laminae contain quartz silt grains which collected on what was probably the lee side of bumps on stromatolite surfaces. Total siliciclastic content locally reaches 20%. Occasional layers contain hematite microlites and dolomite rhombs.

Sediments between individual **Baicalia** columns within bioherms include carbonate mud and stromatolite debris. The massive debris the pinch-and-swell couple sediment types typically fill spaces between bioherms. **Baicalia** are calcitic and lack molar-tooth structures.

Baicalia, together with surrounding debris beds, typically comprise the coarsest sediment type in fining-upward cycles. The **Baicalia** sediment type passes up into **Conophyton**, even couples and couplets, pinch-and-swell, and debris beds. **Baicalia** passes west to pinch-and-swell couples with debris, even couples and couplets with debris, debris beds, and to the east to **Conophyton** and domed stromatolites.

Interpretation: The abundance of debris between **Baicalia** heads and between **Baicalia** bioherms suggests that **Baicalia** formed under high turbulence conditions (Horodyski, 1989). Horodyski (1989) suggests a reef front environment could account for **Baicalia** shapes and associated debris deposits. Siliciclastic layers suggest that the bioherms were occasionally dusted by influxes of silt probably travelling in suspension. Debris probably fell between columns and between the bioherms and eventually filled the spaces in. Horodyski (1989) suggests these stromatolites (and **Conophyton**) grew by in situ carbonate precipitation. However, siliciclastic layers suggest that accumulation of detrital material may be more important than previously realized, especially south and west in the basin. Influxes of siliciclastic sediments attaching to stromatolite surfaces may have forced the microbial communities to produce additional layers of organic growth.

Conophyton Sediment Type

Description: The **Conophyton** sediment type consists of bioherms 3-20 meters across and up to 3 or 4 meters thick with conically laminated stromatolites assignable to the group **Conophyton** (Horodyski, 1989). Unbranching **Conophyton** columns are 5-60 cm across and have a distinct axial zone (Cloud and Semikhatov, 1969). Laminae are typically irregular crystalline microsparite that alternate with other laminae of finer but also irregular crystalline microsparite. Microscopically, micritic **Conophyton** laminae are very similar to micritic **Baicalia** laminae but principally differ in the larger scale lamination form (Horodyski, 1989). In thin section, some laminae are clotty in appearance; others contain siliciclastic material in slightly coarser microspar which fines up to extremely finely crystalline microspar. Carbonate mud and even couplets separate **Conophyton** bioherms in 1-2 m wide (Horodyski, 1989), perhaps quiet water channels.

Conophyton columns are typically calcitic. Sediment between **Conophyton** columns and bioherms consists of dolomitic microsparite assignable to the carbonate mud sediment type.

Conophyton bioherms comprise the upper portion of fining upward cycles (Figure 9). **Conophyton** columns pass westward to even couples and couplets at the tops of cycles, and are locally overlain by **Baicalia** (Horodyski, 1983) and debris beds at the bases of succeeding cycles. **Conophyton** bioherms are limited to the northeastern measured section (Swiftcurrent Glacier, Figure 9) and their eastern extent is unknown.

Interpretation: Based on carbonate mud and even couple and couplet sediment types lateral to and between the **Conophyton** bioherms, **Conophyton** formed under low turbulence conditions. In contrast to **Baicalia**, **Conophyton** is not interstratified with debris beds. Instead it is surrounded by carbonate mud, and therefore, as Horodyski (1989) suggests, was adapted to less turbulent conditions. However, siliciclastic silt layers indicate that **Conophyton** received similar amounts of siliciclastic input as did **Baicalia**.

Domed Stromatolite Sediment Type

Description: The domed stromatolite sediment type consists of beds .5 to 1.5 meters thick containing calcitic domed stromatolites. Laminae are gently domed and locally flat on top. Some domed stromatolites are pseudocolumnar. Domed stromatolite beds locally contain debris deposits between the domes. The domed stromatolite sediment type passes laterally to debris deposits, **Baicalia**, pinch-and-swell couples and couples and couplets.

In some outcrops molar-tooth ribbons radiate through domed stromatolites into the layers above. In other outcrops molar-tooth ribbons orient randomly around domed stromatolites.

Domed stromatolites locally comprise the bases of fining-upward cycles. They pass vertically to the debris sediment type, even couples and couplets, pinch-and-swell couples, and carbonate mud. They are limited in the **Baicalia-Conophyton** cycles to the zone of mixed stromatolites and debris near the bottoms of the cycles.

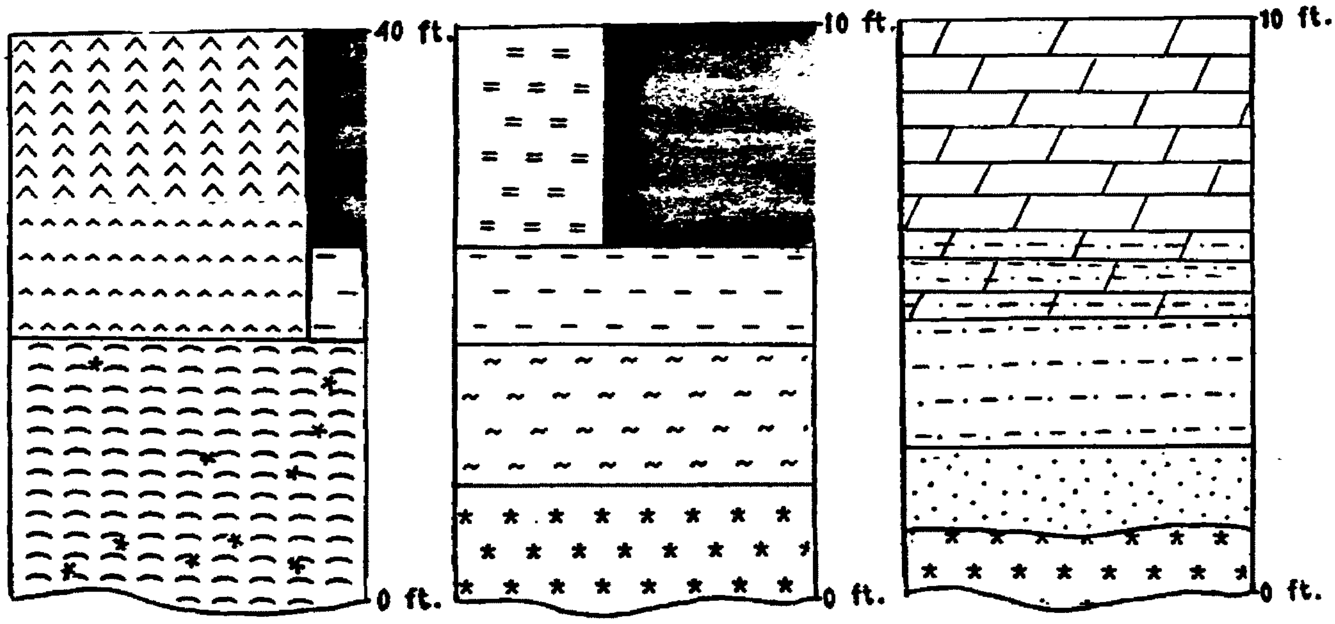
Interpretation: Domed stromatolites in the middle Helena formed by both in situ carbonate precipitation and sediment stabilization (Horodyski, 1989). They may have formed in response to more siliciclastic accumulation than did **Baicalia** and **Conophyton** (Horodyski, 1977). Alternatively, domed stromatolites may reflect a decrease in growth rate relative to siliciclastic input, increasing the relative siliciclastic composition.

STROMATOLITIC SEDIMENTARY CYCLES

At least three different types of cycles (Fig.12) occur in the Helena Formation. They are 1) fining- and thinning-upward siliciclastic cycles (Johnson, unpublished data; Figures 8, 9, 10), 2) siliciclastic-to-dolomitic cycles (O'Connor, 1967; Eby, 1977) (Figure 12), and 3) **Baicalia-Conophyton** cycles (Horodyski, 1983, 1985, 1989; Figure 12). **Baicalia-Conophyton** cycles and siliciclastic-to-dolomitic cycles fine upward and may merely be variations of siliciclastic fining-upward cycles with the addition of stromatolites in one case and dolomite in the other.

If this is so, the **Baicalia**, debris, and pinch-and-swell sediment types occupy the position of the siliciclastic portion of siliciclastic-to-dolomitic cycles (Figure 12). The even couple and couplet, microlamina and carbonate mud sediment types occupy the dolomitic portion of siliciclastic-to-dolomitic cycles (Figure 12). Most siliciclastic sedimentary cycles range from 1 to 3 meters thick; stromatolite cycles are typically much thicker, on the order of 10 meters or more.

In order to interpret the morphologic changes of the fining-upward **Baicalia-Conophyton** cycles it is instructive to compare them with siliciclastic fining-upward sequences. Stromatolite cycles appear to contribute additional information with which to reinterpret siliciclastic cycles.



Baicalia-Conophyton Cycles

Siliciclastic Fining Upward Cycle

Siliciclastic-to-Dolomite Cycle

Notice variation in vertical scale.

Figure 12

Fining-Upward Siliciclastic Cycles

Three fining-upward siliciclastic cycles are developed in the rocks immediately below the **Baicalia-Conophyton** cycles at Holland Lake and Ousel Creek (Figure 8, Cycles #1, #2, #3). One siliciclastic cycle is developed in the sections from Inspiration Pass and Swiftcurrent Glacier (Figure 8, Cycle #3). Above the **Baicalia-Conophyton** cycles one siliciclastic fining-upward cycle is developed in the Swiftcurrent Glacier, Somers and Ousel Creek sections (Figure 10, Cycle #6).

Fining-upward sedimentary cycles generally have scoured surfaces at their bases which are then overlain by debris, domed stromatolites or tabular and hummocky silt sediment types (Figures 8, 10, 12). The pinch-and-swell couple sediment type or the even couple and couplet sediment type overlies the basal layer. Tops of the cycles are either silt to black argillite pinch-and-swell couples, even couple and couplet or microlamina sediment types. Erosion surfaces sharply separate the top of each cycle from the basal debris bed of the overlying cycle.

Interpretation: The basal debris and silt deposits represent sediments which were reworked by an increase in turbulence, perhaps a drop in wave base or exposure or storms. Strong currents and waves probably ripped up clasts or winnowed out fine material from couples and couplets or pinch-and-swell couples and concentrated coarse debris

(Winston, 1989). During intervals of less turbulence, perhaps induced by a rise in base level, episodic storms deposited pinch-and-swell couples, while locally even couples and couplets and microlaminae were deposited in calmer areas with slow deposition, perhaps in areas closer to the eastern margin of the basin, and in shallower, quieter water.

Siliciclastic-to-Dolomitic Cycles

Siliciclastic-to-dolomitic cycles are not developed within the measured sections. The **Baicalia-Conophyton** cycles are calcitic in the lower and upper parts, and the fining-upward siliciclastic cycles do not contain dolomite. However, O'Connor (1967) and Eby (1977) described siliciclastic-to-dolomitic cycles (Fig. 12) from the Mission and Swan Ranges, and further south and east. Although partly based on cycles of molar-tooth structures which are now known to be diagenetic, (Furniss, 1990) the siliciclastic component of O'Connor's cycles fine upward.

Siliciclastic-to-dolomitic cycles begin with an undulose eroded surface overlain by a basal debris bed, sand, and silt. The cycles fine up to carbonate mud through the pinch-and-swell couple sediment type, the even couplet sediment type to the microlamina sediment type. The upper dolomite portion of the cycle begins sharply in the silt and continues up through dolomite mud. The siliciclastic-to-dolomitic cycles are very similar lithologically to the siliciclastic fining-upward cycles described above, but include a dolomitic overprint in the upper part (Winston, personal communication). Johnson (unpublished data) believes that Eby's siliciclastic-to-dolomitic cycles coincide with siliciclastic fining-upward cycles he identified in measured sections from the same locations.

Interpretation: O'Connor proposed that strong waves and currents scoured the basal surfaces of the cycles and concentrated the ripped up clasts in the basal debris beds. Then crossbedded sand and silt were episodically deposited by strong currents and waves over quiet water deposits. O'Connor interpreted the upper dolomite-rich silty sequence to reflect the shift of a shallower water carbonate environment over the siliciclastic portion during marine regression with localized increases in turbulence. Finally intertidal to supratidal dolomite was deposited at the tops of the cycles.

O'Connor interpreted siliciclastic-to-dolomitic cycles as transgressive to regressive marine sequences, although he could not demonstrate the migration of facies within his study area. Eby (1977) interpreted the cycles as the record of marine transgression followed by shoaling upward, and westward regressive migration of facies.

According to O'Connor's and Eby's interpretations the basal terrigenous component of each cycle represents a marine transgression, the upper carbonate-rich silty and then dolomitic portion represents a marine regression. However, in a basin with very low relief like the Belt basin slight changes in base level would affect huge areas at the same time and in some places produce seemingly "layer-cake" stratigraphy (O'Connor, 1967)

Winston (1989) interpreted the siliciclastic half-cycles to record episodic expansions of an enclosed Belt lake across subjacent exposed surfaces in response to humid climatic conditions. In this interpretation the water was undersaturated with respect to calcium carbonate. Winston (1989) interpreted the dolomitic half-cycles to record shrinking of the Belt lake during arid periods and consequent supersaturation with respect to calcium carbonate inducing carbonate precipitation. As the lake shrank and shallowed, turbulence and sediment influx diminished, producing the thinning- and fining-upward cycles (Winston, 1989).

Baicalia-Conophyton Cycles

Horodyski (1989) identified six units within the **Baicalia-Conophyton** cycles (Figure 13): the lower **Baicalia** unit, the lower small-diameter **Conophyton** unit, the lower large-diameter **Conophyton** unit, the middle **Baicalia** unit, the middle sedimentary unit, and the upper mixed stromatolite unit. The lowest stromatolite cycle begins with the lower **Baicalia** unit and continues through the lower large-diameter **Conophyton** unit (Horodyski, 1989). This

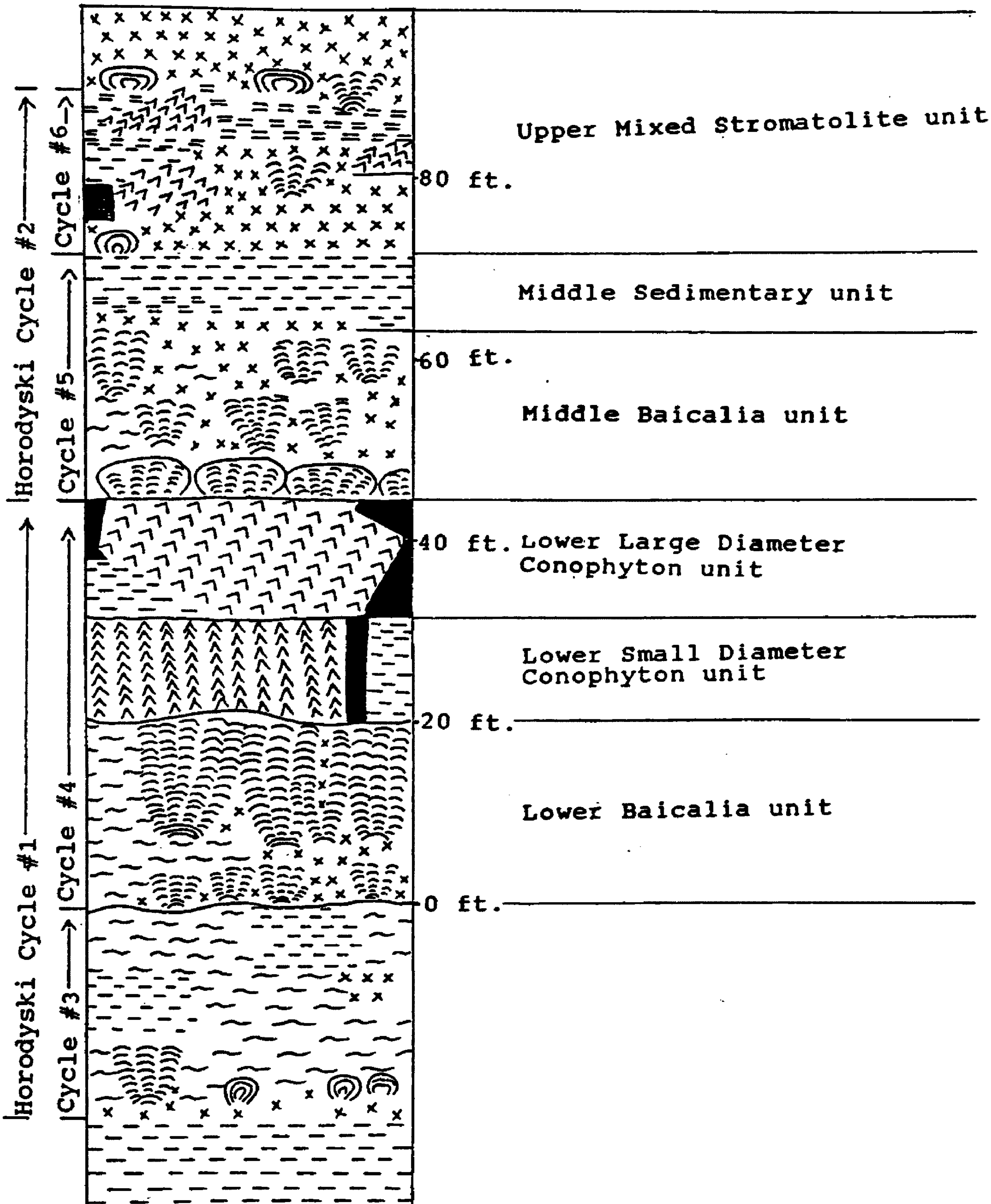


Figure 13. **Baicalia-Conophyton** cycles combined with seidment types described in this study (after Horodyski, 1989).

stromatolite sequence coincides with fining-upward sedimentary cycle #4 (Figure 9).

Horodyski (1989) identified a second stromatolite cycle in the southeastern part of Glacier National Park. However, I have identified two fining-upward cycles (#5 and #6) within the unit Horodyski included in his upper **Baicalia-Conophyton** cycle (Figure 13).

The units comprising the **Baicalia-Conophyton** cycles are here described combining data from Horodyski (1989) with sediment type data from my measured sections.

CYCLE #4

Lower **Baicalia** unit

The base of cycle #4 (Figure 13) is marked by a sharp eroded undulatory surface overlain by the lower **Baicalia** unit which contains stromatolites referrable to the group **Baicalia** (**Baicalia** sediment type). In the upper part of the lower **Baicalia** unit the stromatolites are very closely spaced and display parallel branching. Eroded stromatolite debris of the debris sediment type fills the spaces between bioherms and between columns, but is less evident near the top of the unit.

Vertically, the **Baicalia** bioherms pass to the lower small-diameter **Conophyton** unit in Glacier Park, to even couples and couplets at Ousel Creek, and to pinch-and-swell couples and debris deposits at Holland Lake and carbonate mud at Somers.

Lower Small Diameter **Conophyton** Unit

This unit includes stromatolites referrable to the group **Conophyton** (**Conophyton** sediment type). Cones are typically 3-15 cm across, have vertical axes and form bioherms (Horodyski, 1989).

Carbonate mud and even couple and couplet sediment types fill the space between stromatolite columns and bioherms. To the south and west of Glacier National Park **Baicalia** bioherms, debris and even couples and couplets replace **Conophyton**. The small diameter unit passes upward to the lower large-diameter **Conophyton** unit.

Lower Large-Diameter **Conophyton** Unit

This unit consists of stromatolite columns with diameters from 10-60 cm (Horodyski, 1989, 1985, 1983) attributable to the group **Conophyton** (**Conophyton** sediment type). The axes of the stromatolites are inclined to the north and northeast (Horodyski, 1989). The stromatolites form large bioherms surrounded by carbonate mud. The top of this unit caps a fining-upward cycle that began at the base of the underlying lower **Baicalia** unit and marks the top of cycle #4. A black and calcareous mudstone of the microlamina sediment type underlies the bioherms of the overlying middle **Baicalia** unit in some places (Horodyski, 1989).

Large diameter **Conophyton** bioherms pass up to the middle **Baicalia** unit and associated debris deposits (Fig. 8) that mark the base of cycle #5. South and west of Glacier National Park this unit passes laterally to even couple and couplet, carbonate mud, and microlamina sediment types. At Somers, **Conophyton** passes laterally to pinch-and-swell couple and microlamina sediment types (Figure 9).

CYCLE #5

Middle **Baicalia** Unit

This unit includes stromatolites referrable to the group **Baicalia** (**Baicalia** sediment type) and associated debris deposits. Bioherms with rounded sides and flat tops occur at the bottom of the unit. This unit marks the base of cycle #5 (Figure 13).

South and west of Glacier National Park the **Baicalia** bioherms pass vertically to pinch-and-swell couples at Somers and Holland Lake (Figure 9). At Somers the pinch-and-swell couples are capped by carbonate mud. **Baicalia** bioherms pass laterally to pinch-and-swell couples and couplets at Ousel Creek (Figure 9).

Middle Sedimentary Unit

The lower part of this unit includes beds of the debris sediment type in Glacier Park that pass vertically to microlamina and even couple and couplet sediment type. To the south and west this unit includes the even couple and couplet, pinch-and-swell couple, and carbonate mud sediment types. The top of the unit caps fining-upward cycle #5 started at the base of the underlying middle **Baicalia** unit.

The middle sedimentary unit is overlain by domed stromatolites, **Baicalia**, and debris sediment types at the base of cycle #6.

CYCLE #6

Upper Mixed Stromatolite Unit

This unit includes **Baicalia** and other domed stromatolites or debris beds at the base and local patches of **Conophyton** and **Baicalia** further up. Debris beds surround **Baicalia** and other domed stromatolites, but are replaced vertically by carbonate mud and by **Conophyton**. **Conophyton** does not extend south and west of Glacier Park. Debris beds, even couples and couplets, and pinch-and-swell couples are dominant to the south and west of the Park.

Fining-upward cycle #6 begins at the base of the mixed stromatolite unit (Figure 13). The microlamina sediment type or even couples and couplets cap the fining-upward cycle.

Environmental Interpretation

Evidence from a detailed study of sediment types confirms that **Baicalia** formed in more turbulent conditions and that **Conophyton** formed in less turbulent conditions. On the outcrop scale the pinch-and-swell couple and debris sediment types surround **Baicalia** bioherms which probably formed as patch reefs surrounded by debris beds and pinch-and-swell couples and couplets. Relatively quiet water carbonate mud and even couple and couplet sediment types, surround **Conophyton** bioherms. Therefore the sequence from **Baicalia** to **Conophyton** does represent a vertical sequence of decreasing turbulence, although whether water also shallowed is not so clear. Micrite mud and even couples and couplets are not necessarily shallow water sediments, but such an interpretation is plausible.

Each fining-upward cycle within the stromatolite unit varies laterally in sediment type succession. The individual units comprising the **Baicalia-Conophyton** cycles persist laterally in a northwest to southeast direction within Glacier National Park, probably subparallel to depositional strike (Horodyski, 1983; Eby, 1977). In the western portion of Glacier National Park **Baicalia**, mound-shaped stromatolites, and stromatolite-lamina debris beds replace **Conophyton** (Horodyski, 1983; Figure 9). In the lower part of cycle #4, basal **Baicalia** and debris beds tend to become less prominent to the south and west, away from Glacier National Park, while beds of the pinch-and-swell and microlamina sediment types increase in abundance, replacing **Baicalia** (Figure 9). In the upper part of cycle #4 **Baicalia**, pinch-and-swell couple, even couple and couplet, and carbonate mud sediment types increase in abundance to the south and replace **Conophyton** (Figure 9).

The vertical sequence of sediment types in the **Baicalia-Conophyton** cycles repeats in a series of stacked small to medium scale fining-upward cycles (Figure 14).

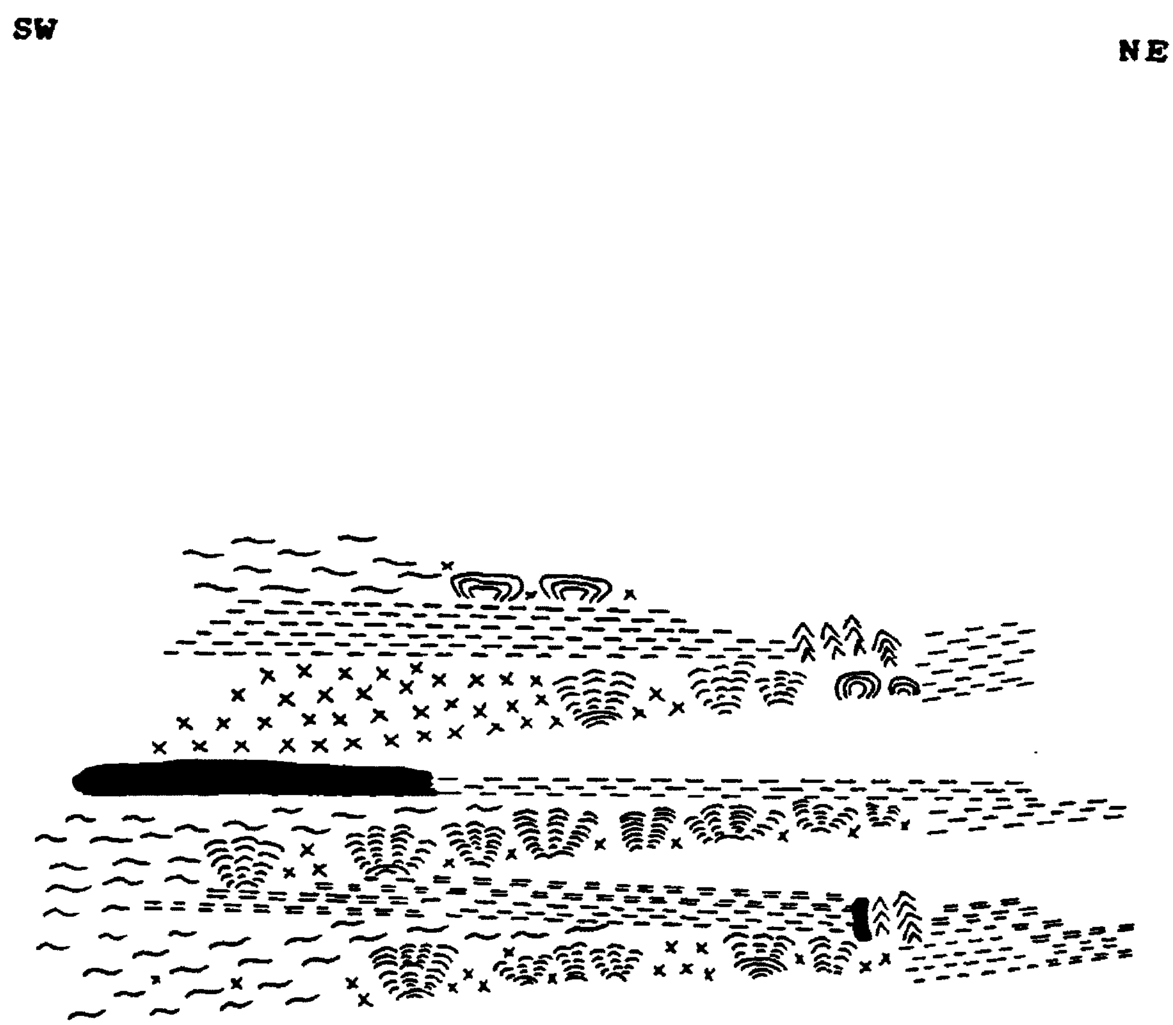
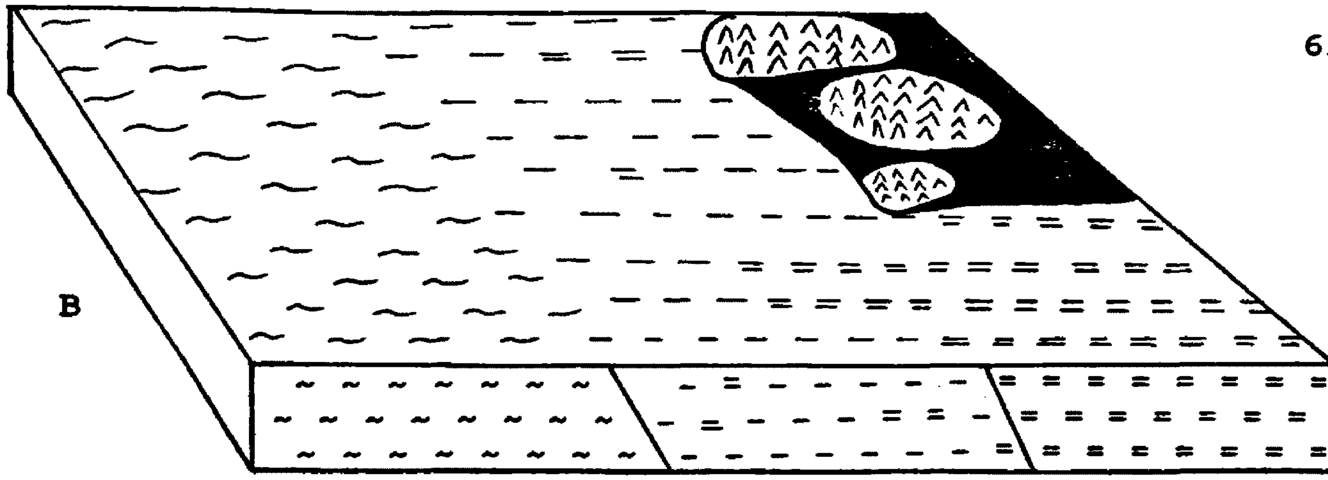


Figure 14. Transgressive to regressive sequences. Lateral facies changes in the far northeastern and southwestern portions of the basin are interpretive.

Each cycle begins with sediment types reflecting abrupt increased turbulence above a scoured surface and ends with sediment types indicating decreased turbulence. The lateral continuity of these relatively small scale cycles suggests that widespread changes in turbulence produced them, not just local cyclic mechanisms. Marine transgressions and regressions may produce similar cycles, or, expansions and contractions of a very large lake.

According to a marine transgressive-regressive interpretation, in a basin as flat as the Belt sea even small scale changes in base level would produce widespread cyclic transgressive and regressive sequences. According to this interpretation each stromatolite cycle began with a transgression (Figure 14): **Baicalia** patches and debris beds migrated to the northeast, Wallace type pinch-and-swell couples already documented from the western portion of the basin by Grotzinger (1981) migrated over **Baicalia** and appear in the Somers section (Fig. 9). This may be due to either shoaling upward or lowering of sea level. According to this interpretation, the regression is recorded by the sequence of quiet water couples and couplets, microlamina and **Conophyton** sediment types that migrated over **Baicalia** and pinch-and-swell couples to the southwest. According to such an interpretation (Figures 15, 16) Wallace pinch-and-swell couples and couplets were being deposited in the west of the basin at the same time **Baicalia** and debris deposits were



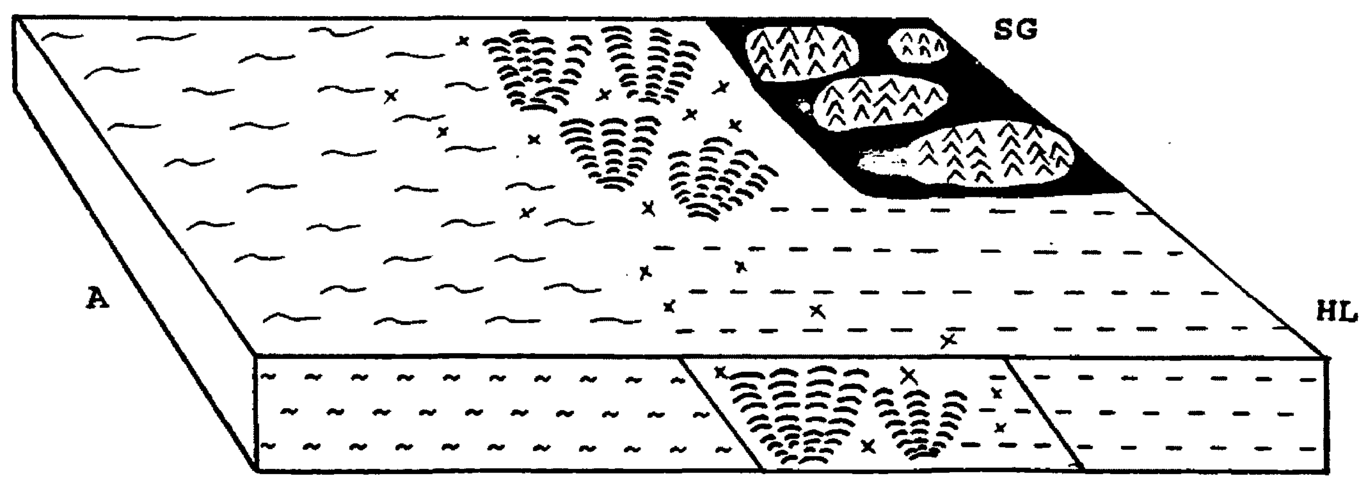
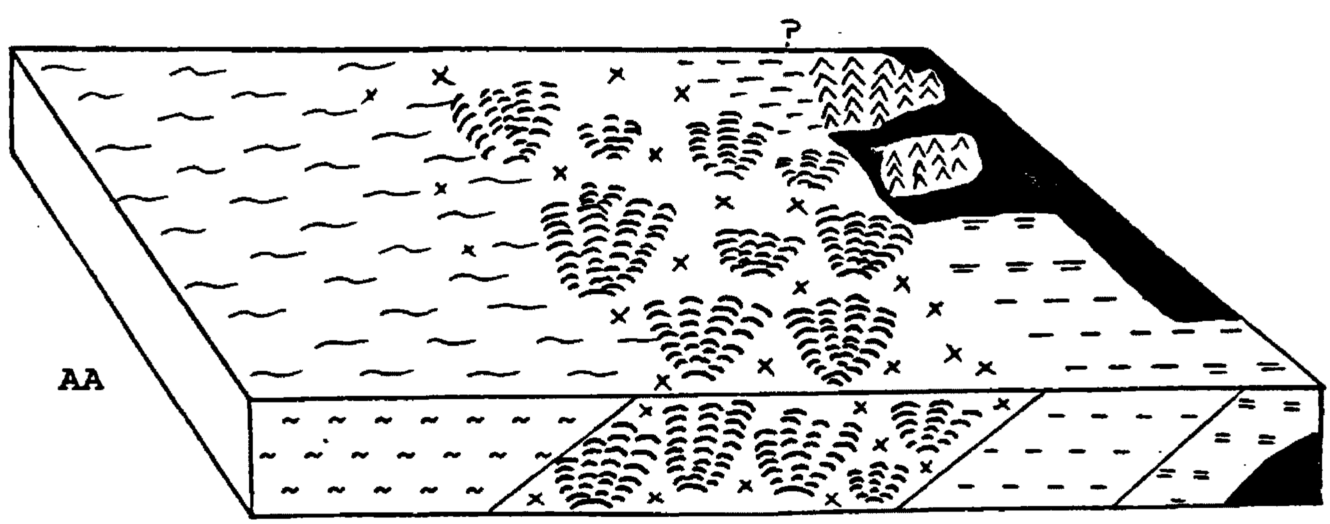
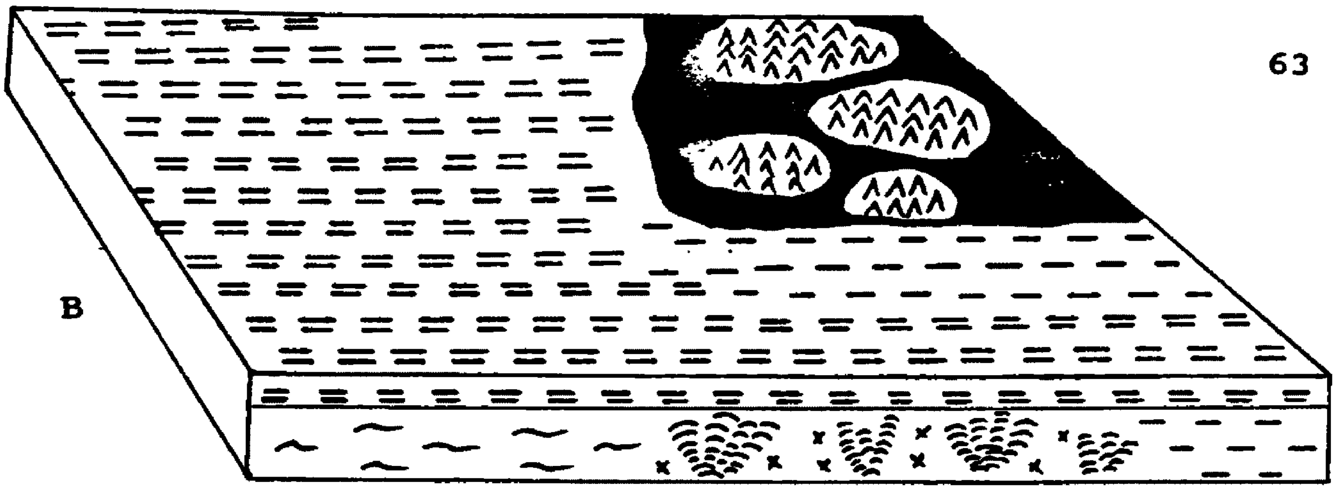


Figure 15. Conceptual paleofacies maps from Baicalia-Conophyton cycles (see Figure 9) at AA (bottom figure), correlation A (middle figure) and correlation B (top figure). SG = Glacier Park, HL = Swan Range.





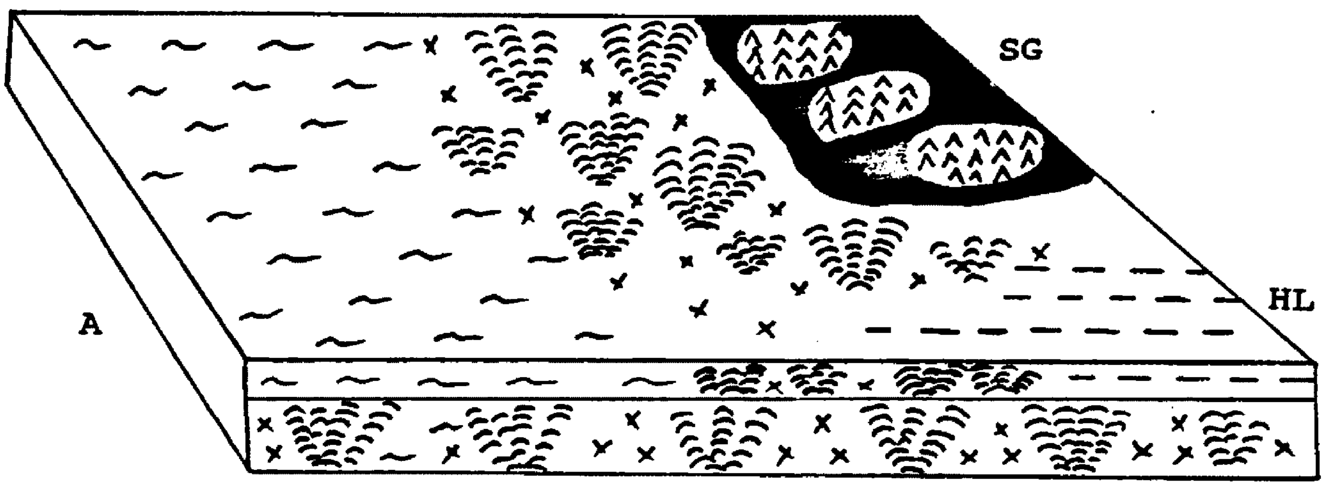
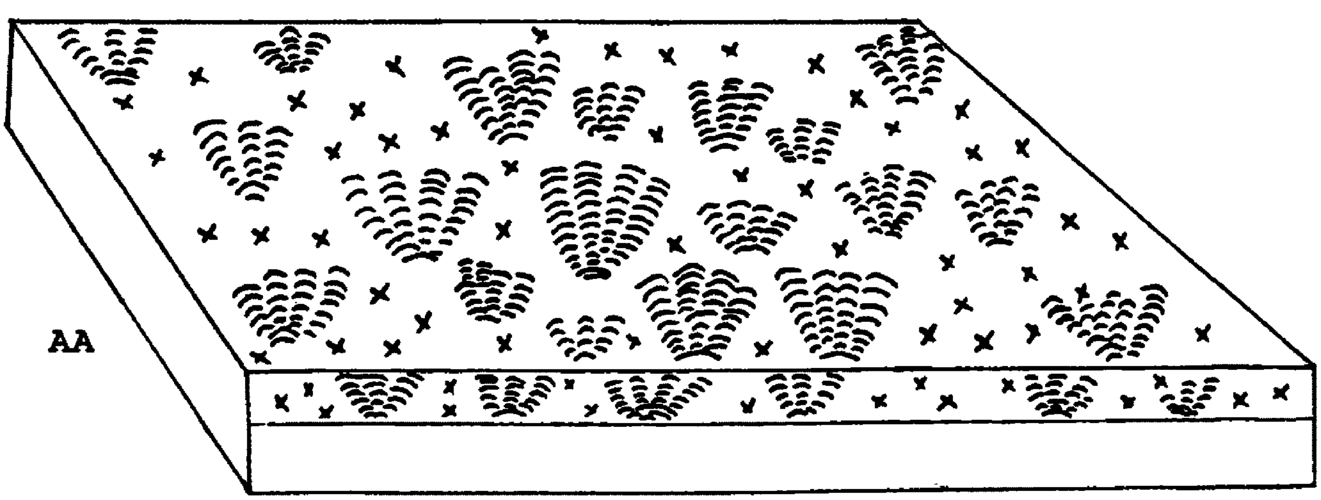


Figure 16. Alternative conceptual paleofacies maps from **Baicalia-Conophyton** cycles (see Figure 9) at AA (bottom figure), correlation A (middle figure) and correlation B (top figure). SG = Glacier Park, HL = Swan Range.



being deposited further northeast. **Conophyton** and other less turbulent sediment types such as micrite mud and even couples and couplets occurred adjacent to **Baicalia** further northeast and were protected from oncoming currents from the southwest.

Although Walther's Law infers that vertically stacked **Baicalia** and **Conophyton** were once laterally associated, neither this study nor Horodyski's work establishes the presence of **Conophyton** or other quiet water sediments at the bases of the cycles. Lateral facies changes (Figure 15) are interpretive in the far northeastern and southwestern portions of the basin.

Because it is not possible to demonstrate complete lateral facies changes typical of transgressions and regressions within the study area, a vertically stacked "layer-cake" arrangement is equally plausible and the lake interpretation is tenable (Figure 16). Additional stratigraphic research may help determine the significance of such an arrangement.

Basin Fill Pattern

The **Baicalia-Conophyton** cycles form a resistant cliff from Glacier National Park to the Mission Mountains. Whereas most Helena rocks are dolomite-rich and contain approximately 50% siliciclastic material, the **Baicalia-Conophyton** unit is calcite-rich and contains only 12-40% siliciclastic material and is therefore a unique stratigraphic interval within the Helena Formation. Perhaps greater calcification occurred during a period of a very pronounced water chemistry change in calcium and magnesium carbonate saturation. Calcite precipitated throughout the fining-upward cycle. If this is so, then as a distinctive calcite rich unit in the Belt basin, the **Baicalia-Conophyton** cycles constitute a chronostratigraphic unit; water chemistry conditions may have been similar most of the way across the basin. Where observed, the cliff containing the **Baicalia-Conophyton** cycles shows no indication of pinching out.

The unusual thickness of the **Baicalia-Conophyton** cycles may reflect an increased rate of sedimentation of both siliciclastic and carbonate material. For example, with the onset of regression and concentration of calcium carbonate in the water, increasing amounts of carbonate would begin to precipitate. Then increased fresh water input, perhaps from storms or floods, would maintain the water chemistry and increased carbonate precipitation while flushing additional siliciclastic material into the system.

The two depositional interpretations discussed above may also account for the unique concentration of branched and columnar stromatolites in a relatively thin unit. Conditions particularly conducive to branching and columnar stromatolites must have prevailed at that time. Increased calcification over an extended period may contribute to the formation of **Baicalia** and **Conophyton** by making the columns and branches stronger and therefore able to grow. Horodyski (1989) suggests that greater calcification may contribute to the formation of **Conophyton** by making columns stronger. However, there is no evidence that **Conophyton** are more calcitic than **Baicalia**.

If indeed the migration of siliciclastic-to-dolomitic cycles can be treated as a time plane, then it may be possible to demonstrate that the cyclic interval described by O'Connor (1967) migrates up in section southwestward across the basin (Figure 16). Near Hungry Horse Reservoir siliciclastic-to-dolomitic cycles occur below the **Baicalia-Conophyton** cycles (WInston, 1989). In the Mission Mountains and in the Swan Range near the Holland Lake section siliciclastic-to-dolomitic cycles are stratigraphically above beds which probably correlate to the **Baicalia-Conophyton** cycles. Wallace-like pinch-and-swell couples underlie the **Baicalia-Conophyton** cycles in the southwest Missions (Winston, personal communication).

The stratigraphic relation of the **Baicalia-Conophyton** cycles to the Helena-Snowslip boundary indicates that the base of the Snowslip climbs to the south (Figure 17). Smith (1963) reported the **Baicalia-Conophyton** cycles at 170 feet below the top of the Helena in the northern Whitefish Range, Barnes (1963) reports the cycles 350 feet below the contact in the south Whitefish Range, Horodyski (1983) reports the cycles 650 below the contact at Piegan Mountain in Glacier Park, and Childers (1963) reports the cycles at 750 feet below the contact near Marias Pass. In the Mission Mountains the **Baicalia-Conophyton** cycles are under more than a thousand feet of siliciclastic-to-dolomitic cycles described by O'Connor (1961) (Figure 16).

The northeastward thinning of the Helena above the **Baicalia-Conophyton** cycles may be accomplished simply by thinning of individual siliciclastic-to-dolomitic cycles to the northeast (Figure 17). Further detailed sedimentologic and stratigraphic work must be done in this area to resolve this question.

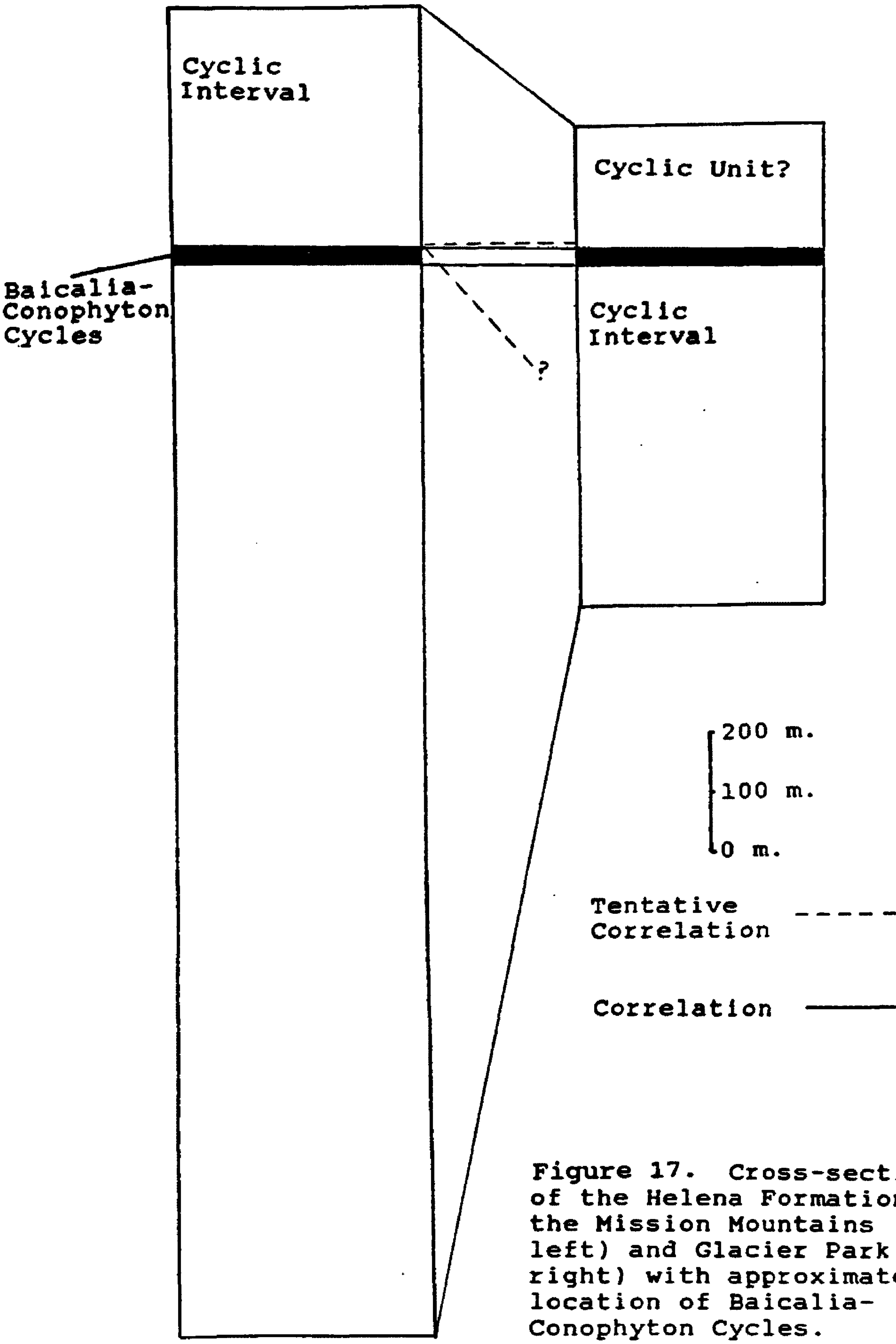


Figure 17. Cross-section of the Helena Formation in the Mission Mountains (on left) and Glacier Park (on right) with approximate location of Baicalia-Conophyton Cycles.

CONCLUSIONS

An analysis of sediment dynamics at three scales combined with an analysis of stromatolite morphology results in the following conclusions regarding the **Baicalia-Conophyton** cycles.

Nine different sediment types comprise the **Baicalia-Conophyton** cycles and reflect a range of environments from turbulent debris, tabular and hummocky silt, and **Baicalia** sediment types, to less turbulent domed stromatolite, pinch-and-swell couple and couplet and even couple and couplet sediment types, to low turbulence carbonate mud, microlamina, and **Conophyton** sediment types.

Vertical sequences of these sediment types form fining-upward cycles, one of which coincides with the lower **Baicalia** to **Conophyton** cycle described by Horodyski (1989). This coincidence provides a basis for comparing siliciclastic-to-dolomite cycles with stromatolite cycles and provides an excellent opportunity to reinterpret paleoenvironmental and stratigraphic interpretations of the **Baicalia-Conophyton** cycles as well as those in the Helena Formation.

The **Baicalia-Conophyton** cycles are set in sediment types that fine upward in cycles with considerable lateral variability in the vertical sediment type succession. Lateral and vertical variability may represent small scale transgressions and regressions or may reflect basinwide changes in environment supportive of expansions and contractions in a restricted environment. This study did not identify cycles with **Conophyton** or quiet water sediments at the base.

Information from sediment types and their vertical sequences confirms Horodyski's (1989; 1983) paleoenvironmental interpretations that 1) **Baicalia** lived in a more turbulent environment and **Conophyton** lived in a less turbulent environment, 2) the sequence from the lower **Baicalia** unit up through the inclined **Conophyton** unit represents a sequence of decreasing turbulence, and 3) changing environmental conditions probably contributed to the morphologic change from **Baicalia** to **Conophyton**, perhaps in addition to a change in the microbe community or a change in the activity of the microbe community.

This study establishes the usefulness of the **Baicalia-Conophyton** cycles as a chronostratigraphic unit and provides an opportunity to reinterpret Helena Formation stratigraphy. The cycles therefore represent a chronostratigraphic unit, and 1) the **Baicalia-Conophyton** cycles may overprint a larger regressive or contractive sequence during which a greater amount of calcium carbonate was deposited, 2) the siliciclastic-to dolomitic cyclic interval identified by O'Connor (1967) and Eby (1977) in Glacier National Park appears to migrate southeastward to in the Mission and Swan Ranges and may migrate across the **Baicalia-Conophyton** cycles, and 3) individual siliciclastic-to-dolomitic cycles above the **Baicalia-Conophyton** cycles may thin substantially from the Mission and Swan Ranges to Glacier Park. This analysis provides a framework for additional detailed stratigraphic work in the Belt Basin, particularly between Glacier Park and the Mission and Swan Ranges.

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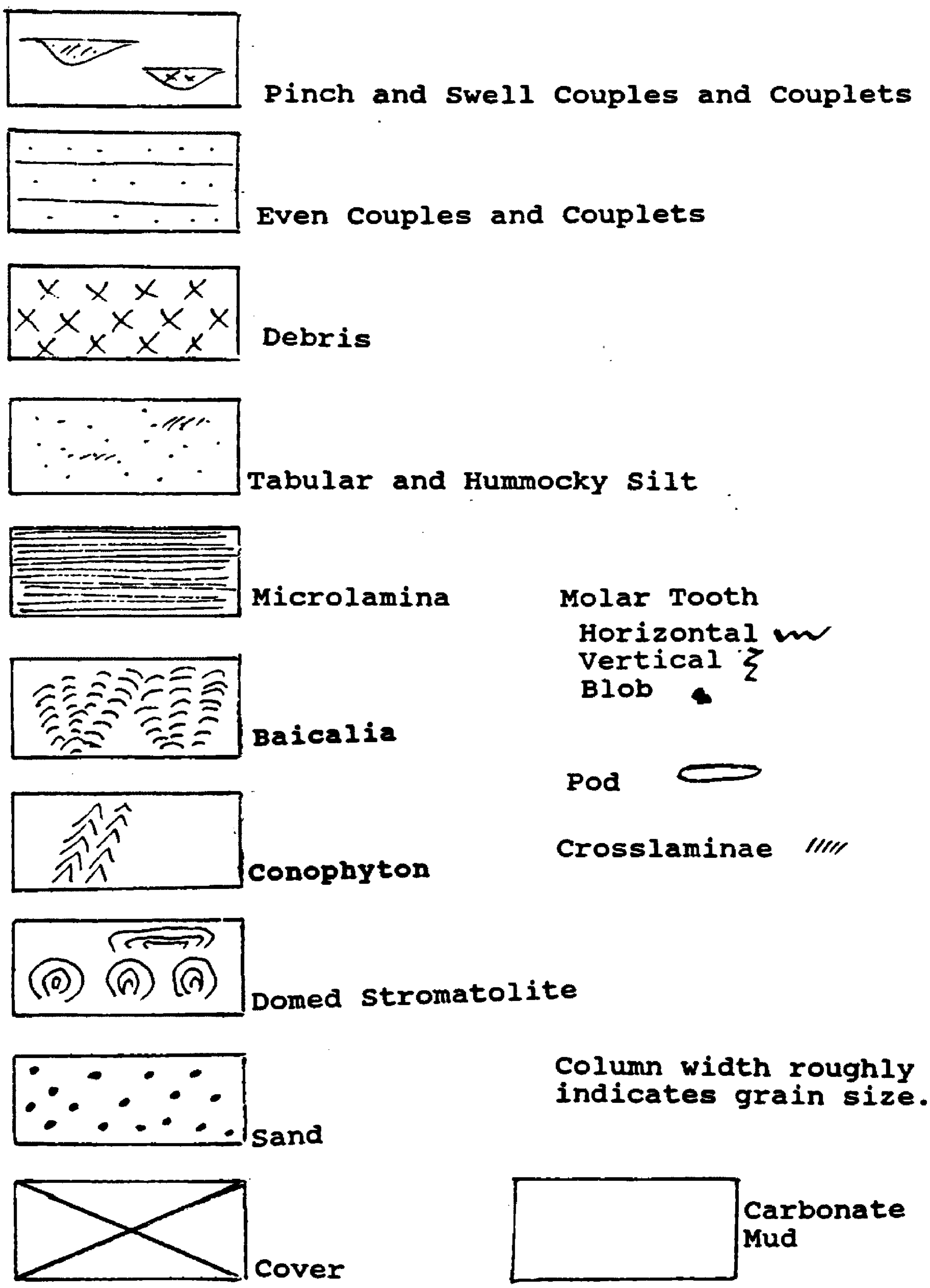
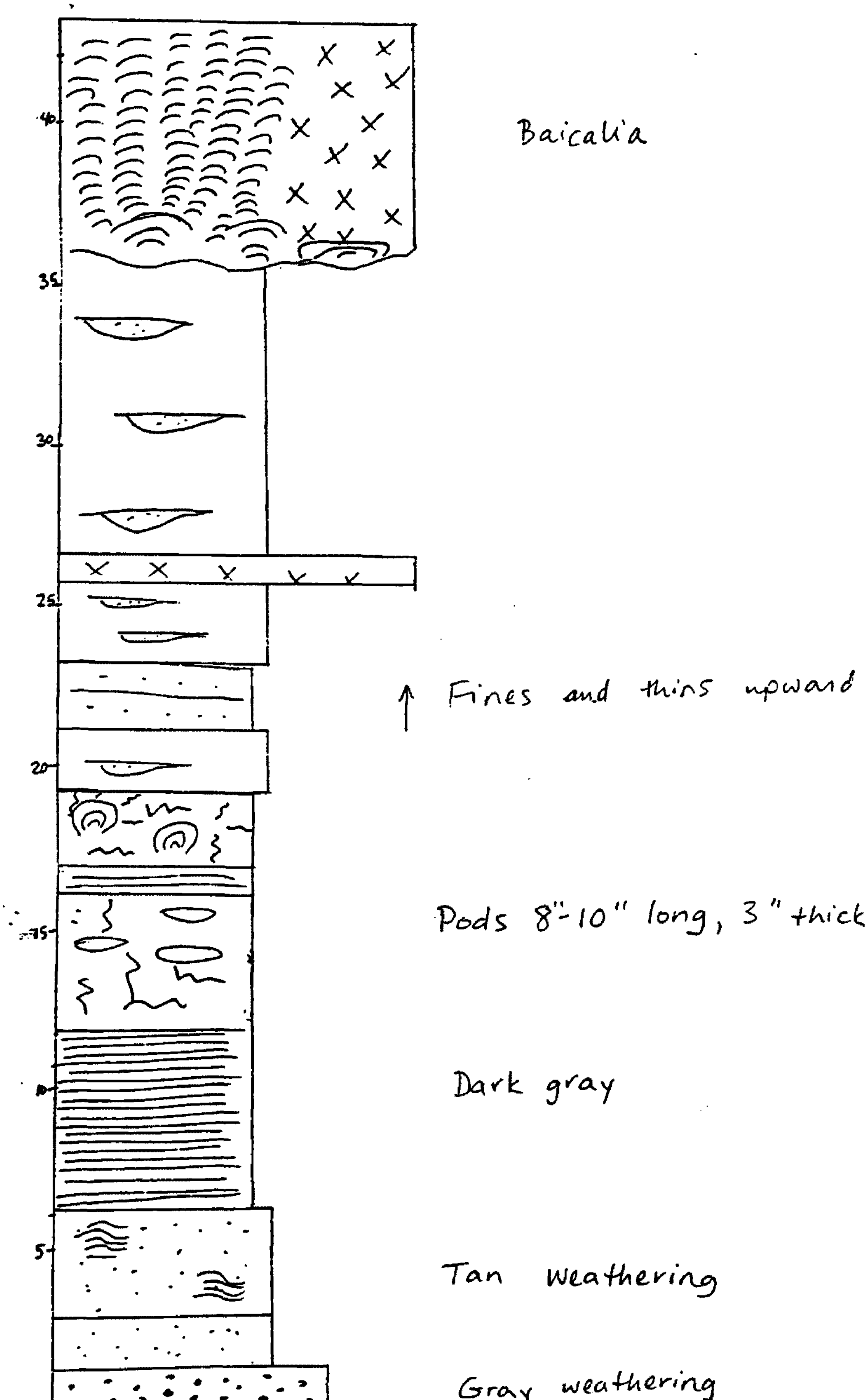
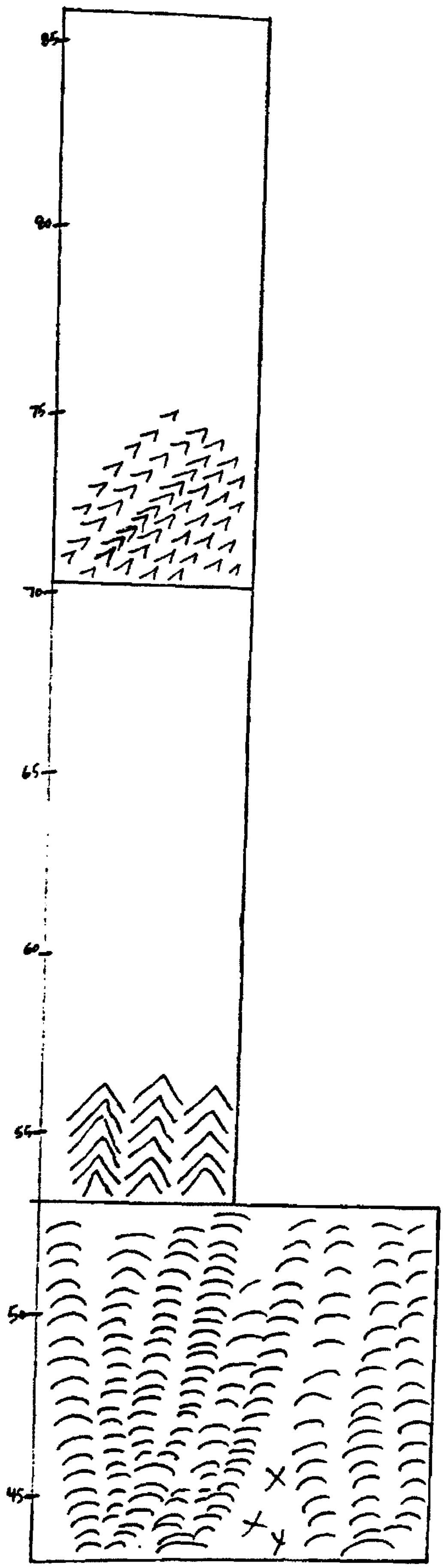
APPENDIX A

Explanation





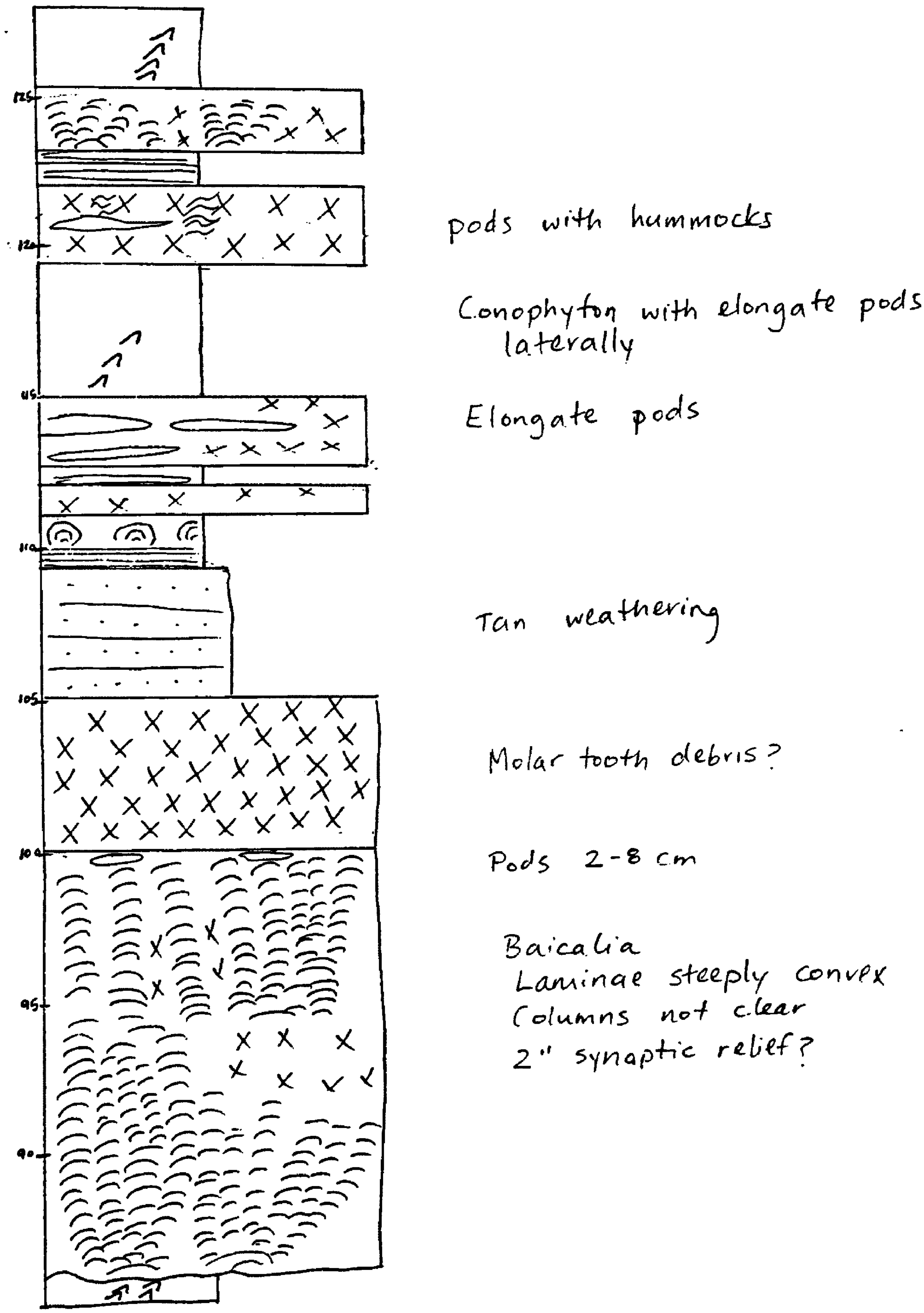
Detailed stratigraphic section from Swiftcurrent Glacier. (in ft)

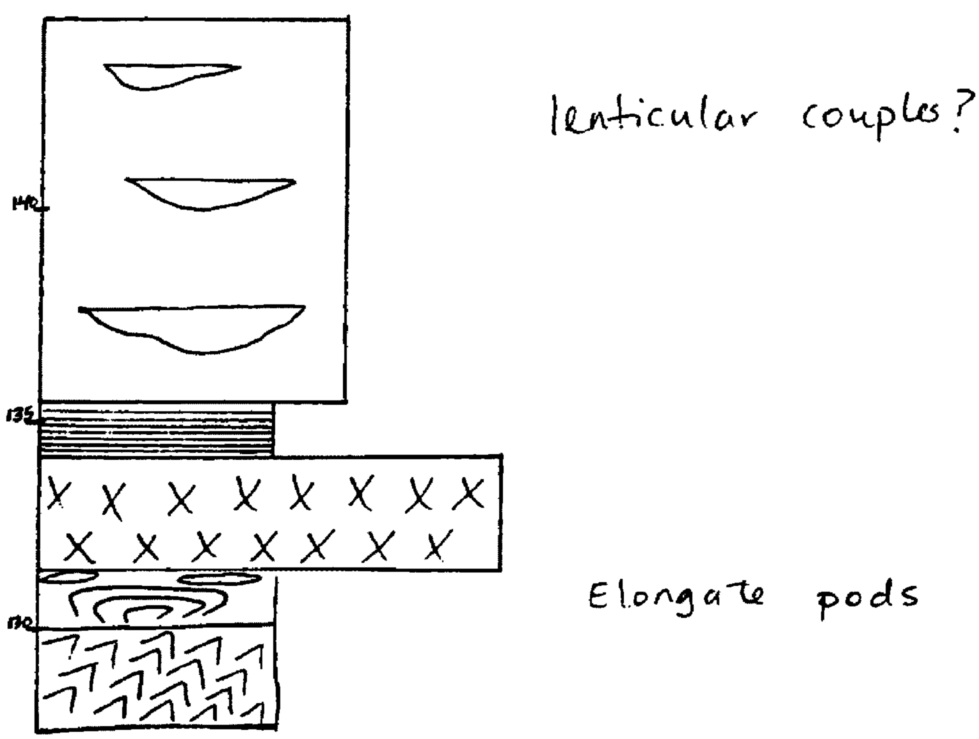


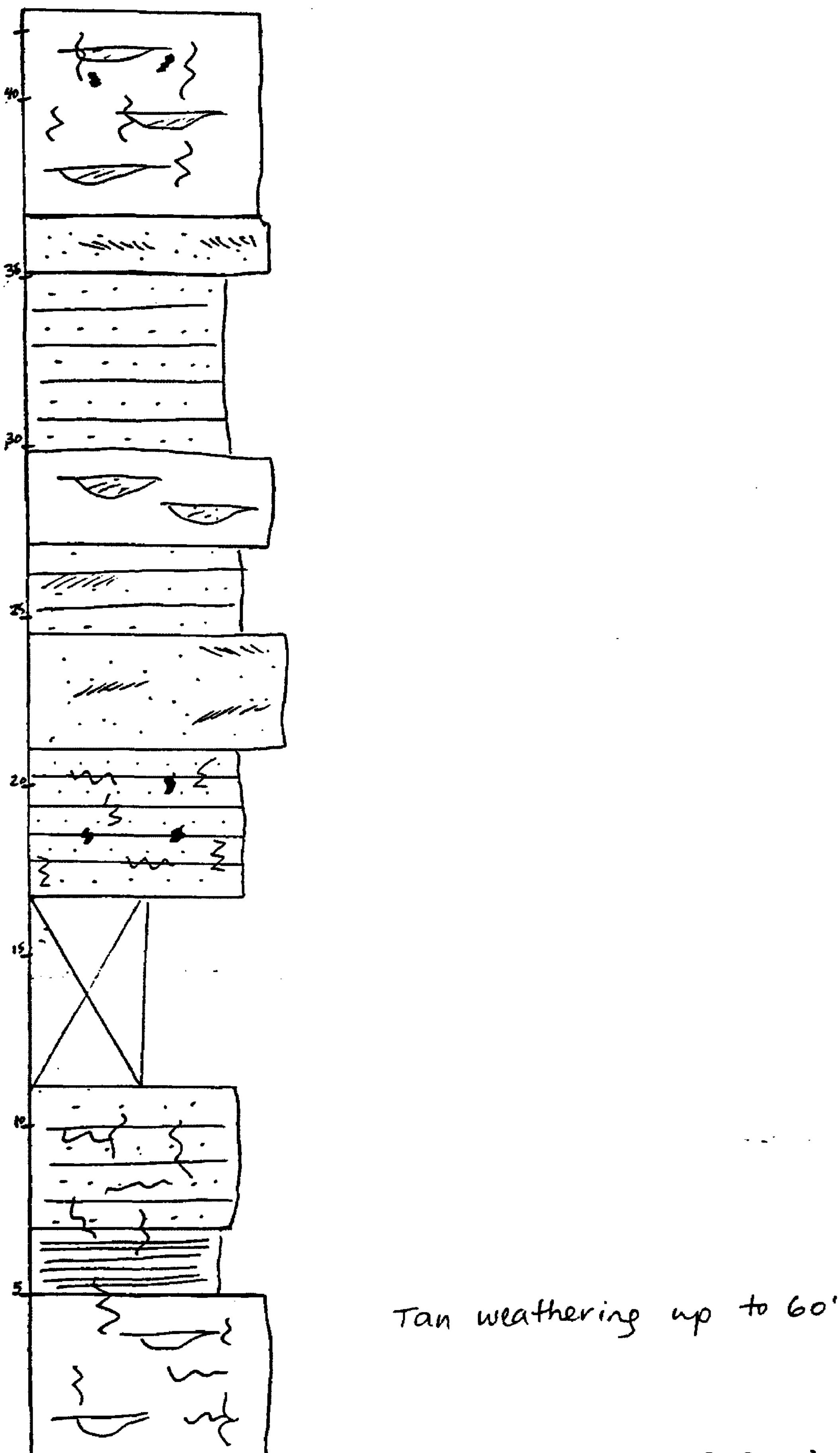
Conophyton
Inclined small diameter
Laminae parabolic, wavy in places
Margins walled

Conophyton - Large diameter
laminae indistinct laterally and discontinuous,
Margins ragged to bumpy

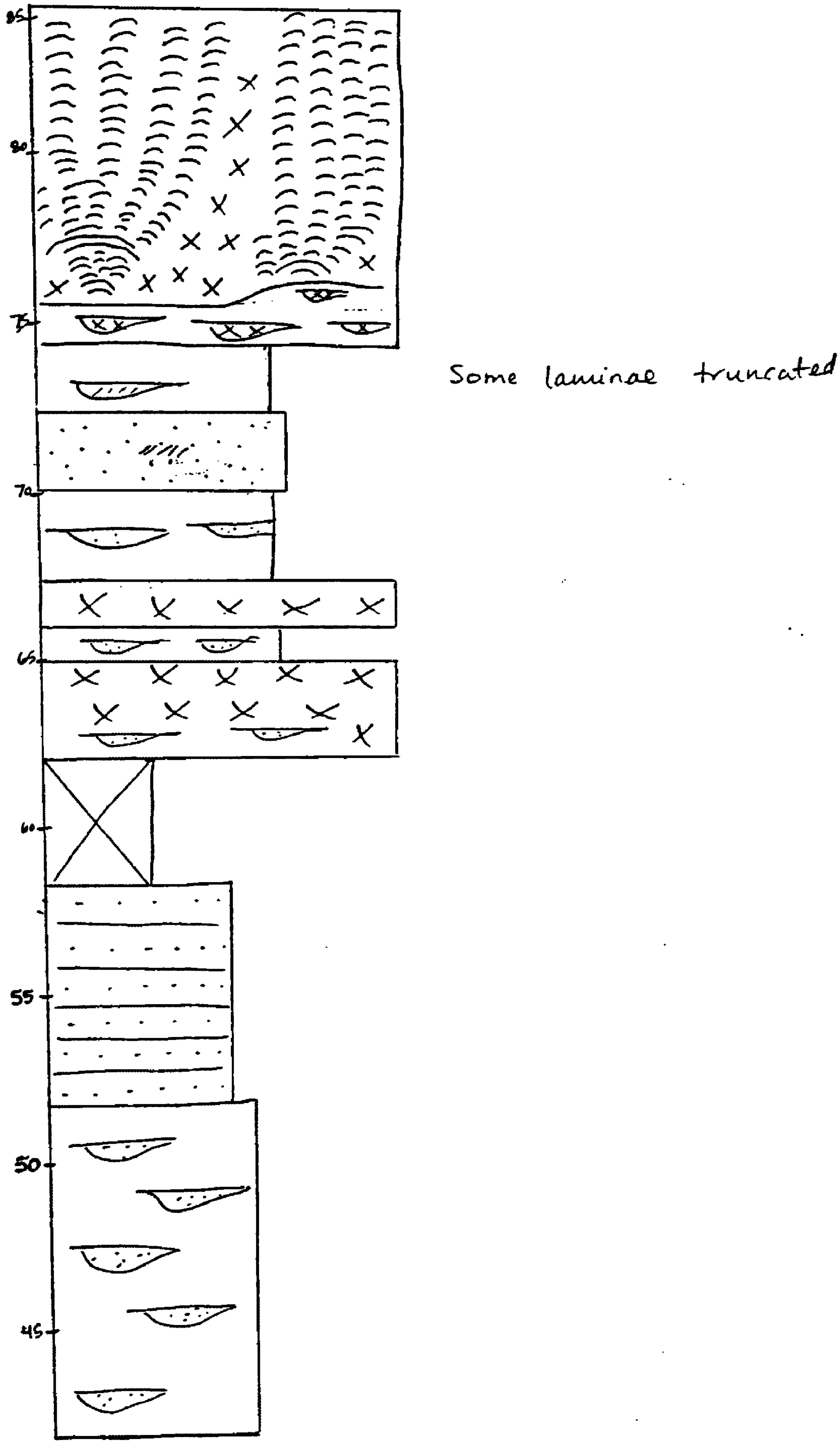
Baicalia bioherms subsphaerical
laminae indistinct and laterally discontinuous
Branching subparallel
Margins ragged
Some oolites laterally?

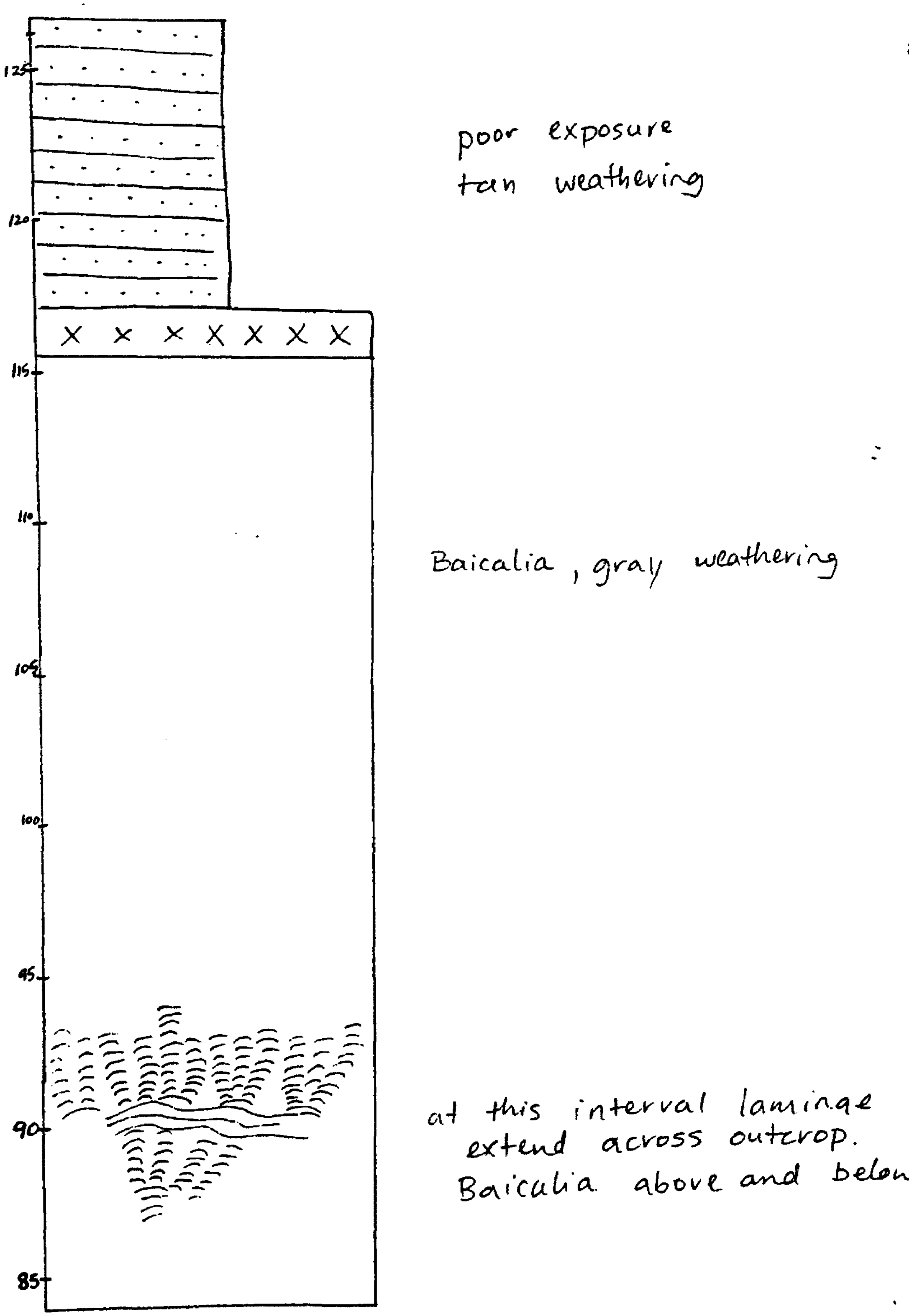

125
120
115
110
105
100
95
90
pods with hummocks
Conophyton with elongate pods laterally
Elongate pods
Tan weathering
Molar tooth debris?
Pods 2-8 cm
Baicalia
Laminae steeply convex
Columns not clear
2" synaptic relief?

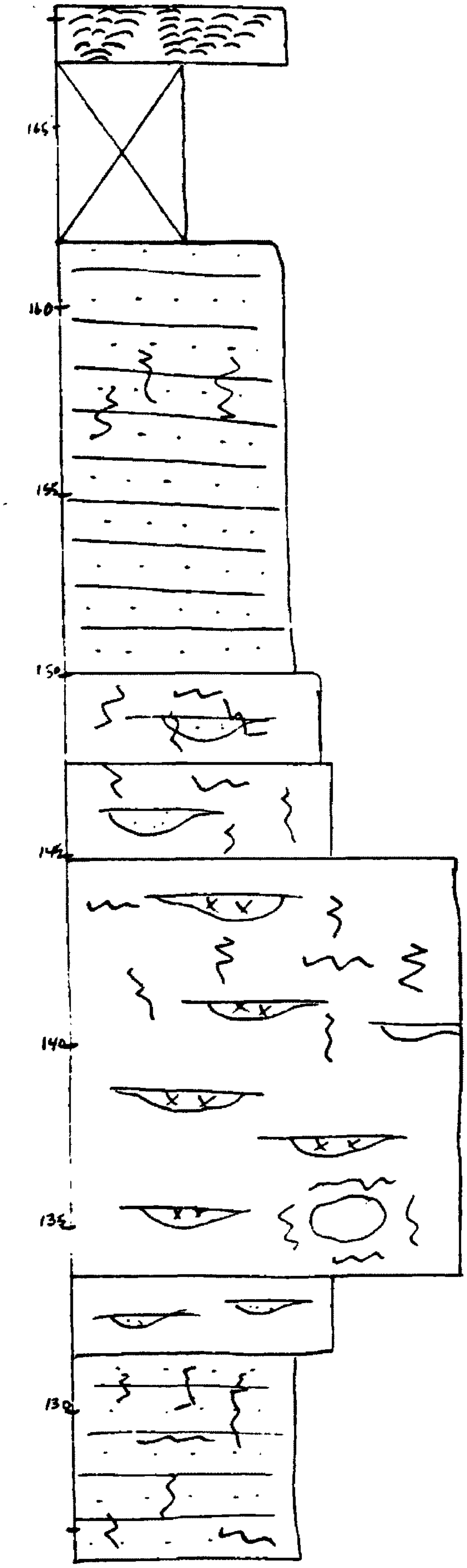

lenticular couples?
Elongate pods



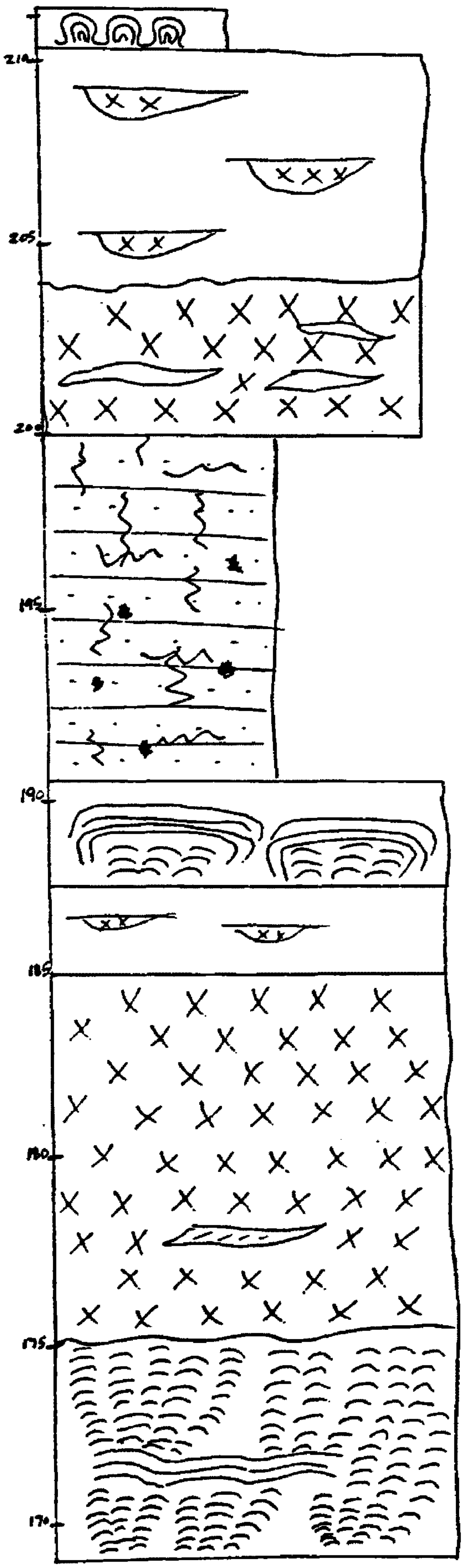
Detailed stratigraphic section from Ousel Creek.


85
80
75
Some laminae truncated
70
65
60
55
50
45

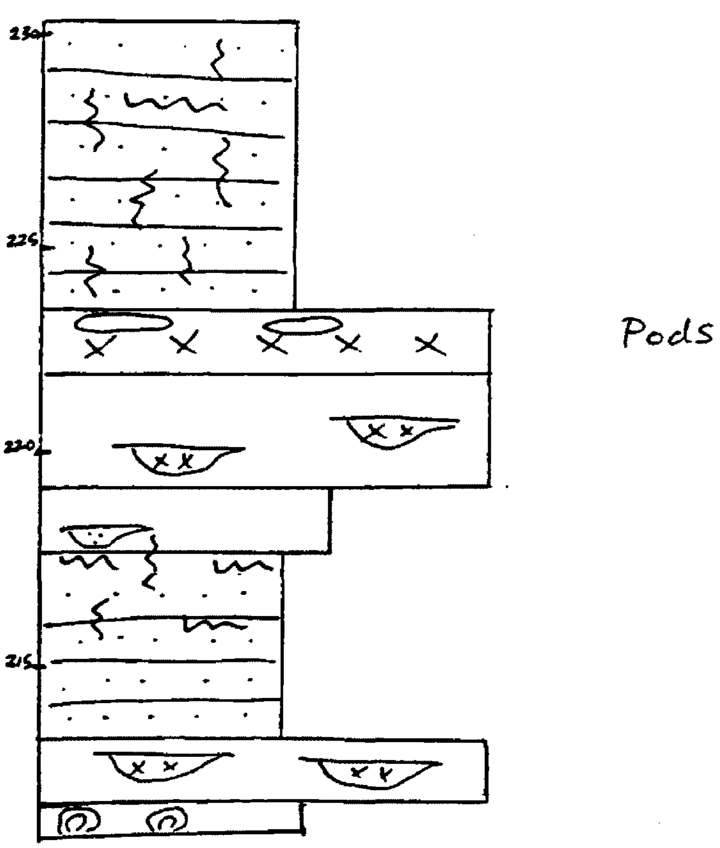

125
120
115
110
105
100
95
90
85
poor exposure
tan weathering
Baicalia, gray weathering
at this interval laminae
extend across outcrop.
Baicalia above and below

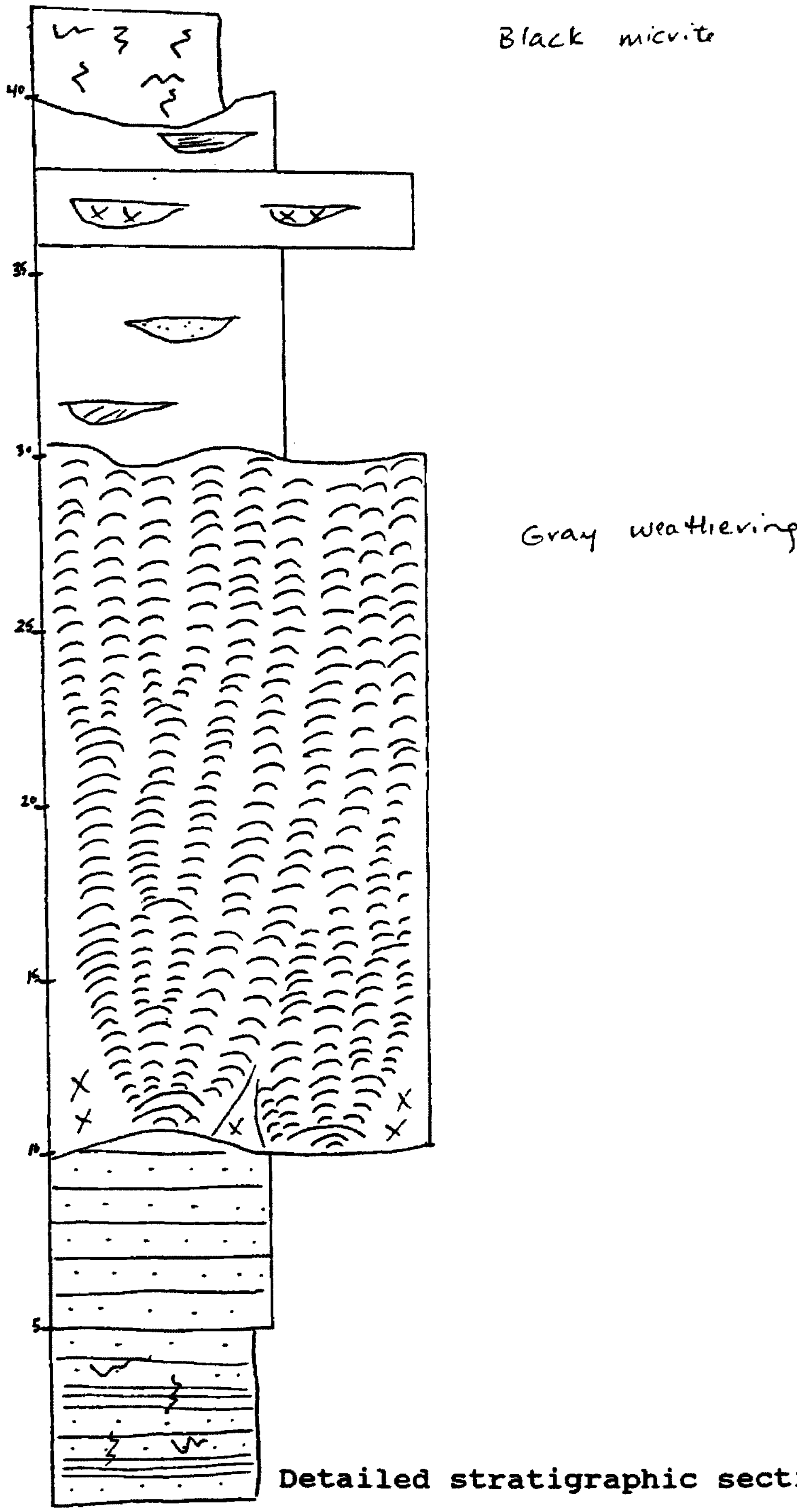


Some large pods with molar tooth wrapped around

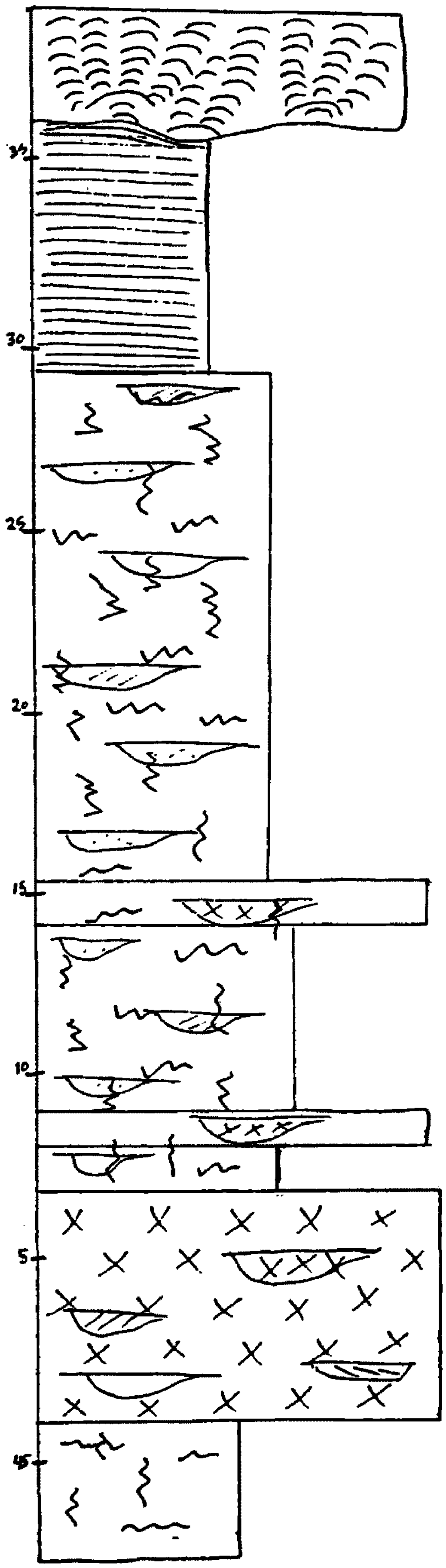


Stromatolite "turtles"?


230
225
220
215
Pods

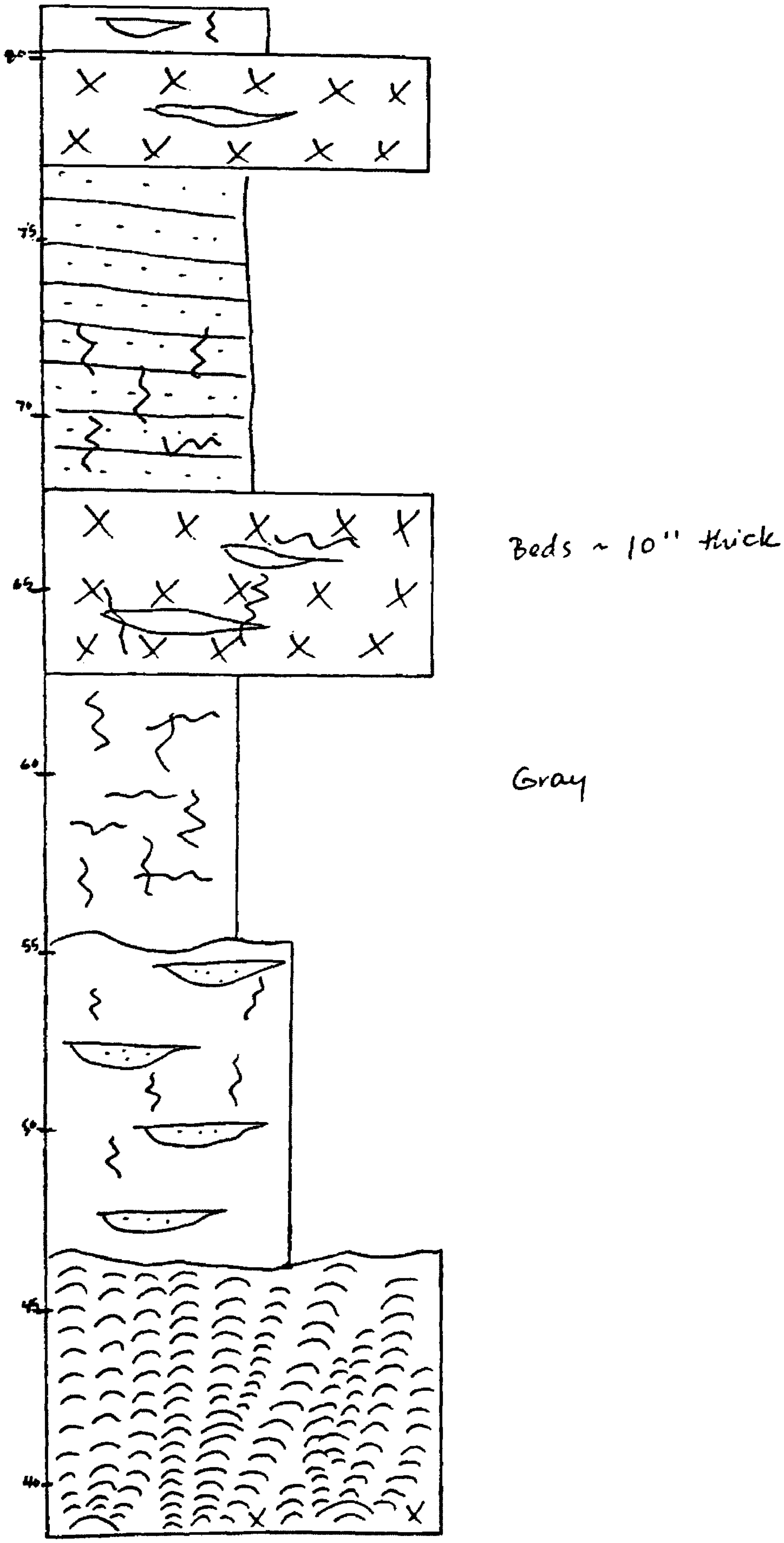


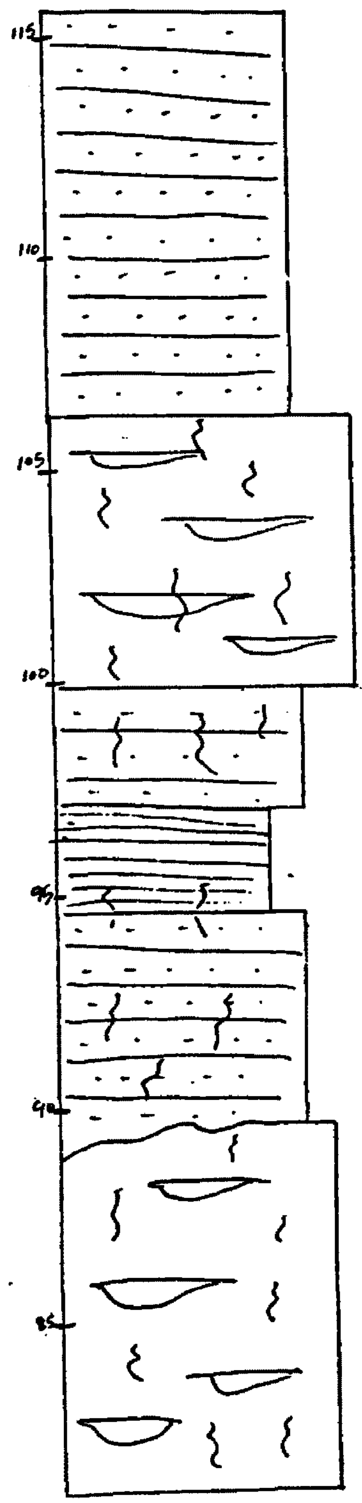
Detailed stratigraphic section from Somers.



Friable

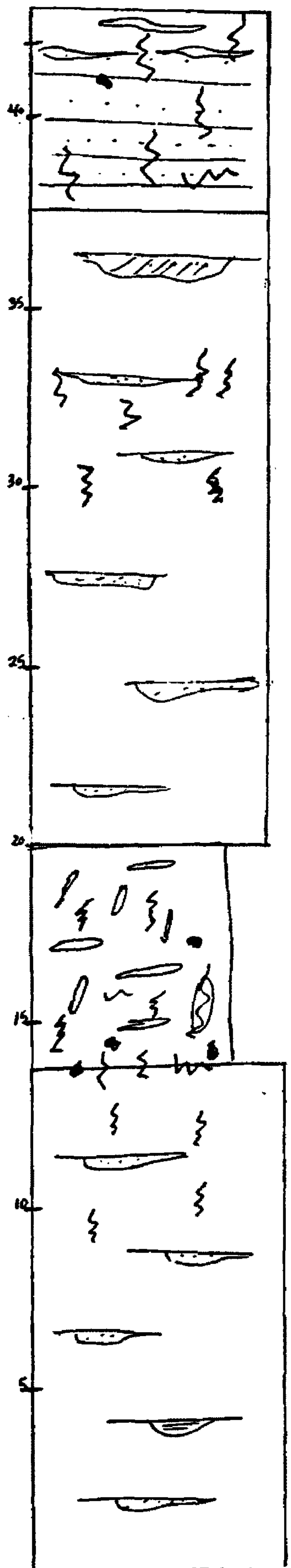
tops and bottoms wavy
calcitic
gray weathering
This portion measured on another day.


80
75
70
65
Beds ~ 10" thick
60
Gray
55
50
45
40



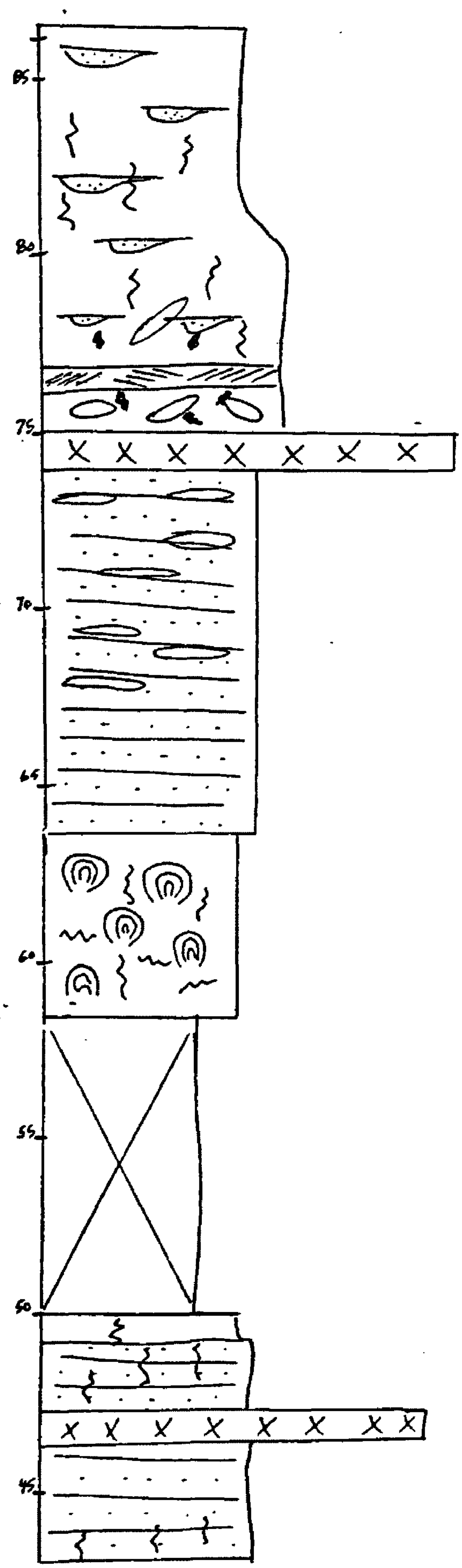
Sandier, beds 2-6" thick

Tan weathering from here up



Dolomitic

Detailed stratigraphic section from Holland Lake.



Silt to black argillite
pinch and swell (>10 cm)

Pod debris

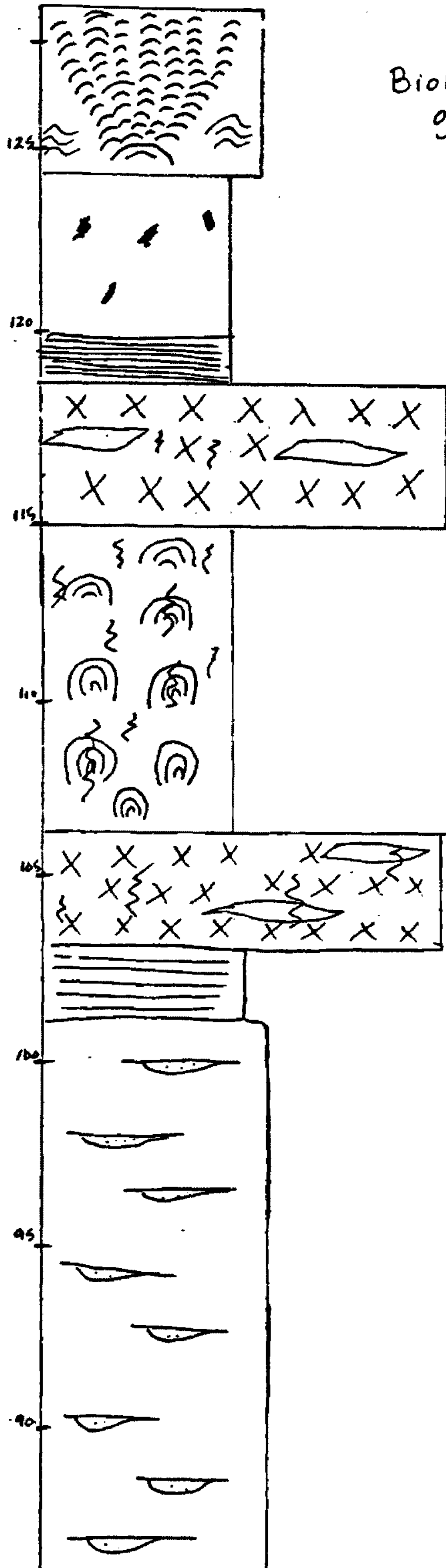
Pods 2-8 cm long, gray

couplets mostly clay

Cryptalgal laminae at base?

Rounded Molar Tooth Debris

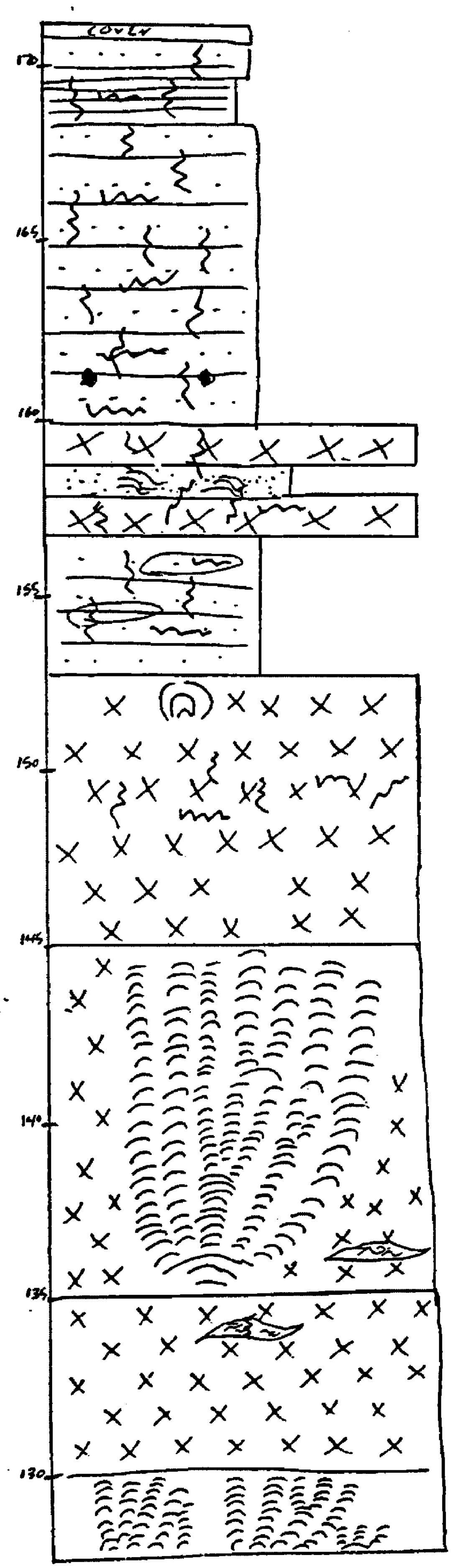
Dolomitic

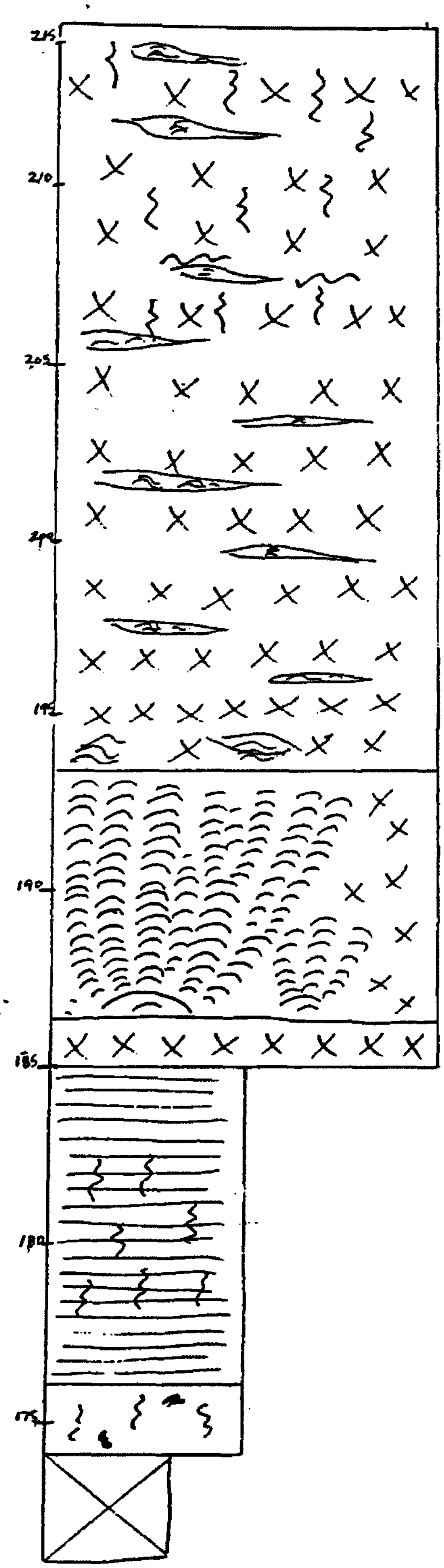


Bioherms 1 m tall, 2-3 m wide
grade laterally into hummocky micrite

Domed stromatolites with vertical
molar tooth in centers

Carbonate mud in lenses occasionally
grades up into debris
Debris 25 cm thick beds


cover
170
165
160
155
150
145
140
135
130
Molar tooth debris ?
Lenses of hummocky micrite lateral to bioherms

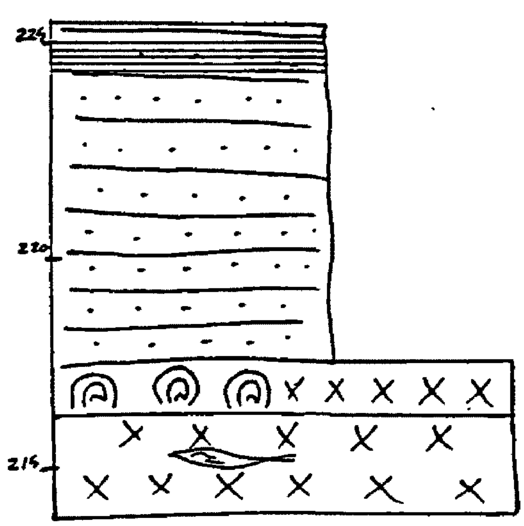


Calcitic and dolomitic lenses (micrite) with vertical molar tooth, hummocky

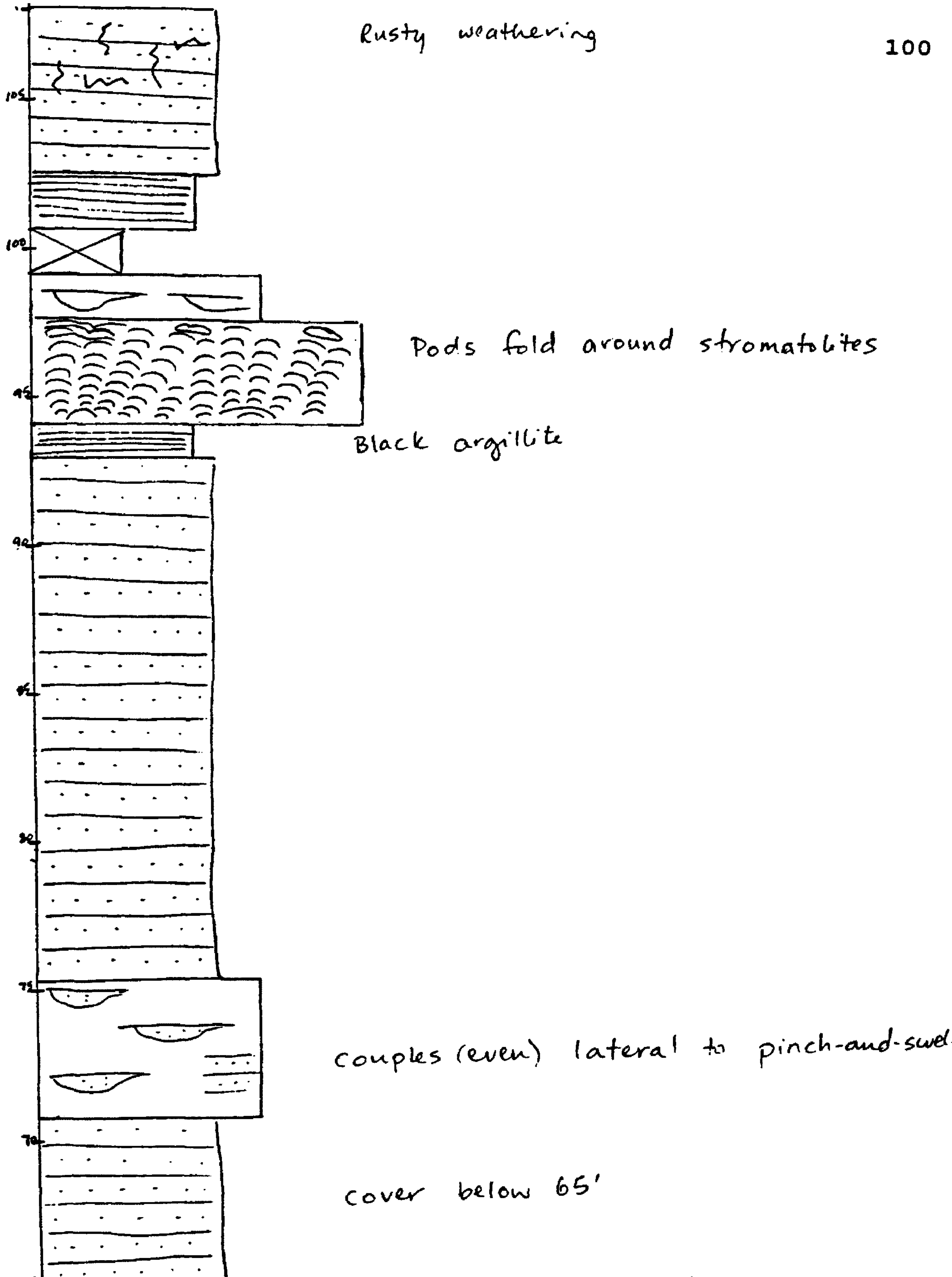
Debris = molar tooth hash? random orientations

Baicalia can be traced 60 ft + laterally in outcrop

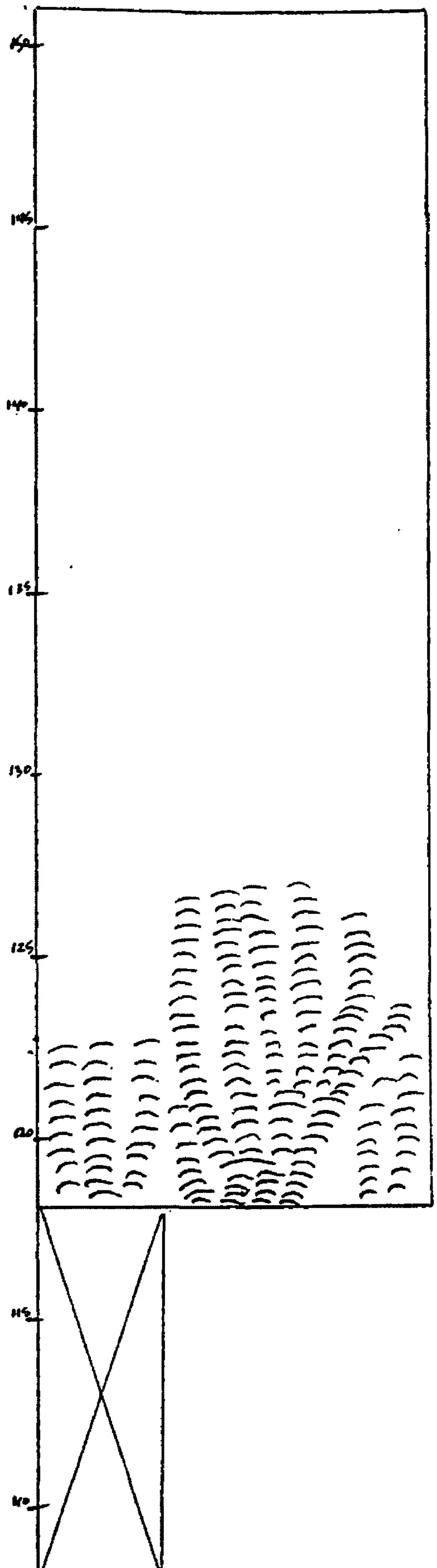
Some silty beds



Dolomitic.



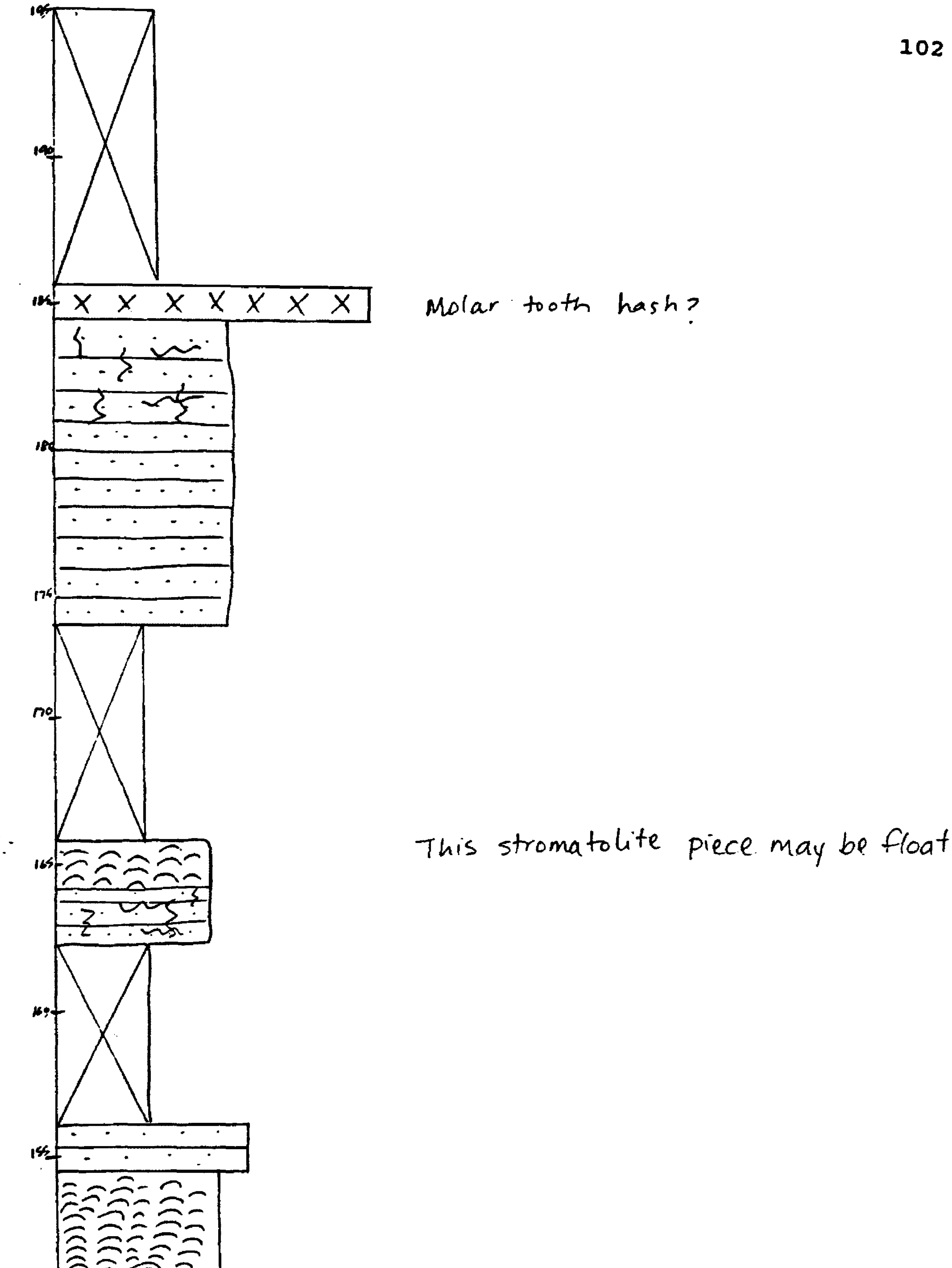
Detailed stratigraphic section from Inspiration Pass.

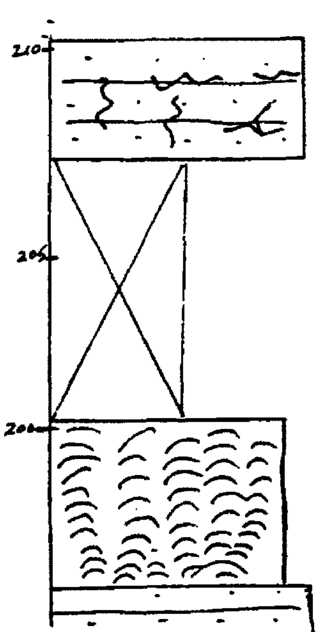


Baicalia, laminae steeply to gently convex

pods fold around tops of bioherms

Lateral?


Molar tooth hash?
This stromatolite piece may be float



Baicalia, laminae gently convex