The origin of flat-pebble conglomerates in the Upper Cambrian of the Clarks Fork region, Park County, Wyoming

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INTRODUCTION

In the Yellowstone area of northwest Wyoming where the Clarks Fork region is located, flat limestone pebble conglomerates are found in the upper Pilgrim Limestone and the lower Snowy Range Formation of the Upper Cambrian. Ruppel (1972) described the Pilgrim as including three main lithologic units: (1) a lower unit of interbedded ribboned limestone, oolitic limestone, and less common flat limestone pebble conglomerate and shale; (2) a middle unit of limestone pebble conglomerate; and (3) an upper unit of mottled oolitic limestone. The Snowy Range Formation conformably overlies the Pilgrim Limestone and is divided into the Dry Creek, Sage, and Grove Creek Members.

The general term "conglomerate" refers to poorly-sorted coarse-grained sedimentary rock. In the case of flat-pebble conglomerates found in the Clarks Fork region, the grains range from large sub-rounded to rounded limestone pebbles down to the silt-sized grains in a sparry limestone matrix. The pebbles tend to have a "flat" appearance in that their width/length is much greater than their thickness/height.

Conglomerates can be divided into two categories: intraformational and extraformational. Flat-pebble conglomerates are intraformational conglomerates because they are composed of clasts which are derived from within the basin of deposition; the clasts are not from a different source outside that environment as is, for example, conglomerate found in a river bed (Tucker, 1991). Intraformational limestone conglomerates composed of rounded, tabular intraclasts are also referred to as calcirudites. These conglomerates are common in shallow-water carbonate facies throughout the geologic column but are especially abundant in early Paleozoic strata. Younger carbonate facies contain much fewer flat-pebble conglomerates, indicating a very uneven distribution of this rock type through geologic time (Sepkoski, 1982).

Geologists have been studying, mapping, and publishing works on the area of northwest Wyoming for over 100 years. However, few geologists have concentrated on research addressing the Cambrian flat-pebble conglomerates. Brett, Liddell, and Derstler (1983) studied Late Cambrian hard substrate communities which were found encrusting the upper surfaces of flat-pebble conglomerates in the Snowy Range Formation. I visited one of their site locations in order to compare their observations to my own. Flat-pebble conglomerates have been studied more extensively in other locations around the world, but there are still several questions which remain to be answered.

The purpose of this project is to investigate the origin of flat-pebble conglomerates and the pebbles that compose them. Specifically, I have developed hypotheses for the formation mechanisms of the pebbles, why they are flat and rounded, how they were deposited, and how they were lithified and cemented to form a conglomerate hardground.

METHODS

Field Methods. Flat-pebble conglomerate beds were examined at ten different sites including roadcuts and outcrops. Field work included observations, measurements, and descriptions of flat-pebble conglomerate and surrounding beds, collecting samples of various forms of the conglomerate, and taking photographs to illustrate certain features.

Laboratory Methods. Acetate peels and thin sections were made from samples collected in the field.

FIELD OBSERVATIONS

Flat-pebble conglomerate is preserved in beds ranging from 4 to 46 cm thick in the Pilgrim Limestone and 7 to 58 cm thick in the Snowy Range Formation. The pebble clasts are rounded to sub-rounded, sometimes having a globular appearance, and are characteristically flat. The size of the pebble clasts can range drastically within a single bed, but usually they measure a few centimeters in length when viewed in cross section. The smaller pebbles are only a couple millimeters long while the largest pebbles are more than 15 cm long, with the longest clast recorded as 29 cm long. The density of pebbles in the conglomerate varies from sparse to densely packed. Their

DIAGENETIC HISTORIES

The cements that form within limestones are a product of specific environmental zones: saltwater or freshwater, vadose or phreatic. A signature of the phreatic zone, where all pores are saturated with water, is a complete filling of all available space with cements. The Meagher and the Pilgrim both exhibit this texture; all grain surfaces and pores contain calcspar. Blocky, coarse, or equant calcspar is precipitated in the freshwater zone. My limestones contain nothing but this type of cement. Therefore, the Meagher and the Pilgrim were cemented primarily in the freshwater phreatic zone. This area is complex and can be further subdivided depending on depth and saturation with calcium carbonate (Longman, 1980). The Pilgrim exhibits characteristics of the active circulation zone, where calcite forms rapidly into a dense, interlocking mass which coarsens towards the center of pores.

The extensive dolomitization suggests a period of deep burial which allowed the formation of large rhombs. Deep burial would also have created the many pressure solution seams and stylolites that run through the rocks. Once these cracks appeared, they allowed dolomitizing fluid to work its way deep into the rock and spread in all directions. Evidence of burial also come from the cathodoluminescence of the rock. As a rock enters increasingly more reducing environments, ferrous iron begins to act as a luminescence quencher, and gradually calcite grows less and less luminescent (Machel et al., 1991). Rocks from the Meagher have bright orange color, which means they were shallowly buried in mildly reducing environments where manganese acted as a luminescence activator. Anhedral calcspar that has dull luminescence formed during periods of deeper burial and more reducing conditions. The rocks of the Pilgrim have dark luminescence, which shows that they were buried quickly and the manganese could not activate.

CONCLUSIONS

Meagher Limestone. The Meagher was deposited in a stable, calm, low-energy environment such as the shallow subtidal or lagoonal zone. Evidence for this comes from the grains and texture of the rock. Oncoids found in the Meagher form by the growth of filamentous cyanobacteria around a nucleus, an activity that takes place in a low-energy environment. The Meagher has been heavily bioturbated by burrowing animals; their traces show as holes and passages in the matrix, and have been filled with calcspar. Bioturbation is common in areas of low energy where the substrate remains stable. The Meagher was cemented within the freshwater phreatic zone, and this is shown by the abundance of blocky calcspar that has covered every available surface. A period of deeper burial is indicated by a number of stylolites and pressure solution seams, which have allowed extensive dolomitization of the rock. Evidence for burial also comes from the cathodoluminescence of the rock, where bright orange is mixed with dull brown, showing progress through different burial depths.

Pilgrim Limestone. The Pilgrim was deposited in an active, high-energy environment, such as an ooid shoal that lay within the intertidal zone. Ooids form easily in this area because the constant wave motion lets aragonite precipitate evenly and concentrically around a nucleus. The smashed-up, fragmented bioclasts also attest to the energy of the water within this zone. Flat-pebble conglomerate is formed by intense storm action ripping up pieces of rock, reshaping, and redepositing them. The wide variety of quartz grains indicates the presence of a nearby continent and fluvial transport of siliciclastic sediments. The Pilgrim was cemented in the freshwater phreatic zone, which is shown by the isopachus, blocky calcite spar. The Pilgrim was buried deeply; evidence for this comes from the dull, dark cathodo- luminescence of the rock.

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orientation is usually close to horizontal but it is not uncommon to see haphazard or imbricated orientations. Pebbles are generally fine-grained in a coarser-grained matrix. Both pebbles and their matrices are calcitic. The colors of pebbles are generally shades of gray or brown and sometimes yellow, orange, or red. The pebbles may be of a lighter color than their matrix or vice versa.

Beds surrounding flat-pebble conglomerate in the Pilgrim Limestone are composed of massive oolite and/or thinly bedded fine-grained limestone alternating with layers of shale. Beds surrounding flat-pebble conglomerate in the Snowy Range are composed of massive, fine-grained, somewhat calcareous (possibly dolomite or carbonate but similar to siltstone with a high percentage of clastic material) orangish brown to greenish gray limestone that breaks along some bedding planes. Both the Pilgrim and the Snowy Range contain beds with light gray patches a few centimeters long and 1-2 cm thick in cross section which are believed to represent calcareous nodules. The patches do not have definitive boundaries; they are similar in texture to the surrounding fine-grained matrix and they stand out only because they have a different color shade and are more calcareous. Some areas show layers of such nodules strung together in a massive fine-grained bed such that they make up light gray thin beds within the greater bed.

When the upper surfaces of flat-pebble conglomerate beds are visible, they reveal several interesting features. Sometimes the upper surface is paved with pebbles to render a cobbled texture, while at other times it is planed smooth and the pebbles have been truncated. Ripple marks were occasionally observed in a fine-grained siltstone that coated the upper surface of the conglomerate. On the top surfaces of conglomerate beds in the Snowy Range Formation, it was not unusual to encounter sparse eocrinoid encrusters or a dense debris layer of fossilized trilobite and eocrinoid skeletal fragments.

PETROGRAPHIC OBSERVATIONS

Examination of acetate peels and thin sections made from flat-pebble conglomerate samples collected from the field have provided further information about the nature of the matrix and grains. The pebble clasts are primarily micrite and the matrix is composed of sparry calcite. Both the pebbles and the matrix include peloids, ooids, and abundant skeletal fragments from trilobites and eocrinoids. Syntaxial calcite cement is evident in the pore spaces between grains.

DISCUSSION AND INTERPRETATION

There are three hypotheses for the origin of the flat-pebble clasts which make up flat-pebble conglomerate. The first possible mechanism by which flat pebbles formed was from filled and cemented burrows (Figure 1). Some of the more globular-shaped pebbles resemble burrow casts. When a burrow was formed by an organism, it was often lined with an organic coating which separated the burrow from the surrounding loosely packed coarser-grained substrate. Fluids moved through the burrow systems with higher porosity faster than the surrounding sediments. The burrows acted as molds which were filled in with micritic material and then preferentially cemented to form a carbonate nodule. It is possible that sulfate reduction played a role in the cementation of the filled burrow. Sulfate reduction is a bacterial process that removes sulfate by reducing organic material in the sediment and increases the relative concentration of bicarbonate in the sediment (Tucker & Wright, 1990).

The second means by which flat pebbles may have formed is as early diagenetic concretions (Figure 2). This idea would explain why most pebble clasts are so rounded (as opposed to hardground rip-up clasts which would be more angular). Concretions form when calcite precipitates around a nucleus. For example, an eocrinoid ossicle skeletal fragment may act as a calcite nucleus around which syntaxial, isopachous, high-Mg cement can precipitate. Concretions can grow to be wide/flat rather than spherical/egg-shaped when they begin growing within permeable layers of sediment and then reach a less permeable layer, causing them to continue growing laterally only. The resulting concretion would hence have a flat appearance. Concretions that grow in laminated sediments would preserve the laminations as they are cemented. This explains why some flat pebbles exhibit laminations.

The third possible explanation of the origin of flat pebbles involves eroded flat-pebble conglomerate clasts and pre-existing hardgrounds (Figure 3). One of the flat-pebble conglomerate samples collected clearly exhibits a composite pebble composed of flat-pebble conglomerate material. The pebble originated from pre-existing flat-pebble conglomerate which was eroded into "rip-up" clasts during a high-energy event such as a storm and then rounded by wave action. It is likely that non-flat-pebble conglomerate hardgrounds could have also been eroded in the same manner to form flat angular clasts that were later rounded.

There are two stages which describe the origin of a flat-pebble conglomerate bed. Wilson et al. (1992) studied Early Ordovician hardgrounds contained in the Kanosh Shale. Their model, involving winnowed cobble lags, rapid sea-floor calcite precipitation, and encrustation, offers a probable explanation that can be applied to the flat-pebble conglomerates of the Clarks Fork region. The first stage of flat-pebble conglomerate hardground development is winnowed cobble lags (Figure 4). Wilson et al. (1992) contend that intraformational conglomerate hardgrounds in the Kanosh Shale formed from cobble lag deposits of diagenetic carbonate nodules that were exhumed when high energy storm currents winnowed away the fine-grained sediments. The accumulation and orientation of pebbles in the flat-pebble conglomerates of the Clarks Fork provides evidence for similar processes; they exhibit patterns that are typical of high energy storm events such as haphazard or imbricated orientation of grain supported flat pebbles in cobble lag deposits.

The second stage of flat-pebble conglomerate formation is rapid lithification and cementation of flat pebbles into a conglomerate hardground. Many geologists (Brett et al., 1983; Hudson and Coleman, 1978; Kazmierczak and Goldring, 1978; Sepkoski, 1982; Wilson et al., 1992) agree that early cementation played a key role in the formation of flat-pebble conglomerates, yet there is much controversy as to the conditions that enabled the process to occur. "Hardgrounds are synsedimentarily lithified carbonate sea-floors that became hardened *in situ* by the precipitation of a carbonate cement in the primary pore spaces... Essentially, sedimentation and cementation occur in the same submarine environment, giving rise to a hard sea-floor which may then be colonized by a fauna and flora that show adaptations to hard-substrate dwelling" (Wilson & Palmer, 1992, p. 3). It is probable that the synsedimentary submarine cementation of the carbonate sediments and flat-pebble conglomerates of the Clarks Fork region took place in the same environment in which they were originally deposited. Using the term "hardground" to describe the flat-pebble conglomerates of the Clarks Fork region refers to "the consequence of the precipitation of cement within a soft sediment on the sea-floor, contemporaneously with or soon after deposition" (Wilson & Palmer, 1992, p. 3). Synsedimentary cement precipitation often occurs during sedimentary hiatuses. The presence of hardgrounds is evidence of a period of rapid lithification and cementation during a pause in sedimentation (Kennedy and Garrison, 1975; Brett et al., 1983). During this pause, an ommision surface is formed and then either the surface of the hardground or the entire hardground itself may be eroded. Erosion of the Clarks Fork flat-pebble conglomerate hardgrounds is evidenced by truncated pebbles along scoured upper surfaces and the formation of intraformational conglomerates when the hardground is fragmented into flat pebble-sized clasts. Evidence for rapid cementation in the Clarks Fork flat-pebble conglomerates includes syntaxial calcite cement surrounding pebbles, truncated pebbles along upper surfaces of beds, and encrusting organisms such as eocrinoids which inhabited the cobbled upper surface of beds. Brett et al. (1983) also referred to the Clarks Fork flat-pebble conglomerates as hardgrounds based on similar observations.

Rapid cementation of the flat-pebble cobble lag into a conglomerate hardground was possible due to the marine chemical conditions of calcite seas at the time. Tucker and Wright (1990) point out a correlation between the mineralogy of marine carbonate precipitates through the Phanerozoic and global sea levels. They explain that "the temporal variation in carbonate precipitates through the Phanerozoic is the consequence of subtle changes in the composition of ocean water" (Tucker and Wright, 1990, p. 409). During the Upper Cambrian, high levels of pCO_2 and low levels of Mg caused the oceans to be supersaturated with calcite. The sea water percolated down into and through the flat-pebble cobble lag, causing the precipitation of calcite cement in the primary pore spaces. The calcite cement rapidly cemented the flat-pebbles and their coarse-grained matrix into a conglomerate hardground.

CONCLUSIONS

Flat-pebble conglomerates are composed of flat pebbles which were formed by three possible mechanisms: 1) cemented burrow fillings, 2) early diagenetic concretions, and/or 3) eroded hardground material including pre-existing flat-pebble conglomerate clasts. Flat-pebble conglomerate began as winnowed cobble lag storm deposits which were rapidly lithified and cemented due to the calcite sea conditions at the time. Precipitation of calcite cemented the pebbles and their matrix into a hardground which was then encrusted by eocrinoids.

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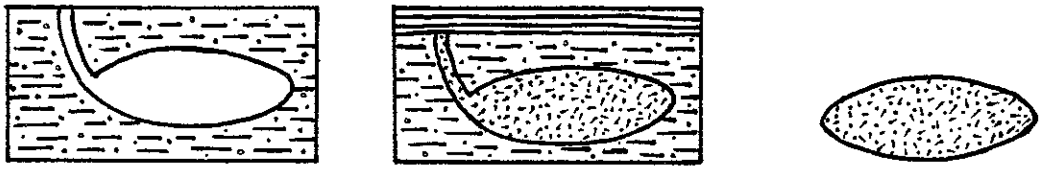
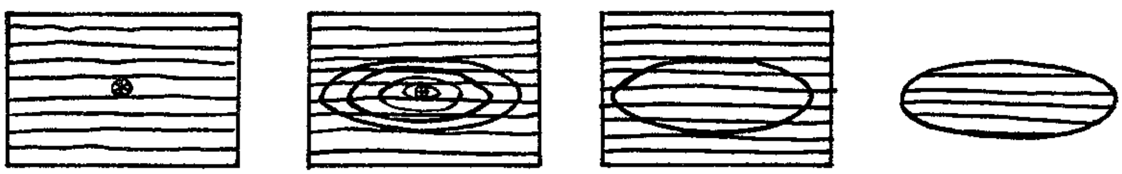
Figure 1. Filled and cemented burrows: (a) An organism creates a burrow in the sea floor which is (b) filled in with micritic sediment and preferentially cemented to form (c) a carbonate nodule.



(a) (b) (c)

Figure 2. Early diagenetic concretions: (a) A grain or skeletal fragment in the sea floor acts as a nucleus around which (b and c) syntaxial, isopachous, high-Mg cement can precipitate to form (c) a carbonate nodule.



(a) (b) (c) (d)

Figure 3. Eroded flat-pebble conglomerate clasts: (a) A flat-pebble conglomerate hardground is (b) eroded into clasts and (c) rounded by wave action. It is likely that non-flat-pebble conglomerate hardgrounds could have been eroded in the same manner.

(a) (b) (c)

Figure 4. Winnowed cobble lags: (a) Carbonate nodules in the sea floor sediments were (b) exhumed by high energy storm currents which winnowed away the fine-grained sediments resulting in (c) an accumulation of flat pebbles in a cobble lag.

(a) (b) (c)

Regional Fracture Trends in Clarks Fork Valley, Park County, Wyoming

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INTRODUCTION AND TECTONIC SETTING

Clarks Fork Valley lies along the southern boundary of the Beartooth Range, where the Clarks Fork of the Yellowstone River is entrenched into Precambrian granites and gneiss. The NW-SE trending valley approximately parallels the contact between the Archean basement rock and overlying sedimentary units. North of Clarks Fork Canyon, the eastern front of the Beartooth Uplift is bounded by a series of N-S trending Laramide normal faults and a thrust dipping to the west. Just south of the valley, the Heart Mountain Thrust has displaced most of the Ordovician and younger Paleozoic cover and the Absaroka Volcanics. The rocks underlying the valley are broken into numerous blocks by local steeply dipping Laramide faults and have undergone multiple deformational events. Both the Archean bedrock and overlying sedimentary units are complexly fractured.

Several studies of fracture trends have been conducted in areas surrounding the Clarks Fork Valley, particularly in the Beartooth Range to the north (Spencer, 1959 and Wise, 1964) and the Bighorn Mountains to the east (Hudson, 1969, and Wise, 1964). In addition, Wise (1982) described prominent fracture trends in the Archean basement and overlying Cambrian Flathead sandstone in the Sunlight Creek-Dead Indian Creek region. Together these studies provide a regional pattern of fracture development for the central Rocky Mountains and also suggest a Precambrian control of later Laramide structural features in the area.

The aims of this study are to determine the regional fracture pattern in the Clarks Fork Valley, to compare this pattern to that of the Beartooth Range to the north, to compare the trends in the Archean bedrock with those in overlying Cambrian sedimentary units (Flathead Sandstone, Meagher Limestone, and Pilgrim Limestone), and to relate these observations to the regional tectonic pattern.

DATA COLLECTION

Ground Measurements. Over 4000 field measurements were gathered from 64 stations along the Clarks Fork Valley and southern Beartooth Mountains (Figure 1). Measurement locations were chosen to provide as detailed coverage of the region as time and accessibility allowed. Forty-eight localities of Archean granite and gneiss, 6 localities of Flathead Sandstone, 5 localities of Meagher Limestone, and 5 localities of Pilgrim Limestone were sampled Starting at an arbitrary point on the outcrop, strike and dip measurements were taken of each fracture in the vicinity, excluding those which were exceptionally small and/or irregular. The number of measurements taken at each locality varied, with a greater number being taken at outcrops with systematic and or prominent fracture trends. Nearly all dips measured were vertical or near vertical.. In addition, related structural features, such as dikes, faults, slickensided surfaces, and en echelon shears were noted where observed.

Aerial Photograph Lineaments. One thousand three hundred and fifty-three lineament strike measurements were taken from 1:24 000 aerial photographs of the study area. Lineaments were traced onto transparent acetate. The acetate was then re-aligned to north-south on adjacent photos to minimize distortion on the photo's boundaries.

Structural Features. Major fault strikes were measured from 1:62,500 USGS Deep Lake, Pat O'Hara, and Beartooth Butte, geological maps (Pierce 1965, Pierce and Nelson 1968, Pierce and Nelson 1971).

DATA ANALYSIS

Ground measurements for each individual location were plotted on the lower hemisphere of a 10 cm equal-area Schmidt net using the computer program Stereo for Macintosh. Since all dips measured were near vertical, the fractures appeared only along the perimeter of the Schmidt nets. To make it easier to compare fracture orientations between locations, dip measurements were discarded and strike measurements were replotted as rose diagrams using the computer program Rosy for Macintosh.

The ground measurements for the entire valley were subdivided into 11 geographic / tectonic sections (A-K, Figure 1). The boundaries for each section were chosen to separate areas between major fault zones where possible. The aerial photograph lineaments were divided into the same subdivisions for comparison.

Rose diagrams were plotted for the valley as a whole, subdivisions of the valley, the lineament subdivisions, the major faults in the area, and dike trends. Rose plots were also made separately for each lithology. The rose plots were used to make comparisons between areas, between lithologies, across structural features, and with regional trends in the Beartooth Range and Bighorn Mountains.