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Flat-pebble conglomerate: its multiple origins and relationship to metre-scale depositional cycles

PAUL M. MYROW*, LAUREN TICE*, BONNY ARCHULETA†, BRYN CLARK‡, JOHN F. TAYLOR§ and ROBERT L. RIPPERDAN¶

*Department of Geology, The Colorado College, 14 E. Cache La Poudre, Colorado Springs, CO 80903, USA (E-mail: pmyrow@coloradocollege.edu)

†Department of Geology, Washington State University, Pullman, WA 99164, USA

‡Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071-3006, USA

§Department of Geosciences, Indiana University of Pennsylvania, Indiana, PA 15705, USA

¶Department of Earth and Atmospheric Sciences, Saint Louis University, St Louis, MO, USA

ABSTRACT

Carbonate flat-pebble conglomerate is an important component of Precambrian to lower Palaeozoic strata, but its origins remain enigmatic. The Upper Cambrian to Lower Ordovician strata of the Snowy Range Formation in northern Wyoming and southern Montana contain abundant flat-pebble conglomerate beds in shallow-water cyclic and non-cyclic strata. Several origins of flat-pebble conglomerate are inferred for these strata. In one case, all stages of development of flat-pebble conglomerate are captured within storm-dominated shoreface deposits of hummocky cross-stratified (HCS) fine carbonate grainstone. A variety of synsedimentary deformation structures records the transition from mildly deformed *in situ* stratification to buckled beds of partially disarticulated bedding to fully developed flat-pebble conglomerate. These features resulted from failure of a shoreface and subsequent brittle and ductile deformation of compacted to early cemented deposits. Failure was induced by either storm or seismic waves, and many beds failed along discrete slide scar surfaces. Centimetre-scale laminae within thick amalgamated HCS beds were planes of weakness that led to the development of platy clasts within partly disarticulated and rotated bedding of the buckled beds. In some cases, buckled masses accelerated downslope until they exceeded their internal friction, completely disarticulated into clasts and transformed into a mass flow of individual cm- to dm-scale clasts. This transition was accompanied by the addition of sand-sized echinoderm-rich debris from local sources, which slightly lowered friction by reducing clast–clast interactions. The resulting dominantly horizontal clast orientations suggest transport by dense, viscous flow dominated by laminar shear. These flows generally came to rest on the lower shoreface, although in some cases they continued a limited distance beyond fairweather wave base and were interbedded with shale and grainstone beds. The clasts in these beds show no evidence of extensive reworking (i.e. not well rounded) or condensation (i.e. no rinds or coatings). A second type of flat-pebble conglomerate bed occurs at the top of upward-coarsening, metre-scale cycles. The flat-pebble conglomerate beds cap these shoaling cycles and represent either lowstand deposits or, in some cases, may represent transgressive lags. The clasts are well rounded, display borings and have iron-rich coatings. The matrix to these beds locally includes glauconite. These beds were considerably reworked and represent condensed deposits. Thrombolites occur above the flat-pebble beds and record microbial growth before initial transgression at the cycle boundaries. A third type of flat-pebble conglomerate bed occurs within unusual metre-scale, shale-dominated, asymmetric, subaqueous cycles in Shoshone Canyon, Wyoming. Flat-pebble beds in these cycles consist solely of clasts of carbonate nodules identical to those that are *in situ* within underlying shale beds. These deeper water cycles can be interpreted as either upward-shoaling or -deepening cycles. The flat-pebble conglomerate beds record winnowing and reworking of shale and carbonate nodules to lags, during either lowstand or the first stages of transgression.

Keywords Cambrian, depositional cycles, flat-pebble conglomerate, Montana, Snowy Range Formation, Wyoming.

INTRODUCTION

Carbonate intraclastic rudstone to floatstone (Embry & Klovan, 1971), herein referred to collectively as flat-pebble conglomerate, is abundant within Precambrian to lower Palaeozoic carbonate-rich successions. There are several published accounts of modern examples of vertically imbricated flat pebbles (Dionne, 1971; Sanderson & Donovan, 1974) and shells (Greensmith & Tucker, 1968, 1969; Sanderson & Donovan, 1974). Although some ancient flat-pebble conglomerate is well sorted and shows vertical packing of clasts (e.g. Roehl, 1967), most is poorly sorted and tends to have relatively flat-lying clast orientations compared with modern examples (McKee, 1945; Jansa & Fischbuch, 1974; Kazmierczak & Goldring, 1978; Chow, 1986; Myrow *et al.*, 2003). Numerous authors have hypothesized about its origin and the reason(s) for its stratigraphic restriction to older strata (e.g. Sepkoski, 1982). Although petrographic and macroscopic textural features of flat-pebble conglomerate have been used to construct plausible mechanisms for its origin (e.g. combined flows: Mount & Kidder, 1993), the highly variable depositional processes that created these beds have remained elusive. This is due, in part, to the fact that transitional development of these beds has not been documented from ancient deposits. It also results from the paucity of flat-pebble conglomerate in modern deposits, and thus a lack of uniformitarian models. This reflects different geotechnical and diagenetic characteristics of Precambrian to early Palaeozoic sediment, compared with that of the rest of the Phanerozoic. Such conditions, which included the absence of abundant and deep-burrowing organisms that churned marine sediment after the Ordovician radiation (Sepkoski, 1982; Droser & Bottjer, 1989), imparted unusual geotechnical properties to the sediment at that time (Bottjer *et al.*, 2000). This study examines the sedimentological and stratigraphic aspects of flat-pebble conglomerate beds in the uppermost Cambrian (upper Sunwaptan Stage and lower Skullrockian Stage) in the northern Rocky Mountains and demonstrates four origins of these deposits and their depositional mechanics.

The Middle Cambrian to Lower Ordovician stratigraphy of Montana and Wyoming has been studied for more than 100 years and given a plethora of lithostratigraphic names (Peale, 1890, 1893; Blackwelder, 1918; Deiss, 1936, 1938; Dorf & Lochman, 1940; Mills, 1956; Goodwin, 1961; Martin *et al.*, 1980). Two of the more frequently applied formation names for the uppermost Cambrian and basal Ordovician strata in this succession are the Gallatin Formation and Snowy Range Formation. The latter term is used in this paper because several of the key sections are within or near the type areas of that formation and its members as they were thoroughly characterized by Grant (1965). These strata were the subject of pioneering biostratigraphic work, regional mapping studies and examined as part of exploration efforts for oil and gas, but few modern process-oriented sedimentological studies have been undertaken on these units. The basal Middle Cambrian transgressive Flathead Sandstone is overlain by a succession of shale- and limestone-rich units that lie below a prominent Middle Ordovician unconformity at the base of the Bighorn Formation. The Upper Sunwaptan to Skullrockian Snowy Range Formation provides a relatively complete succession of trilobite and conodont zones that span the Cambrian–Ordovician boundary interval (Grant, 1965). It contains lithofacies typical of the inner detrital belt of western North America (Lochman-Balk, 1971), namely shale, grainstone and flat-pebble conglomerate. Time-equivalent strata in central and western Colorado contain similar lithologies and represent a southern extension of the same inner detrital belt (Myrow *et al.*, 2003). The shoreline of this belt is not easily constrained, given recent detailed stratigraphic studies indicating that many tectonic elements of the Transcontinental Arch may not have developed until the Early Ordovician (Runkel, 1994; Myrow *et al.*, 2003). Thus, shale-rich deposits of the inner detrital belt may have covered much of the Rocky Mountain region and other areas of central Laurentia during deposition of the Snowy Range Formation in the latest Cambrian.

Exposures of the Snowy Range Formation examined in this study are located across northern Wyoming and south-central Montana in the Bighorn, Absaroka, Big Snowy and Pryor Mountains (Fig. 1). Lithofacies of the Snowy Range Formation are described and interpreted below to provide a stratigraphic and sedimentological framework for the analysis of depositional mechanics of these flat-pebble conglomerate beds.

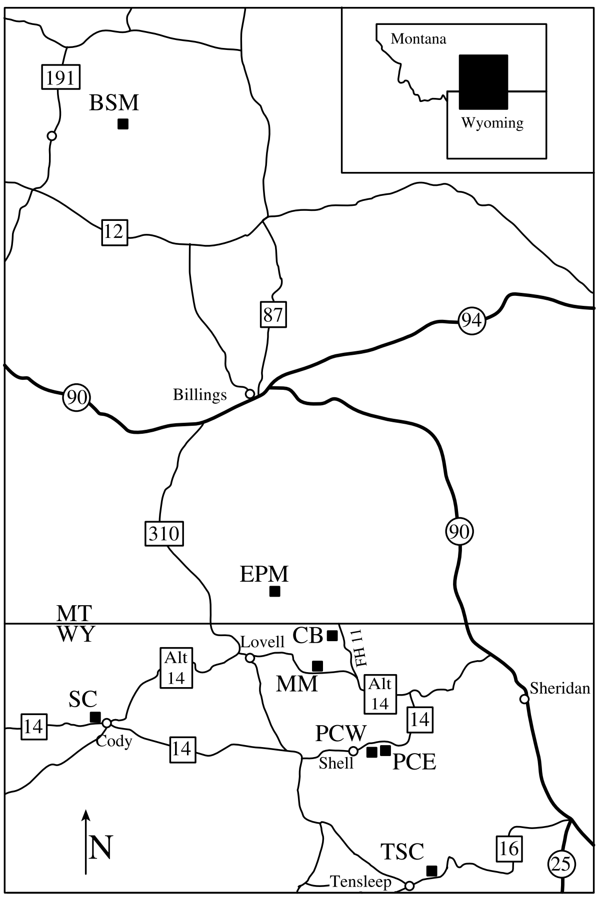


Fig. 1. Location map of field sites in Wyoming and Montana. BSM, Careless Creek, Big Snowy Mountains; CB, Cookstove Basin; EPM, East Pryor Mountain; MM, Medicine Mountain; PCE, East Post Creek; PCW, West Post Creek; SPW, Sheridan Pass; SCW, Shoshone Canyon; TSC, Tensleep Canyon.

FACIES DESCRIPTIONS

Shale facies

This facies consists of dark grey to greenish-grey shale. Bed thicknesses range from millimetre scale to 60 cm and average 7 cm thick. The shale is commonly interbedded with grainstone and flat-pebble conglomerate beds (Fig. 2A and B). At Shoshone Canyon (Fig. 1), this facies contains rounded carbonate nodules that range in shape from irregular spheres to flattened discs in shale-dominated cycles.

Grainstone facies

This facies is composed of grey to reddish-grey weathering grainstone. Fine-grained, well-sorted grainstone is most abundant, although beds of coarse-grained, bioclast-rich grainstone are also common. Beds range from ≤ 1 cm to 130 cm thick, but average ≈ 4 cm. Petrographic study reveals that the fine grainstone is well laminated, with considerable variability in composition between laminae. It consists of fine sand-sized bioclastic grains and 10–30% peloids. Siliciclastic-rich laminae contain up to 45% silt-sized quartz and feldspar grains (average 20–25%) and 15% glauconite grains, whereas carbonate-rich laminae average $\approx 5\%$ quartz/feldspar and 1–2% glauconite. The quartz and feldspar silt grains are variably rounded, but most are subangular to angular. Coarser grainstone (coarse to very coarse grains) generally contains abundant brachiopod and echinoderm fragments and less quartz/feldspar (generally $< 5\%$) and glauconite ($< 2\%$). Both fine and coarse grainstones generally contain fine-grained syntaxial sparry cement.

Grainstone beds are commonly interlayered with shale beds of subequal thickness (Fig. 2A and B). Most grainstone beds are tabular and laterally extensive, although some pinch-and-swell and others are discontinuous. Grainstone locally forms isolated gutter casts up to several centimetres thick within shale beds. Very thin grainstone lenses also form isolated starved symmetrical ripples within shale beds (Fig. 2A). Sedimentary structures include wave- and current-generated, ripple-scale cross-stratification, hummocky cross-stratification (HCS) and parallel lamination (Fig. 2B).

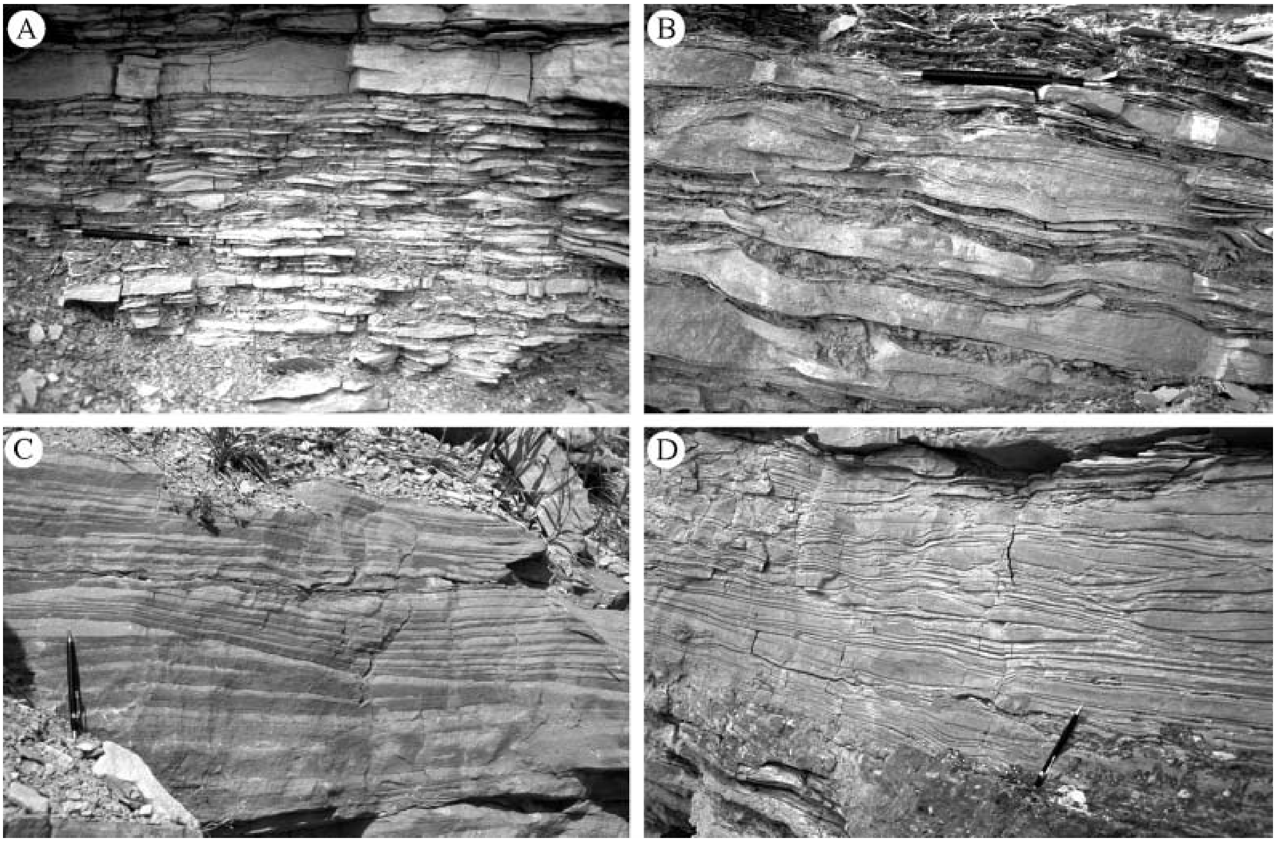


Fig. 2. (A) Very thin-bedded grainstone and shale. Note abundant starved symmetrical ripples. (B) Thin-bedded grainstone and shale. Grainstone beds are highly irregular in thickness and show wave-ripple lamination, small-scale HCS and parallel lamination. (C) Amalgamated HCS grainstone. Note low-angle truncation surfaces and cm-scale breaks in lamination. (D) Unusual pinch-and-swell HCS lamination within amalgamated grainstone. Pencil is 14 cm long.

Amalgamated hummocky cross-stratified and parallel-laminated grainstone beds form units up to 1·5 m thick. There are two types of HCS: (1) a typical style with 1 cm breaks that define tabular laminae (Fig. 2C); and (2) an unusual style with uneven, pinch-and-swell lamination (Fig. 2D).

Flat-pebble conglomerate facies

This facies consists of 1–75 cm thick beds of grey, green and brown weathering flat-pebble conglomerate with variable amounts of grainstone matrix. This facies has a diverse set of characteristics that depend in part on the stratigraphic context. Fabrics range from clast to matrix supported (Fig. 3A and B) and grade continuously into grainstone beds with scattered flat pebbles. Bed geometries range from tabular to pinch-and-swell to lenticular, and bed contacts vary from relatively planar to highly irregular. Flat-pebble clasts are tabular, and most are composed of very fine-grained grainstone identical in composition and texture to that of the fine-grained grainstone facies. Matrix-rich beds generally contain much smaller, mostly pebble-sized clasts only 2–20 mm long. Clast-rich beds contain larger, flat, ellipsoidal pebbles to cobbles 30–150 mm long (Fig. 3C). Most flat-pebble clasts are 5–20 mm thick in cross-section (average $\approx$10 mm). Clasts at the tops of some beds contain abundant borings (Fig. 3E). The degree of rounding is highly variable from highly rounded to angular clasts that in some cases show partial brittle deformation.

Petrographically, most clasts are identical in character to the grainstone facies. They are laminated and generally contain between 10% and 35% quartz and feldspar silt and up to 5% glauconite grains. The matrix of the conglomerate varies in grain size and composition, but it is coarser than that found within clasts on average (Fig. 3C), has more abundant brachiopod and echinoderm fragments and contains less quartz/feldspar (5–10% average). The glauconite and

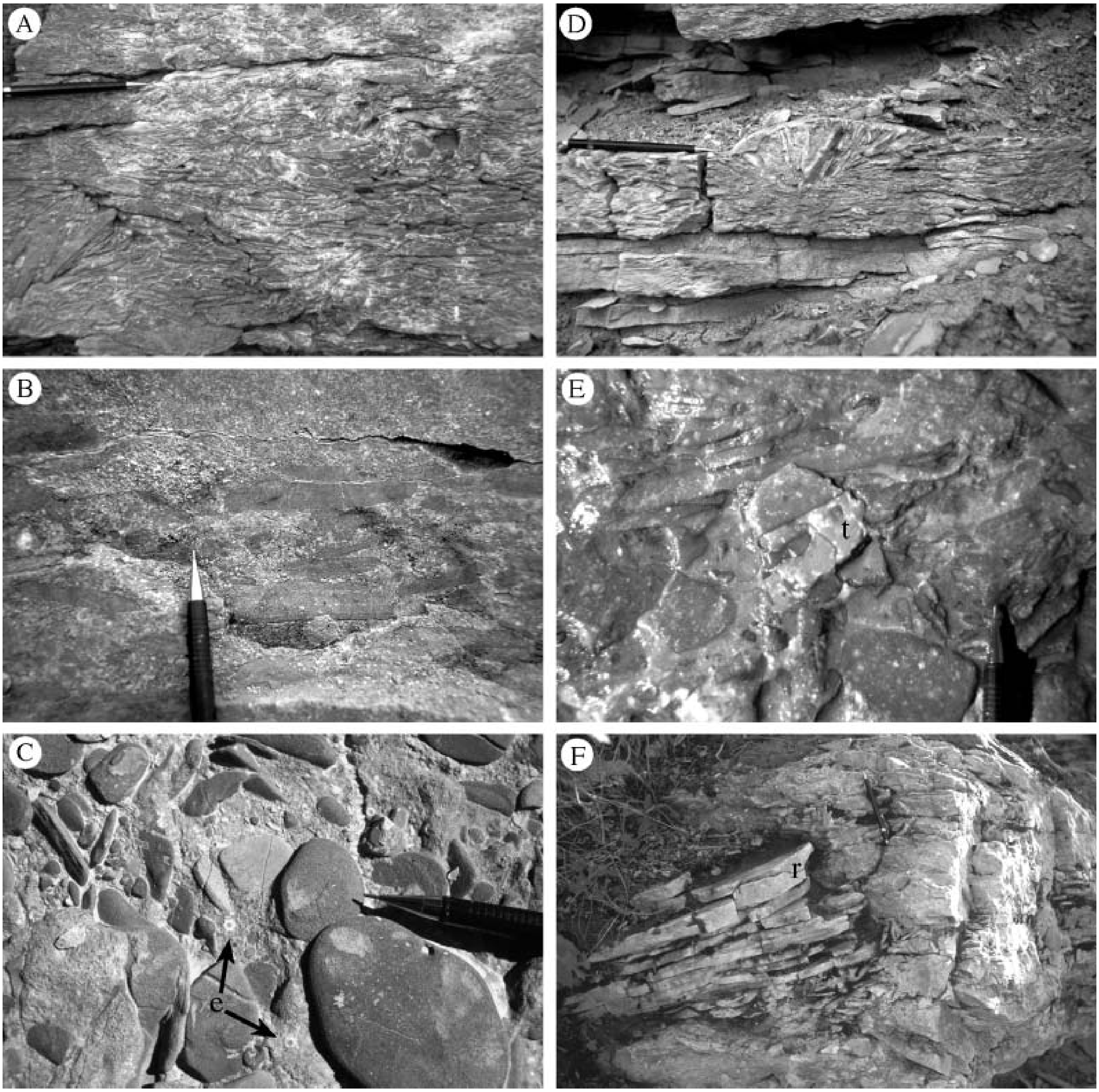


Fig. 3. (A) Clast-supported flat-pebble conglomerate. Note dominantly horizontal orientations of flat pebbles. (B) Close-up of grainstone-supported flat-pebble conglomerate. Matrix consists of coarse echinoderm-rich grainstone. (C) Bedding plane view of flat-pebble conglomerate bed with large rounded flat pebbles. Note large star-shaped echinoderm ossicles (e). (D) Flat-pebble conglomerate bed with dominantly horizontal clast orientations. A large rosette of imbricated clasts extends above the general level of the bed. (E) Top of flat-pebble conglomerate bed with thrombolite matrix (t) between the clasts. Note the circular borings on many of the clasts. (F) Large (55 × 20 cm) raft of laminated grainstone within a flat-pebble conglomerate bed. Pencil is 14 cm long.

peloid content is comparable to that found within clasts. Flat pebbles at the top of some beds are separated by white, thrombolitic boundstone (Fig. 3E).

Intraclasts are variably oriented, but they are subhorizontal in most beds, particularly in beds with higher grainstone matrix content (Fig. 3B). Isolated vertically imbricated rosettes (small fans of clasts) exist both within and on top of beds (Fig. 3D), but these are extremely rare. Many beds contain evidence of amalgamation, such as changes in average clast size, degree of clast support, sorting and grainstone content. Some flat-pebble beds contain large thrombolite clasts up to 24 cm across, and a few flat-pebble beds contain large grainstone blocks up to 60×20 cm across (Fig. 3F). In a few cases, flat-pebble conglomerate beds grade laterally into brittly and ductilely deformed, thickly laminated carbonate grainstone, referred to below as buckled beds.

Thrombolite facies

This facies consists of discrete masses of white, grey and yellow weathering thrombolite boundstone (Fig. 4). Thrombolites range up to 44×95 cm in cross-section. Many weather massively, but some exhibit a characteristic mottled internal

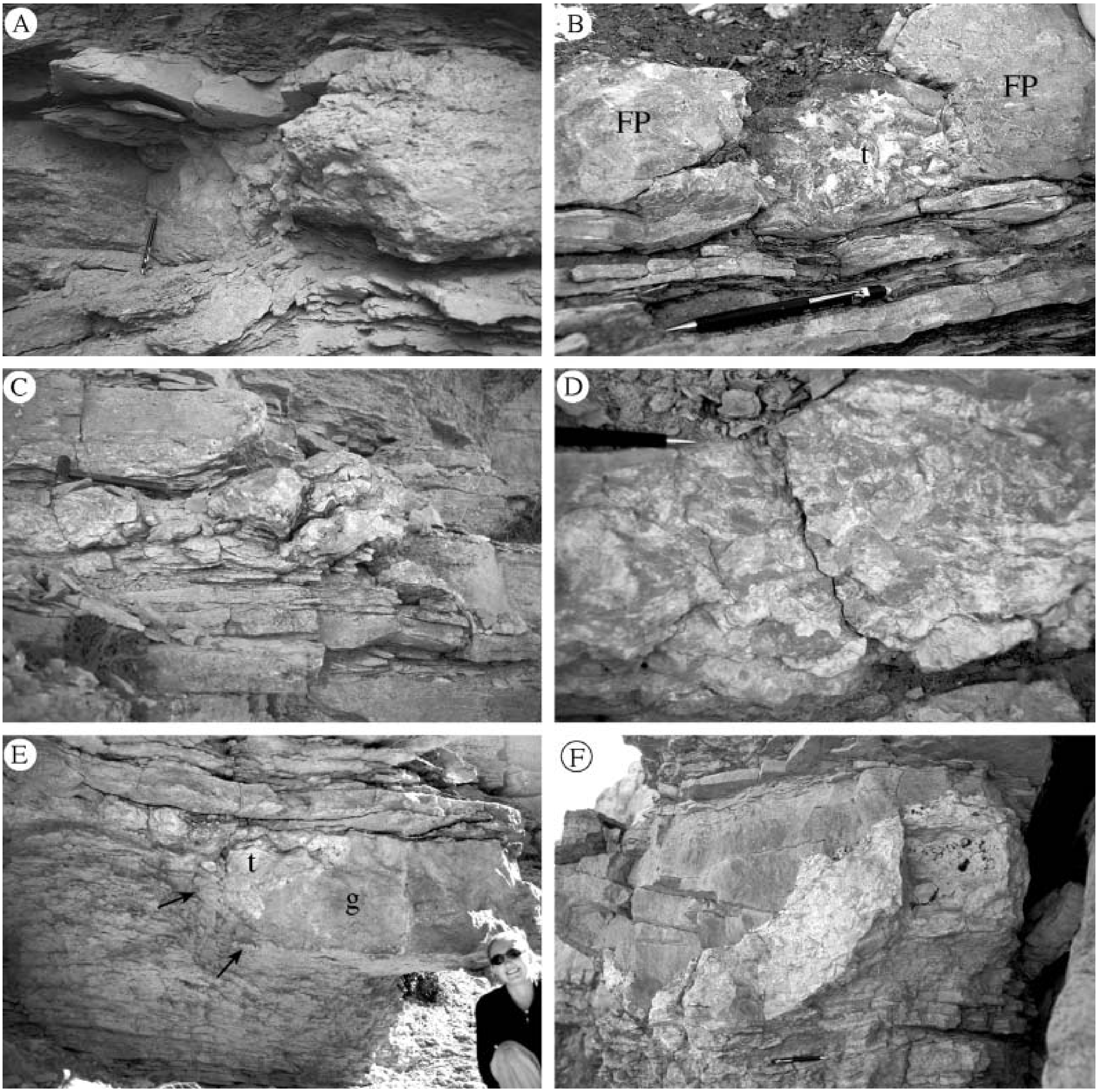


Fig. 4. (A) Thrombolite (to right of pencil) and adjacent flat-pebble bed with local thrombolite matrix. (B) Thrombolite mound (t) with abundant flat pebbles surrounded by flat-pebble conglomerate (FP). This layer is underlain by very thin grainstone and shale beds and overlain by shale. (C) White-weathering thrombolite mound (43 cm thick) among grainstone and minor shale beds. (D) Close-up of thrombolite mound with typical mottled fabric. (E) Channel of grainstone (g) cut into bioturbated carbonate mudstone with overhanging thrombolite mound (t) along the edge of the channel (arrowed). (F) Thick (78 cm) channel fill of cross-bedded grainstone with white-weathering thrombolite along the edge of the ancient channel. Pencil is 14 cm long.

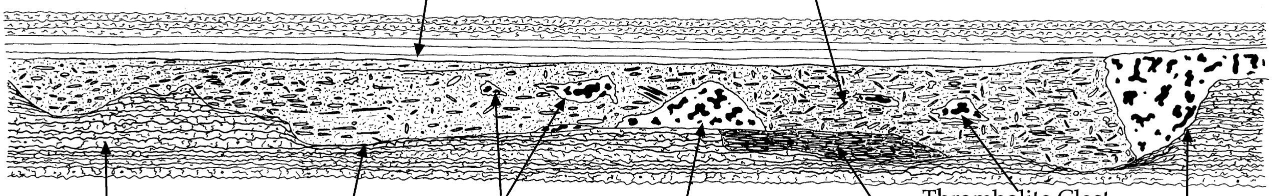


Fig. 5. Channel-fill deposits at 26·0 m in measured section at Cookstove Basin, WY. Note thrombolite mounds along edge of channel. Thrombolites also grew in part on flat-pebble conglomerate fill.

fabric (Fig. 4D). Thrombolites form mounds on top of, and locally within, flat-pebble conglomerate beds (Fig. 4A and B). Thrombolite mounds locally grade upwards from underlying flat-pebble conglomerate beds through a zone of flat pebbles with thrombolitic carbonate matrix. Some thrombolites contain flat pebbles that range from a few scattered clasts to highly abundant (Fig. 4B). Thrombolites rest on the tops of tabular beds but also overlie channel surfaces (Fig. 4E and F and 5), particularly along their steep edges, where they exhibit overhanging geometries (Fig. 4E).

Buckled bed facies

This facies ranges from mildly disturbed, platy, fine-grained grainstone beds to clast-supported flat-pebble conglomerate with relict, partly disarticulated bedding (Fig. 6). Beds of this facies range from 5 cm to 80 cm thick and average about 30 cm thick. Clasts range from 1 to 20 cm in length. The least deformed beds have gentle irregular folds and minor brittle deformation. More intensely deformed beds show abundant breakage of lamination into flat-pebble clasts that exist in domains with fitted fabrics. These domains record rotation and both ductile and brittle deformation of cm-scale grainstone laminae. Although the fabrics may locally resemble rosettes produced by wave reworking of loose clasts, the fabric is much more fitted and simply results from local vertical rotation and fracturing of bedding. The platy clasts and deformed, relatively intact laminae have sharp edges reflecting brittle deformation, although some of both are gently folded (Fig. 6). Isolated clasts have more rounded edges. The resulting fabrics are highly irregular and change laterally over short distances. Buckled beds are intimately interlayered and interfingered with thick HCS grainstone beds (Figs 6A, D and F and 7). These transitions range from subtle and gradational to sharp along truncation surfaces. These surfaces truncate as much as 55 cm of HCS grainstone (Fig. 7). The buckled beds are bounded by highly irregular contacts and thus abruptly thicken and thin laterally due to a combination of mounding at their tops and erosion along their bases (Fig. 7). Hummocky cross-stratified grainstone beds locally onlap buckled beds (Figs 7 and 6F). Thrombolitic boundstone fills the spaces between the clasts at the top of a few buckled beds at East Pryor Mountain, just as it occurs at the top of some non-deformed flat-pebble beds. In several cases, the truncated upturned edges of buckled bedding are encrusted by echinoderm holdfasts up to 1·8 cm in diameter (Fig. 6E). In several localities, buckled beds are laterally transitional into flat-pebble conglomerate beds. Although these transitions are in many cases too poorly exposed to examine thoroughly, several examples are documented below.

Facies associations

Two facies associations are recognized in the Snowy Range Formation. A mixed facies association consists of all the facies described above, namely shale, starved ripples to thin beds of fine grainstone, coarse grainstone, flat-pebble conglomerate beds, buckled beds and thrombolites. Shale content varies but generally ranges from 30% to 60% of these deposits. Most of the Snowy Range (≈ 90%) consists of this mixed facies association. The second, grainstone-rich facies association consists of thick intervals of HCS fine grainstone, buckled beds and flat-pebble conglomerate beds. Shale is notably absent or is less than 5% of this facies association.

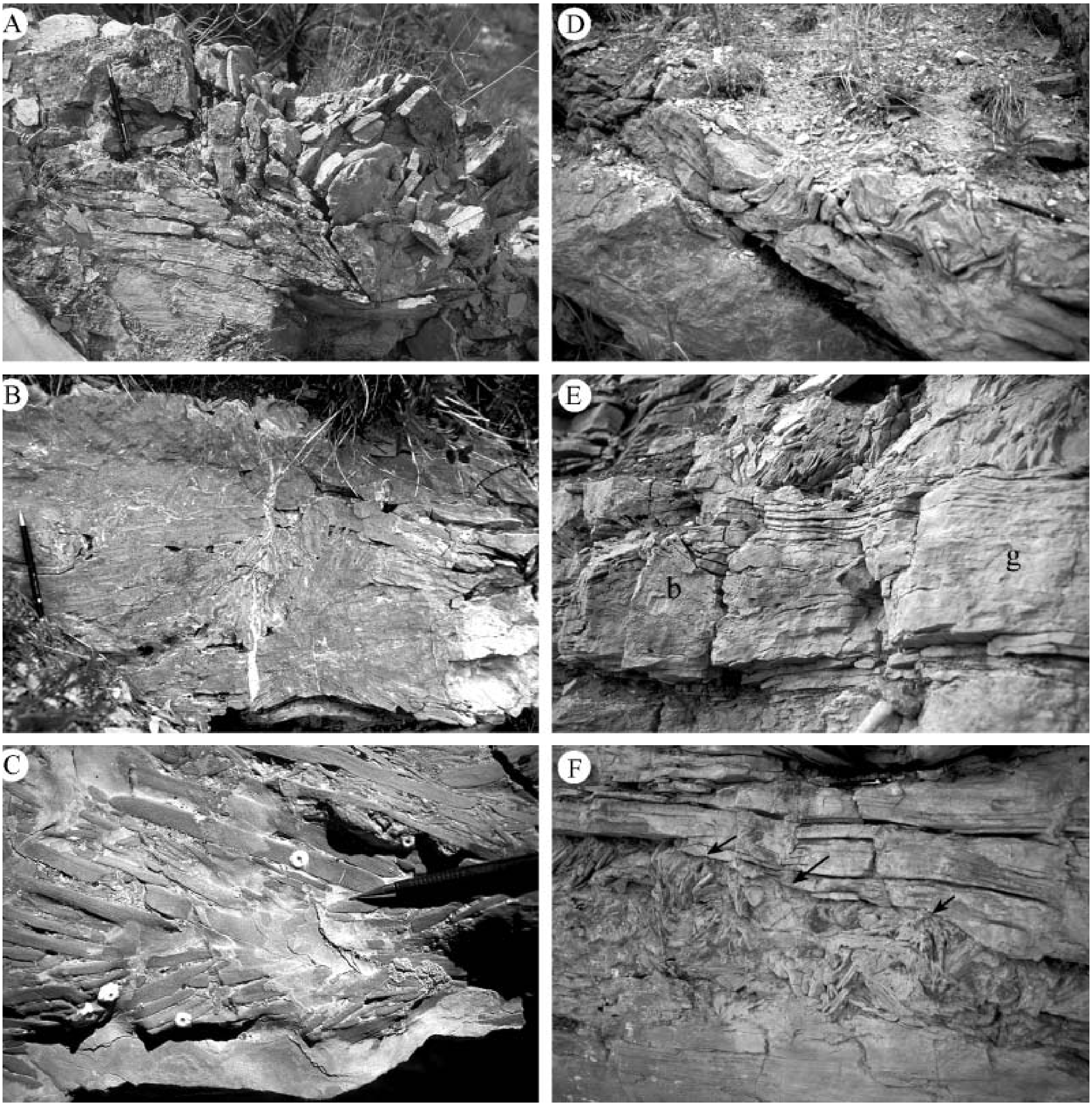


Fig. 6. (A) Buckled bed with irregular base overlying amalgamated HCS grainstone. (B) Buckled bed that is almost transitional to flat-pebble conglomerate bed. Bedding is nearly intact to right of pencil. (C) Bedding plane view of buckled bed with echinoderm holdfasts on upturned and broken grainstone bedding. (D) Buckled bed that overlies a flat-pebble bed and underlies more shaly facies. (E) Transition from parallel-laminated grainstone (g) to buckled grainstone (b). Note highly gradational transition. Hammer for scale. (F) Buckled grainstone within thick unit of amalgamated HCS grainstone (see Fig. 7). Note irregular top and base of buckled unit. Arrows point to onlap of grainstone above the buckled mass. Field of view = 1·4 m. Pencil in other photos is 14 cm long.

PALAEOENVIRONMENTAL INTERPRETATION

The Snowy Range Formation was deposited in an epicratonic setting, within the inner detrital belt of Laurentia (Lochman-Balk, 1971; Sepkoski, 1982). Hence, maximum water depth was probably several tens of metres. The grainstone-rich facies association with thick units of amalgamated HCS grainstone and near absence of shale reflects deposition in a shoreface setting, i.e. above fairweather wave base (cf. Walker, 1984).

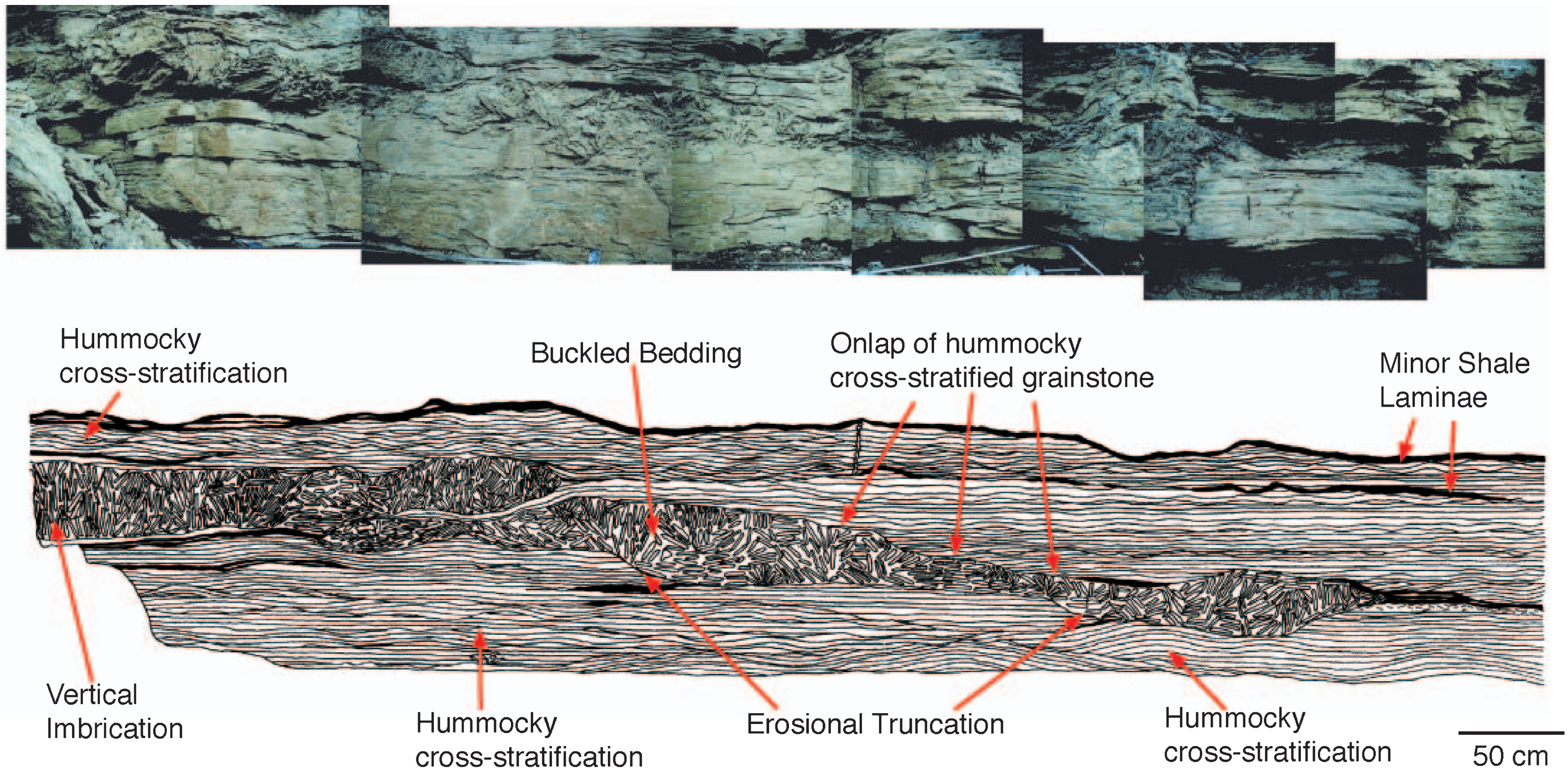


Fig. 7. Photomosaic and corresponding field sketch of amalgamated HCS grainstone and associated buckled beds at Post Creek East locality (11–12 m). Note downcutting at base of buckled bedding (slide surface) and onlap of grainstone above.

Abundant fine-grained HCS grainstone indicates that the shoreface existed in a storm-dominated setting, and parallel lamination indicates that these storm flows reached upper flow regime plane bed conditions. High-resolution stratigraphic correlation of numerous outcrops in Wyoming and Montana is under way, and it appears that shoreface environments may have been patchily distributed in space and time. In other words, large sand bodies might have been scattered throughout the inner detrital belt and, whether or not they were completely emergent, the processes of deposition and geomorphological character of these sand bodies indicate deposition above fairweather wave base in a manner identical to that of a shoreface of a single linear shoreline.

Abundant shale beds in the mixed facies association indicate deposition in a low-energy setting below fairweather wave base. A near total absence of desiccation cracks in these deposits places this facies association in a more seaward palaeoenvironment than that of the shoreface deposits of the grainstone-rich association. Well-sorted, fine-grained grainstone beds were deposited predominantly by storm-generated flows, as indicated by the presence of gutter casts, symmetrical ripples and HCS, features common to tempestites (Kreisa, 1981; Myrow, 1992). Well-sorted, fine-grained carbonate sand was presumably eroded from the shoreface and transported offshore during storms. Interbedded shale and starved symmetrical ripples of fine grainstone represent the most distal deposits, whereas thicker fine grainstone beds with well-developed HCS interbedded with less shale represent more proximal deposits (i.e. standard tempestite proximality trends: Walker, 1984; Aigner, 1985).

The difference in grain size between the quartz and feldspar grains (silt) and the carbonate grains (fine sand on average) in the grainstone of the Snowy Range Formation probably reflects deposition of the siliciclastic component by aeolian processes. The compositional ($\approx$ 20% feldspar) and textural immaturity of the siliciclastic component of the grainstone may reflect one or more factors: (1) relatively minor abrasion in aeolian transport because of low mass (silt-sized grains); (2) arid climatic conditions; and (3) an origin as first-generation grains that have undergone little transport in fluvial environments. Given the considerable thickness of Cambrian strata that underlie the Snowy Range across the northern Rocky Mountain region, the siliciclastic grains were either derived from local unrecognized highlands or were carried long distances by wind and deposited across the inner detrital belt. Angular quartz silt is described from the shaly half-cycles of Grand Cycles by Chow & James (1987) and, in their interpretation, the strata were deposited on the flanks of carbonate shoal complexes that were located on the seaward side of an intrashelf basin far from cratonic sources of quartz silt. Aeolian transport of siliciclastic silt may have been important for many such Upper Cambrian intrashelf basins.

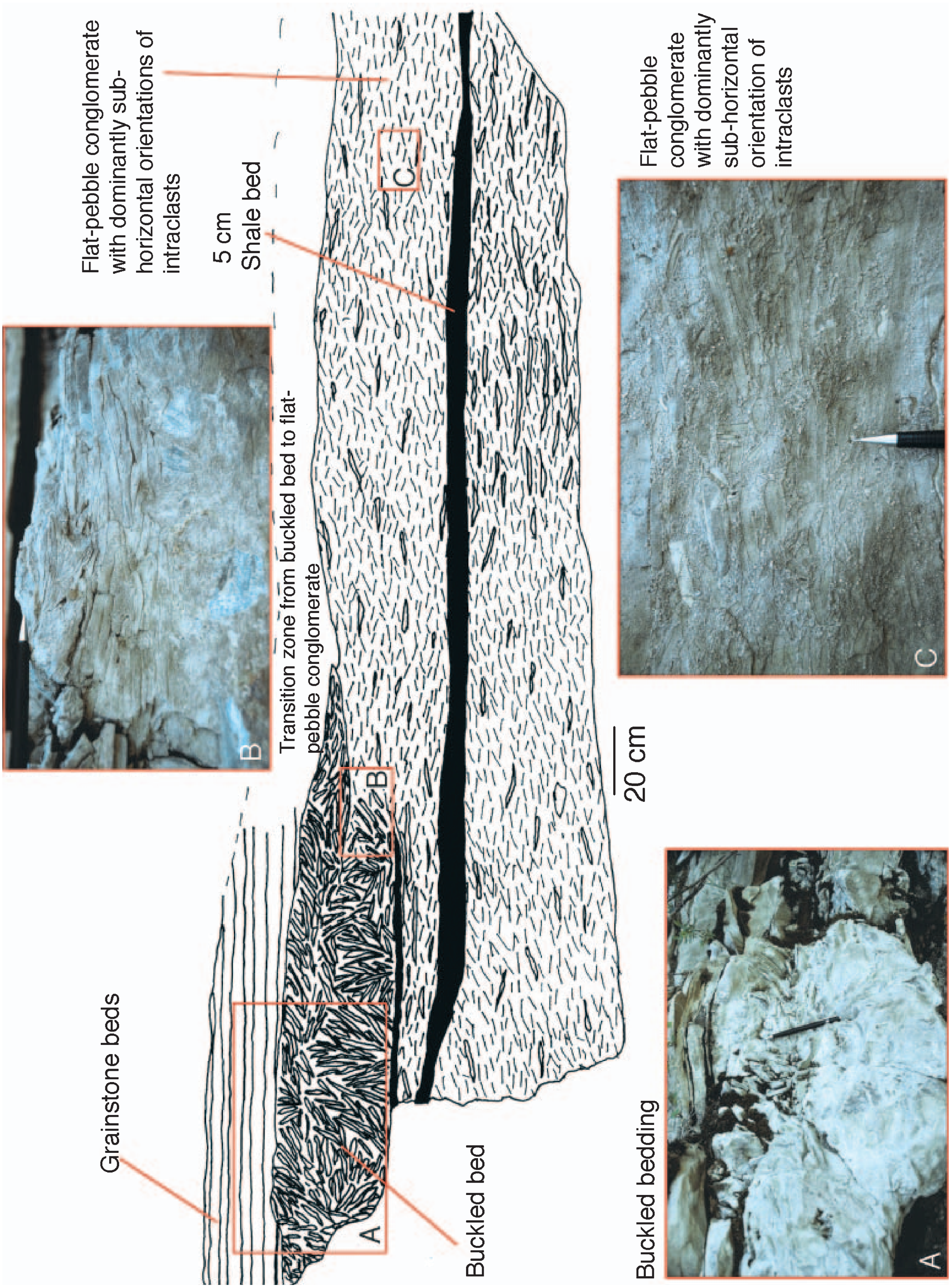
The thrombolite facies was deposited in clear shallow water as a result of the buildup of small microbial mounds. In some sections, the thrombolitic facies occurs as the highest and shallowest facies in shale-based, metre-scale subtidal cycles. These cycles and their significance with regard to changes in relative sea level are described later in this paper. The origin of buckled beds and flat-pebble conglomerate beds is the main focus of this paper and is discussed in detail below.

Synsedimentary deformation structures and relationships to flat-pebble conglomerate

A variety of mass flow and synsedimentary deformation features exist within the Snowy Range Formation, including slumps, slide scars and thrust-duplicated beds. Of particular importance are transitions from buckled beds to flat-pebble conglomerate, which are exposed at a number of sections. At Post Creek East (Fig. 1), amalgamated HCS grainstone grades laterally into a buckled bed that in turn grades laterally into a flat-pebble conglomerate bed with echinoderm-rich grainstone matrix and subhorizontally oriented flat-pebble clasts (Fig. 8). The gradational transition from the buckled bed to the flat-pebble conglomerate is subtle. A second transition between buckled grainstone and flat-pebble conglomerate occurs less than 4 m higher in the same section (Fig. 9). Here, two large rafts of thin-bedded grainstone occur within this interval. One 86×25 cm raft rests on buckled bedding but is otherwise surrounded by flat-pebble conglomerate (Fig. 9). The other raft (60×20 cm across) is partly covered at one end but appears to be encased within flat-pebble conglomerate.

At Medicine Mountain (Fig. 1), a prominent slide scar truncates amalgamated grainstone, and

Fig. 8. Field sketch from Post Creek East locality (12·61 m) that highlights features of buckled beds, flat-pebble conglomerate beds and the transition between the two facies.



Flat-pebble conglomerate with dominantly sub-horizontal orientations of intraclasts
5 cm
Shale bed
Transition zone from buckled bed to flat-pebble conglomerate
Grainstone beds
Buckled bed
20 cm
Flat-pebble conglomerate with dominantly sub-horizontal orientation of intraclasts
Buckled bedding
A
B
C

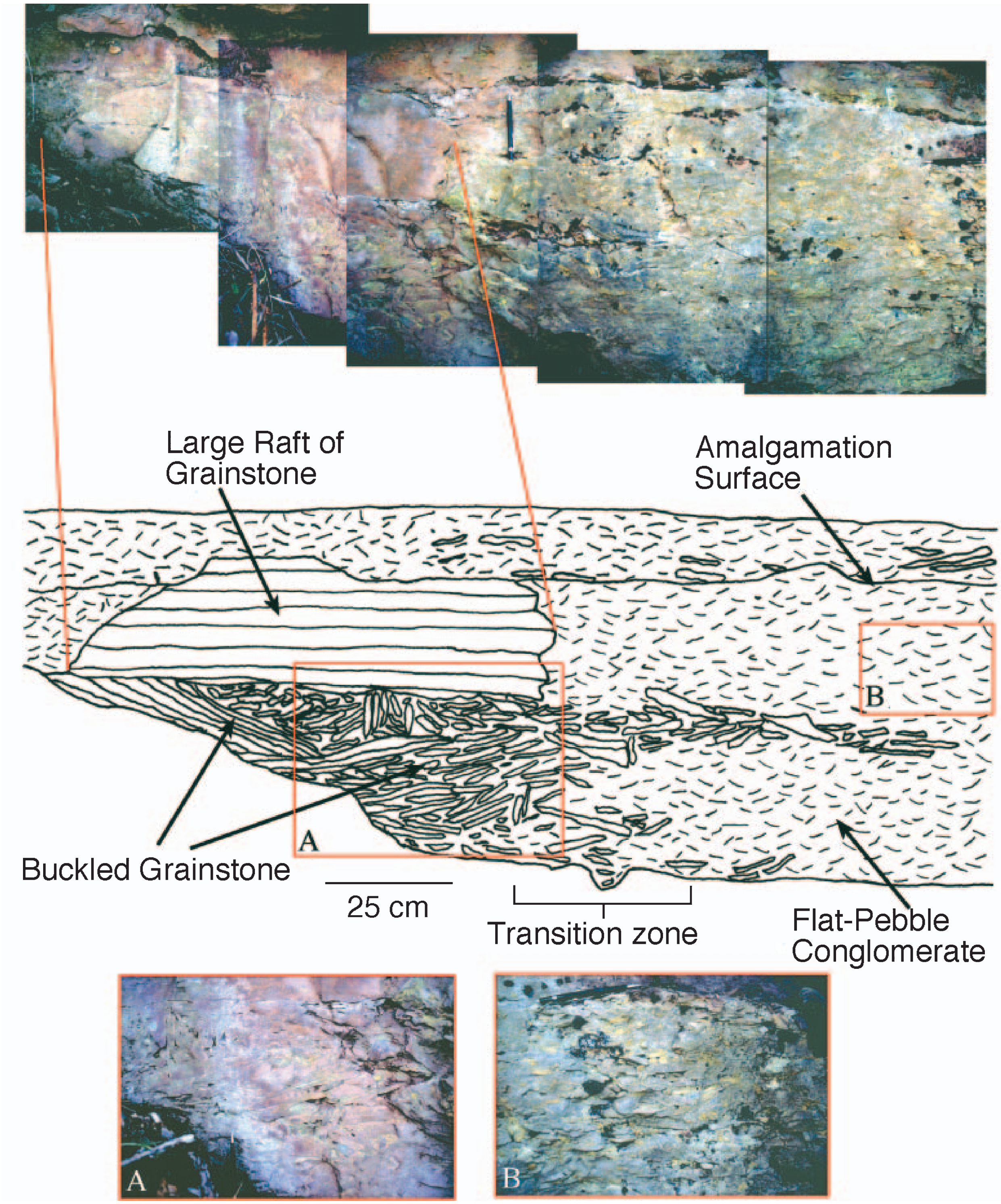


Fig. 9. Photomosaic and corresponding field sketch of transition from buckled bedding to flat-pebble conglomerate at Post Creek East locality (16·36 m). Note large raft of parallel-laminated fine grainstone resting on buckled bedding and surrounded by flat-pebble conglomerate.

the sides of the scar are overlain by buckled grainstone. The buckled deposits grade laterally into flat-pebble conglomerate. At East Pryor Mountain (Fig. 1), a complex buckled and flat-pebble conglomerate unit has an upper zone of buckled beds covering a slide scar that cuts amalgamated grainstone. Below the slide scar, the grainstone grades into buckled grainstone and then flat-pebble conglomerate. Transitions between amalgamated grainstone and buckled grainstone are generally gradational and show all degrees of deformation of amalgamated grainstone from minor disruption to extensive brittle and ductile deformation. Transitions from buckled bedding range from gradational to sharp. Even where the transition is covered, buckled grainstone and flat-pebble conglomerate beds occur laterally along the same stratigraphic horizon. In some cases, the ends of the buckled beds are abruptly truncated, and adjacent beds consist of shale and grainstone that were deposited subsequent to failure and removal of buckled grainstone.

In all the cases described above, the flat-pebble conglomerate lacks much of the evidence for physical reworking and condensation described earlier (e.g. extensive rounding, clast coatings, borings), which is common to beds that cap shoaling cycles.

INTERPRETATION

The common continuum of amalgamated HCS grainstone into buckled bedding within the grainstone-rich facies association indicates that failure of the shoreface gave rise to brittle and ductile deformation of these compacted to early cemented deposits. Failures were both gradational, as evidenced by lateral transitions with buckled beds, or more catastrophic and localized, as evidenced by slide scars that mark sharp facies boundaries. These failures were probably also in part gravity-driven, although on a regional scale slopes were almost negligible in the epicratonic setting of the inner detrital belt (Myrow *et al.*, 2003). Equilibrium slopes on the ancient carbonate sand shorefaces were probably steeper (1° or more) as a result of sediment buildup by strong wave and storm influence.

The buckled beds appear to be surface phenomena, based on a number of criteria. First, buckled beds form mounded structures with snouts that are similar to those of debris flows. Snouts are onlapped by overlying beds and thus do not appear to have been intrastratally inserted into surrounding bedding. Secondly, echinoderm holdfasts are attached to the broken edges of clasts at the top of numerous buckled beds. Thirdly, thrombolitic microbial communities colonized the tops of the buckled and flat-pebble beds and also occupied open space between clasts, the latter indicating growth of microbes within open-framework crypts at the depositional interface. Fourthly, within thick shoreface deposits of the grainstone-dominated facies association, buckled beds that rest on slide scars are onlapped by draping grainstone (Fig. 7), indicating that the buckled beds were surface features with relief of tens of centimetres.

Sediment removed along slide scars was deposited laterally as buckled beds or slumps and, in some cases, became involved in transitions to flat-pebble conglomerate. A model for these transitions is shown in Fig. 10. Buckling presumably resulted from external body forces followed by downslope movement along the shoreface. It involved brittle deformation of early cemented layers and folding of less cemented, but well-compacted bedding. The cm-scale lamination developed within the amalgamated HCS provided natural breaks along planes of weakness that directly yielded cm-thick, platy, early cemented clasts. These clasts are preserved as partially disarticulated and rotated bedding within the buckled beds. Friction between thin, large clasts kept the bedding relatively intact. Once downslope acceleration of slump masses exceeded the internal friction of the slump masses, they broke into disarticulated clasts, resulting in a mass flow of individual cm- to dm-scale clasts. These clasts presumably moved as a dense, friction-dominated debris flow to yield flat-pebble conglomerate. In other cases, clasts that formed by slumping may have been extensively reworked by waves and currents and then deposited as typical flat-pebble beds with rounded clasts and evidence of condensation.

The development of flat-pebble conglomerate from failure of thick amalgamated grainstone units is supported by the presence of large rafts of bedded grainstone within flat-pebble beds (Fig. 9). These rafts reflect wholesale failure of the shoreface and incorporation of large coherent blocks into mass flows, probably as a result of failure along slide scars that are well developed in the amalgamated grainstone facies. This transition to debris flow was in most cases also accompanied by the addition of sand-sized echinoderm-rich debris (Fig. 10). This debris is notably much coarser that the fine grainstone that makes up the amalgamated HCS shoreface deposits. Thus, this debris was carried shoreward by shoaling waves and/or currents from deeper water settings where stalked echinoderms grew (Fig. 10), presumably in response to the same forcing mechanism (e.g. storm) that caused failure of the shoreface. Mixing of coarse carbonate sand

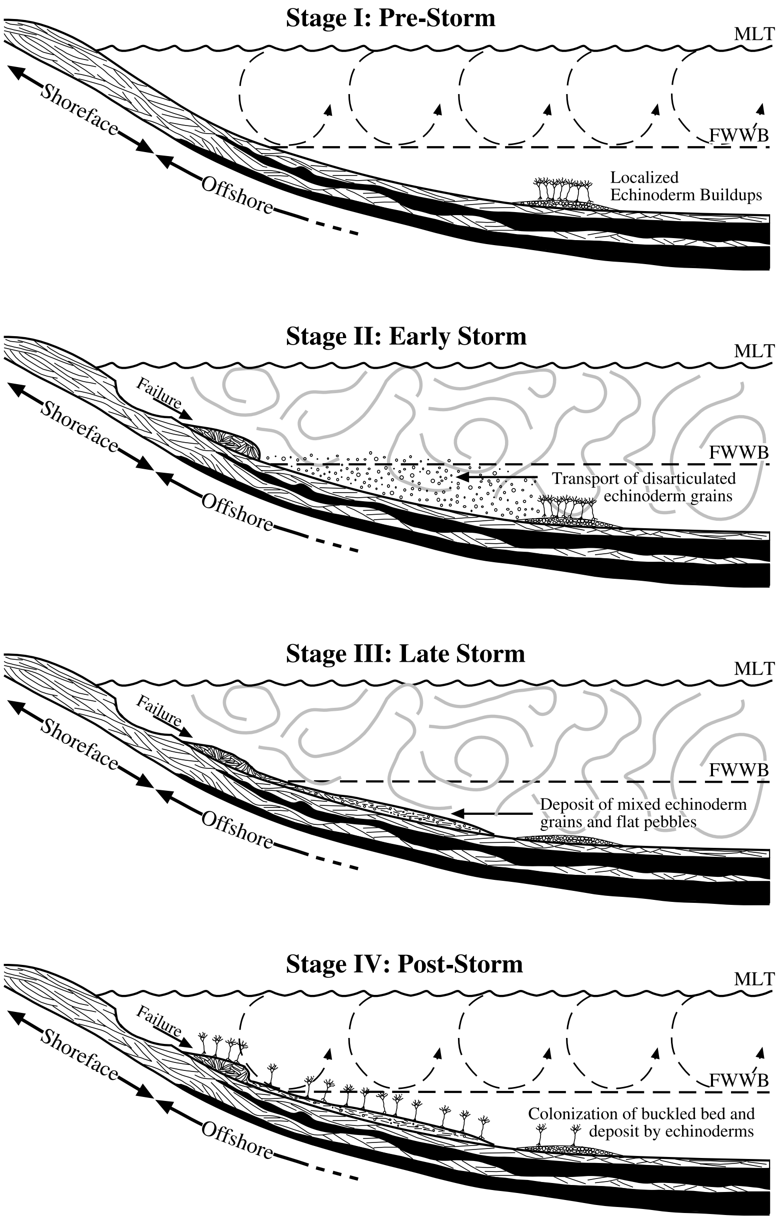


Fig. 10. Model for the formation of flat-pebble conglomerate along a wave/storm-dominated carbonate shoreline. Stage I: conditions before storm. Stage 2: cyclic wave loading during storm causes failure of the fine grainstone and downslope movement, resulting in buckled bed. This is accompanied by shoreward transport of locally derived echinoderm debris. Stage 3: disarticulation of clasts in buckled bed and mixing with transported echinoderm debris leads to mass flow and deposition of a flat-pebble conglomerate with subhorizontally oriented clasts in a coarse bioclastic matrix. Stage 4: post-storm colonization of hard surfaces, including buckled bed and flat-pebble bed.

with flat-pebble debris probably lowered overall friction by allowing tabular clasts to slip along small rounded grains and thus reduced clast–clast interactions. The dominantly horizontal fabric of these flat-pebble beds (e.g. Fig. 8) also supports the interpretation of these as mass flow deposits. This fabric is less likely in subaqueous settings influenced by storm-generated waves and currents, where incremental buildup of clasts would probably have formed strong edgewise fabrics including wave-generated rosettes (Dionne, 1971; Sanderson & Donovan, 1974; Mount & Kidder, 1993). The dominantly horizontal fabric is considered to be a result of viscous flow dominated by laminar shear. These friction-dominated flows accelerated down the front of the shoreface and generally came to rest on the lower shoreface, thus producing the common association of amalgamated grainstone, buckled bedding and flat-pebble conglomerate. However, some flows may have continued a limited distance beyond the shoreface, as indicated by the presence of some flat-pebble conglomerate beds interbedded with shale and grainstone that record deposition beyond the lower shoreface transition. Emplacement by such a mechanism explains an enigmatic aspect of these flat-pebble conglomerate beds, namely the fact that many of the beds are tabular (on the scale of metres to tens of metres) and rest directly on shale with relatively planar lower surfaces. This is consistent with laminar flow and argues against *in situ* reworking by waves and currents that would be expected to produce highly irregular depressions on a muddy surface. Deposition of buckled and flat-pebble beds produced abundant hard surfaces for colonization by stalked echinoderms (Fig. 10).

The mechanism(s) for the proposed failures of the shoreface are difficult to discern. Disruption of strata by body forces is generally linked to failure induced by shaking created by earthquakes or the passage of storm-generated waves. Distinguishing between these causal mechanisms is extremely difficult and, in most ancient deposits, it is not possible. Purported seismites generally consist of *in situ* liquefaction features such as sedimentary dikes, convolute bedding and ball-and-pillow (Pope *et al.*, 1997; Obermeier, 1998; Obermeier & Pond, 1999), and there is a surprising lack of such features in the rocks of this study.

Storm waves have long been considered as triggers for failure of marine sediment (e.g. Henkel, 1970; Prior & Coleman, 1982; Clukey *et al.*, 1985; Prior *et al.*, 1989). Failure results when fluctuations in bottom pressure associated with the passage of large surface waves create cyclic shear stresses, which in turn cause an increase in pore fluid pressure and associated decrease in strength, leading to failure and downslope movement. Such failure has been suggested for the mobilization of fine sand from shoreface settings during storms (Walker, 1984) and for soft-sediment deformation features resulting from liquefaction, as mentioned above (Molina *et al.*, 1998). However, the shoreface grainstone deposits of this study show evidence for early compaction and cementation in the form of brittle deformation structures, so it is unlikely that these deposits could have had enough pore fluid to fail by liquefaction. The transmission of pressure waves generated by storms could nonetheless have caused failure of these deposits and the initial movement of buckled masses. The transport and mixing of coarse echinoderm grains from offshore with flat pebbles during these events is more compatible with storm-generated failure and transport than with the passage of seismic waves.

The flat-pebble conglomerate deposits described above are an extraordinary example in which transitional stages of development were captured in the rock record, and these allow for the reconstruction of depositional processes. Flat-pebble beds also occur in three other types of cyclic and non-cyclic deposits within the Snowy Range Formation, and these are described below. These demonstrate the multiplicity of origin of flat-pebble conglomerate within even a single formation, and emphasize the importance of the stratigraphic and sedimentological context of flat-pebble facies for their proper interpretation.

FLAT-PEBBLE CONGLOMERATE BEDS AS SHORELINE DEPOSITS

Description

The youngest (highest Sunwaptan and basal Skullrockian) strata of the Snowy Range Formation in most localities constitute a relatively resistant, carbonate-rich unit that forms a cliff directly below the base of the Bighorn Formation, The base of this relatively resistant unit (Fig. 11; 24·05–26·65m) is in relatively sharp contact with an underlying much shalier facies that contains several thrombolite-capped cycles (described below) at Cookstove Basin (Fig. 1). The uppermost part of this cyclic interval is a 53 cm thick unit of shale with < 1–3 cm thick grainstone beds, including starved wave ripples and shrinkage cracks in the top 10 cm. Directly above is an anomalously thick (75 cm) flat-pebble conglomerate with vertically imbricated flat pebbles across the top layer and in multiple microdomains within the bed (Fig. 12b). The flat-pebble conglomerate is in turn overlain by 68–90 cm of thinly to thickly laminated grainstone with parallel lamination and HCS (Fig. 12a). A 0–22 cm thick lenticular flat-pebble conglomerate bed with a concave-up basal erosion surface caps this grainstone. Both this lenticular flat-pebble bed and the underlying/adjacent grainstone bed are overlain by a discontinuous 0–14 cm thick bed of coarse grainstone and iron-coated flat pebbles with borings. This bed has an irregular upper surface that is in sharp contact with 76 cm of shale with very thin to thin beds of grainstone (≈ 50% shale).

A second, 1 m thick, amalgamated unit of flat-pebble conglomerate exists at 30·8 m at Cookstove Basin (Fig. 11). This unit also rests on a metre-scale shoaling cycle with thin-bedded grainstone and mud-cracked shale directly below the flat-pebble unit. The flat-pebble conglomerate displays a variety of fabrics from flat-lying clasts to vertically oriented rosettes.

Interpretation

The strata directly above 24·05 m have many features diagnostic of a storm-influenced shoreline. The amalgamated, parallel-laminated and

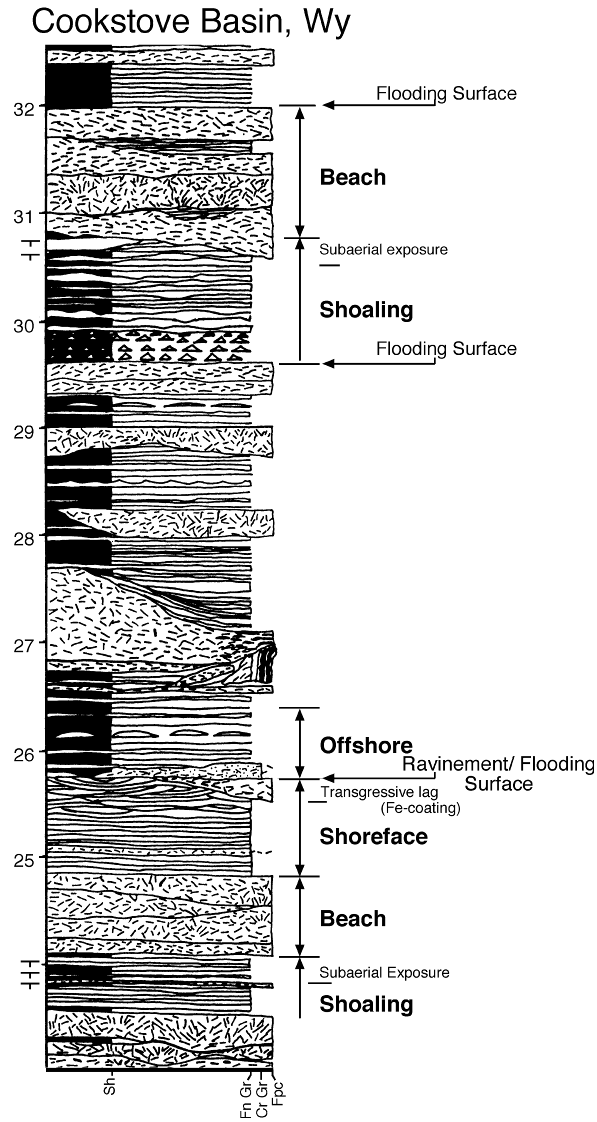


Fig. 11. Part of stratigraphic section from Cookstove Basin, WY. A transition from beach flat-pebble conglomerate to shoreface grainstone to shale-rich offshore deposits is captured between 24 and 26 m. A second thick flat-pebble conglomerate unit of beach origin occurs between 31 and 32 m. Scale in metres. T-shaped symbols to left of column indicate desiccation cracks. Sh, shale; Fn Gr, fine grainstone; Cr Gr, coarse grainstone; Fpc, flat-pebble conglomerate.

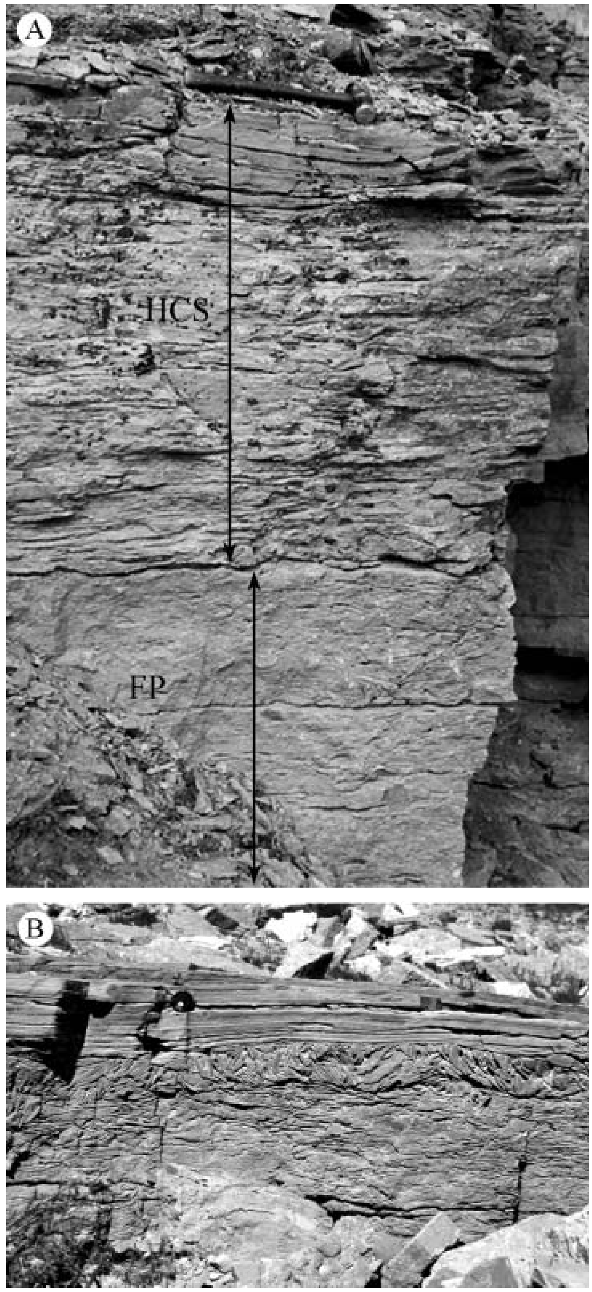


Fig. 12. (A) Thick amalgamated flat-pebble conglomerate bed and overlying amalgamated HCS bed at Cookstove Basin, WY. Sledgehammer for scale. (B) Close-up of transition between the flat-pebble conglomerate and HCS beds. Note thin layer of vertically imbricated pebbles at the top of the flat-pebble bed. Lens cap is 5·5 cm across.

HCS grainstone beds are diagnostic of a wave- and storm-influenced shoreface environment, as discussed earlier. The stratigraphic transition at 25·65 m to distal shaly facies with starved ripples represents a fairly profound flooding surface. The thin, lenticular coarse grainstone and flat-pebble beds that mark this transition represent a lag deposited on a ravinement surface caused by shoreface retreat associated with transgression. The iron-coated flat pebbles with borings in the lag deposit are analogous to the hardgrounds described by Osleger & Read (1991). The chemical reactions that create these coatings and the abundance of borings probably resulted from a rapid decrease in the rate of sediment accumulation across the flooding surface.

The stratigraphic position of the thick flat-pebble conglomerate (24·05 m) below the shoreface deposits of the amalgamated grainstone facies suggests that it represents an environment near and above mean low tide. It formed in a similar shoreline position to the underlying shale-rich deposits, which were subaerially exposed and probably represents a mud-flat environment. This change records a shift towards strong wave and storm activity, as evidenced by the rosettes of edgewise clasts. In these examples, the flat-pebble conglomerate represents either a beach setting or less continuous flat-pebble shoals on a mud flat. The transition from the flat-pebble conglomerate to the amalgamated grainstone represents a marine flooding surface. It is unclear whether the flat-pebble foreshore deposits formed as a transgressive lag or from reworking during lowstand conditions just before relative sea-level rise.

The second unit of flat-pebble conglomerate at 30·8 m is similarly interpreted as a beach deposit. It also rests on shale with desiccation cracks and consists of multiple beds of flat pebbles. The flat-pebble units at the base of the relatively resistant uppermost Snowy Range (Fig. 11) are anomalously thick relative to others within the formation. In addition, both 24·05 and 30·8 m beds rest on mud-cracked intervals, which are extremely rare within these inner detrital belt deposits.

SHOALING CYCLES

Flat-pebble beds in the Snowy Range Formation occur most commonly interbedded with shale and grainstone beds without any apparent vertical stratigraphic trends in facies or grain size. This is somewhat remarkable given the generally shallow-water setting of the Cambrian–Ordovician inner shelf lagoon of Laurentia and the fact that nearshore to shoreline deposits of this age are commonly cyclic (Aitken, 1978; Markello & Read, 1982; Osleger & Read, 1991, 1993). However, upward-coarsening cycles (Fig. 13) do occur in the upper part of the Snowy Range Formation at some localities. The cycles vary in degrees of completeness, consist of three or four facies and range in thickness from 0·95 to 1·89 m. Shoaling cycles are best developed at Careless Creek (Fig. 1) where 10 cycles occur within < 10 m of section (Fig. 14). Each cycle begins with 4–23 cm of shale that in some cases contains interbedded millimetre-scale grainstone laminae. The shale to grainstone ratio is ≈ 9:1. Above these units are 6–51 cm of intercalated 1–8 cm thick grainstone beds and very thin shale beds. The shale percentage decreases upwards to ≈ 10–15%. The grainstone beds tend to pinch-and-swell, and some have wave-rippled upper surfaces (Fig. 13C). The tops of the cycles consist of flat-pebble conglomerate beds ranging from 5 to 26 cm thick (Fig. 13A and B). The beds are laterally continuous and tabular, although some

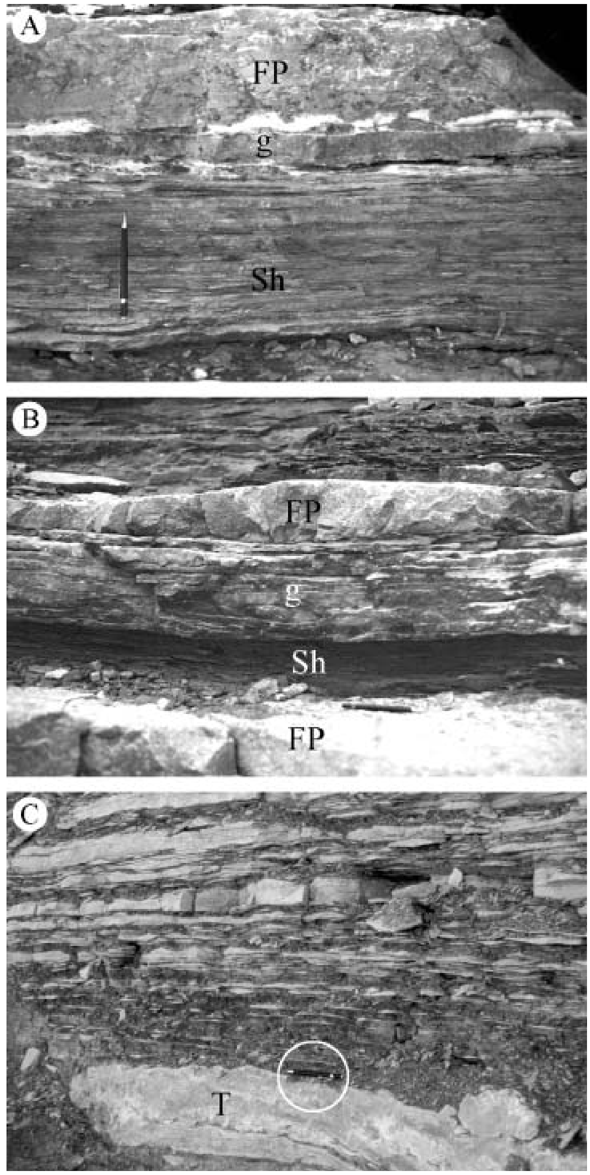


Fig. 13. (A) Shoaling cycle with thick lower unit of shale (Sh) with very thin grainstone beds, a thin grainstone bed (g) and a capping flat-pebble conglomerate. (B) Shoaling cycle with shale (Sh), grainstone (g) and flat-pebble conglomerate (FP) beds. Cycle overlies flat-pebble bed at top of underlying cycle. (C) Thrombolite bed (T) overlain by the base of shoaling cycle. The cycle illustrates the upward decrease in shale and increase in grainstone content and bed thickness. Pencil is 14 cm long.

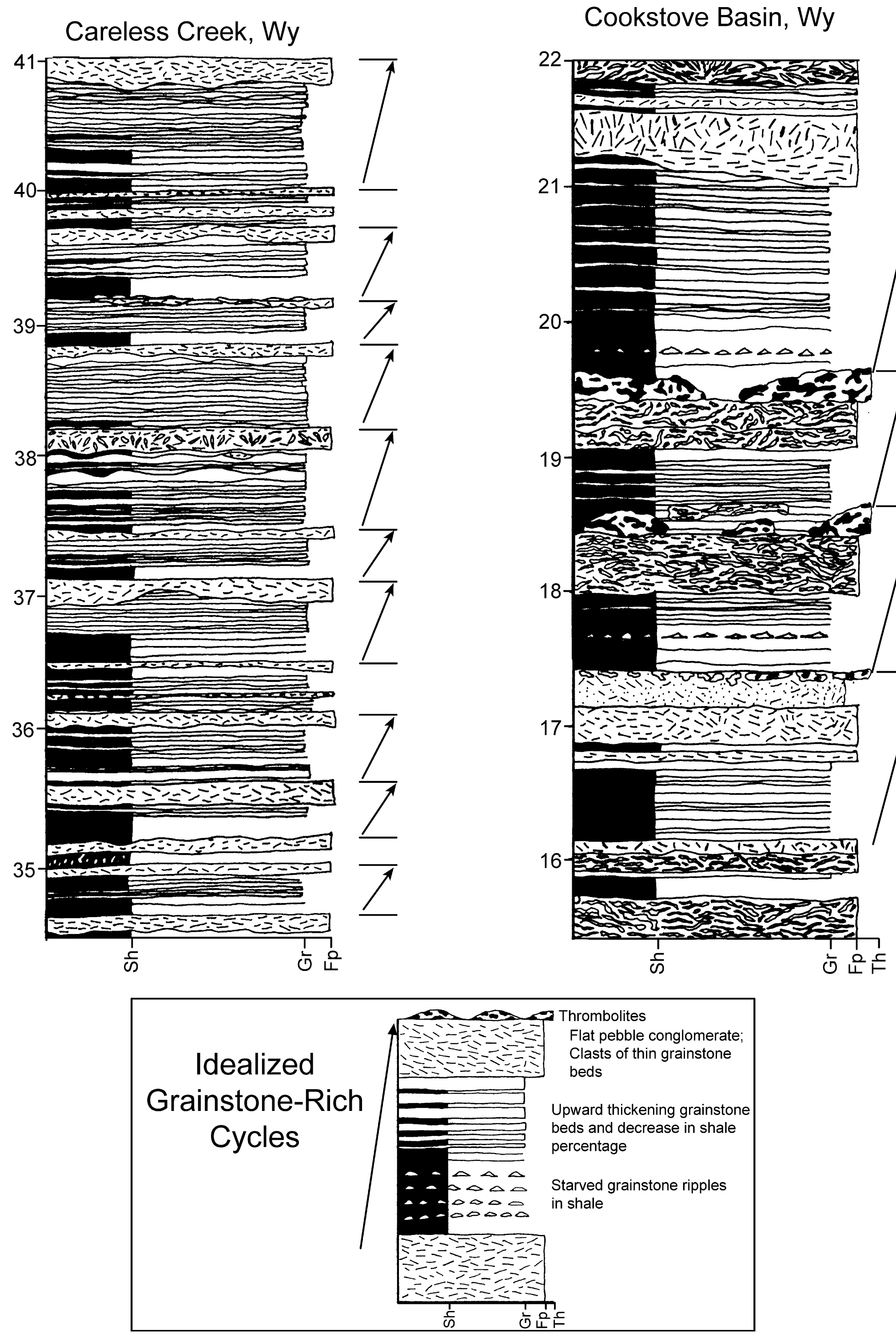


Fig. 14. Measured section with upward-shoaling cycles. The Careless Creek section contains 10 upward-shoaling cycles (arrowed), none of which contains thrombolite caps. The Cookstove Basin section shows four cycles, three of which are capped by prominent thrombolites. Scale in metres. Sh, shale; Gr, grainstone; Fp, flat-pebble conglomerate; Th, thrombolite. Idealized cycle is shown on bottom.

have mildly erosional bases. The clasts in these beds are highly rounded, locally contain abundant borings and, in some cases, display dark brown iron-rich coatings, as seen in bedding plane exposures. The matrix of these beds is rich in coarse bioclasts, particularly echinoderm fragments, and in many cases contains glauconite grains.

Thrombolites are absent from the cycles at Careless Creek (Fig. 1) but cap flat-pebble conglomerate beds in similar cycles elsewhere (Fig. 13C). Many of these thrombolitic mounds grade upwards from the flat-pebble conglomerate through a zone of clast-supported flat pebbles with thrombolitic boundstone filling much of the space between them. Variations from the idealized cycle include the absence of thrombolitic mounds, some interbedding of grainstone with flat-pebble conglomerate at the base of the flat-pebble beds and the presence of buckled beds in place of (or laterally adjacent to) the flat-pebble beds. Additionally, the lower shale units in some cases contain thicker grainstone beds up to 1 cm thick (Fig. 13C). The top of one cycle at Tensleep Canyon (Fig. 1) is marked by a 36 cm thick bed of very coarse crinoidal grainstone with abundant flat pebbles instead of a flat-pebble conglomerate bed. The upper 10 cm of this coarse grainstone contains thrombolite clasts and overlying thrombolite mounds up to 8 cm thick that cap the cycle.

Interpretation

The upward-coarsening cycles of the Snowy Range Formation contain no evidence for subaerial exposure such as shrinkage cracks, palaeokarst or other features indicative of meteoric vadose or phreatic diagenesis, and are thus inferred to be wholly subaqueous. The upward increase in bed thickness and percentage of fine grainstone reflects shoaling and a shift to shallower water conditions. The grainstone beds may in some cases represent deposition in a lower shoreface. The flat-pebble conglomerate beds that cap these cycles may represent foreshore deposits or nearshore deposits (below fairweather wave base) transported from the shoreline either during lowstand by storms or during subsequent transgression by various marine processes. The tabular nature of many of the beds and their relatively flat lower surfaces (Fig. 13) argue against *in situ* erosion of underlying grainstone as a source of the clasts, but instead suggest some transport and deposition of the flat pebbles. Evidence for such transport includes the rounded nature of the clasts. These beds also contain evidence of condensation in the form of borings, clast coatings and glauconite grains. The general lack of chaotic fabrics and edgewise rosettes (cf. Mount & Kidder, 1993) brings into question the depositional mechanics of these beds. Edgewise fabrics are generally attributed to waves and combined-flow storm currents, but little or no experimental work has been done to determine whether dominantly horizontal fabrics could also form in bedload transport of flat pebbles under such conditions. These questions are also important for the interpretation of flat-pebble beds that rest on shale in non-cyclic strata in the Snowy Range Formation, as these beds also lack edgewise fabrics and are in many cases tabular.

Numerous authors have described peritidal metre-scale carbonate cycles, and these commonly have flat-pebble conglomerate and thrombolites at their bases and overlying cryptalgal laminite with evidence of desiccation (see review by James, 1984). These are generally interpreted as having subtidal bases and intertidal tops. The flat-pebble conglomerate beds at the base are commonly interpreted as transgressive lags (e.g. James, 1984; Wright, 1984; Grotzinger, 1986; Tucker & Wright, 1990). The cycles described herein are shale based and entirely subaqueous. They resemble, in scale and facies arrangement, the shale-based cycles described by Markello & Read (1982) and Osleger & Read (1991). The latter interpreted their cycles as having aggraded from below to above storm wave base, with the flat-pebble conglomerate beds representing reworking of underlying grainstone. A similar interpretation is likely for the Snowy Range cycles, but it is suggested here that the transition from shale with grainstone to amalgamated grainstone near the top of these cycles may instead represent a transition across fairweather wave base and the lower shoreface transition zone. The palaeoenvironmental setting of the thrombolites is also problematic. In the cycles described by Demicco (1983) and Koerschner & Read (1989), microbial mounds are considered to be subtidal to lower intertidal features. In this study, there is no evidence for subaerial exposure, and thus the thrombolites are considered to be entirely subaqueous, although they probably formed during the late stage of shoaling and thus represent the shallowest facies (cf. Markello & Read, 1982). The thrombolite growth was substrate controlled by a shift to the hard sea floor surfaces underlain by flat pebbles. Thrombolite facies described by Saltzman (1999) from slightly older rocks in the field area also rest directly on flat-pebble conglomerate and attest to this substrate control. No independent evidence (high-resolution geochronological data) has been collected to demonstrate that these cycles were driven by eustasy, but an origin from high-frequency sea-level fluctuations is likely.

SHALE-DOMINATED CYCLES

A second, more enigmatic type of asymmetric cycle is found in the Shoshone Canyon section (Figs 1, 15 and 16), where five cycles exist within 5 m of section. The cycles commence with 10–32 cm of shale with relatively abundant carbonate nodules and, in some cases, thin grainstone beds.

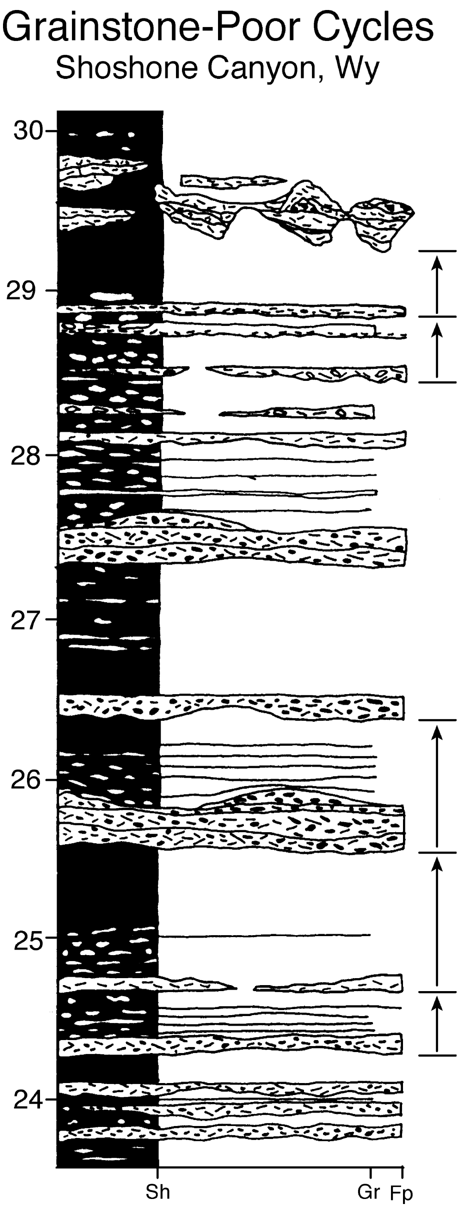


Fig. 15. Part of a stratigraphic section from Shoshone Canyon, WY, showing five grainstone-poor cycles (arrowed). Scale in metres. Sh, shale; Gr, grainstone; Fp, flat pebble conglomerate.

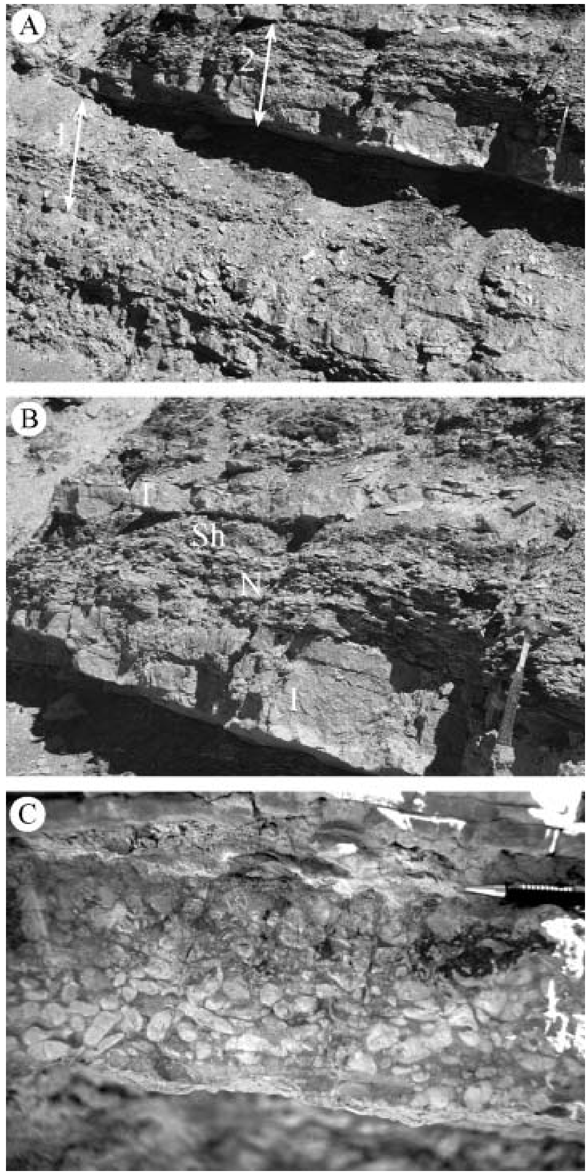


Fig. 16. Shale-rich cycles from Shoshone Canyon, WY. (A) Two shoaling cycles. Lower cycle has a much thinner intraclast conglomerate bed at the base. (B) Close-up of upper cycle in (A). Cycle consists of basal intraclast bed (I), shale with carbonate nodules (N) and shale without nodules (N). Upper intraclast bed is base of another cycle. Hammer for scale in (A) and (B). (C) Close-up of intraclast bed. Note that intraclasts are rounded carbonate nodules similar to those interbedded with the shale within the cycles. Pencil for scale.

These nodule-rich shale units directly overlie flat-pebble conglomerate beds and are overlain by 26–60 cm units of shale with sparse nodules. Pebble conglomerate beds containing clasts of carbonate nodules overlie these shale units. The pebble conglomerate beds range from 8 to 34 cm thick, are generally laterally continuous and have mildly irregular upper and/or lower surfaces.

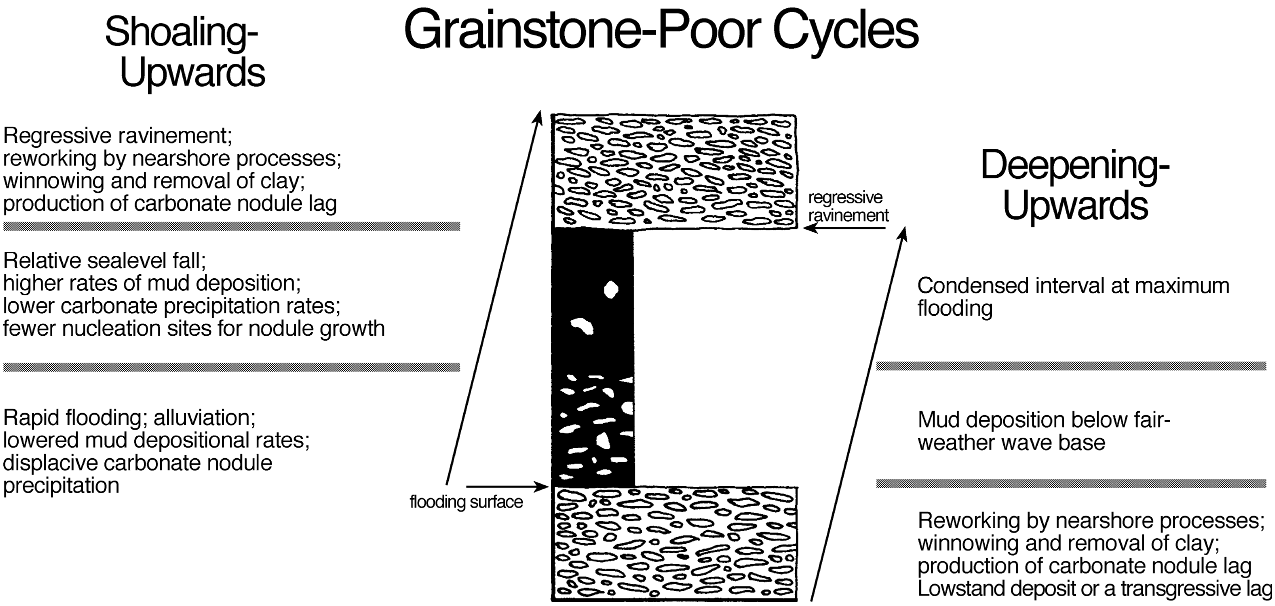


Fig. 17. Alternative hypotheses for grainstone-poor cycles.

Interpretation

The asymmetric shale-dominated cycles from Shoshone Canyon can be interpreted as either shoaling cycles or deepening cycles (Fig. 17). In either case, they are considered to be wholly subaqueous, as they are shale rich and contain no evidence for subaerial exposure. These cycles differ from the upward-coarsening cycles described earlier in two ways. First, carbonate nodules are present within the shale facies and are the sole source of clasts within the pebble conglomerate. Secondly, these cycles contain very little grainstone and no thrombolites.

If the cycles record shoaling (Fig. 17), the top surface of the flat-pebble conglomerate beds would represent the bases of the cycles. Rapid flooding of a flat-pebble bed and deposition of mud would have initiated these cycles. Carbonate nodules were precipitated and, in some cases, sparse thin lime sand beds were deposited. If one assumes that precipitation of carbonate nodules is a function of time in which the sediment is in a shallow, geochemically distinct layer in the sediment column, then nodule growth would be in part a function of the accumulation rate of mud. Lower rates would prolong the time that a particular layer of sediment would be in the shallow diagenetic zone in which nodules grow, whereas higher rates would tend to bury a layer below the zone of nodule precipitation. If the basal nodule-rich units at the bases of these cycles record relative sea-level rise, they may reflect alluviation and a general decrease in sediment delivery to the shelf. In this case, nodule precipitation was enhanced by reduction in mud accumulation rates. The upward change from shale with abundant nodules to shale with sparse nodules would represent a fall in relative sea level, increased sediment accumulation rates and lower rates of nodule growth. Continued relative sea-level fall would have resulted in deposition of nearshore/shoreline pebble deposits. The fact that there are no grainstone beds at the top of these cycles, and that the intraclastic conglomeratic beds are not composed of flat pebbles derived from thin grainstone beds, but instead reworked nodules, indicates that the shoreline was too distal or not sandy during deposition of these cycles. Reworking by nearshore processes in these grainstone-starved settings would have involved removal of mud and production of a nodule lag. The excavation and winnowing of early cemented carbonate nodules is similar to that described by Mount & Kidder (1993), although the flat-pebble beds they describe rest directly on nodule-rich strata. In the present study, shale directly underlying the intraclast conglomerate beds contains relatively few nodules, so it is likely that laterally, more nodule-rich layers were being reworked and transported some distance to the site of deposition. The presence of thin grainstone beds within lower shale beds in three of the cycles is problematic in this hypothesis.

A second hypothesis is that these represent upward-deepening subaqueous cycles (Fig. 17). In this case, the cycles would begin with near-shore processes reworking shale with carbonate nodules to form intraclastic conglomerate. The flat-pebble beds could represent either a lowstand deposit or a transgressive lag. Relative sea-level rise would cause mud to be deposited on top of the intraclastic conglomerate. In this case, thin grainstone beds within shale in three of the cycles would represent a transition from limited near-shore sources of grainstone to deeper settings that are more distal from a source of grainstone. The shale with very few nodules might represent a maximum flooding interval. The reason for the stratigraphic distribution of carbonate nodules is not readily obvious in this hypothesis. Shallow-marine, metre-scale deepening cycles are not common features in the rock record, and so the shoaling hypothesis is considered to be the more likely of the two. In either case, the general lack of grainstone in these shale-dominated cycles may reflect deposition in deeper water environments away from the shoreline sources of grainstone, although the production of intraclast conglomerate requires that shoaling took place to a level at which marine processes could rework deposits into a nodule lag.

SUMMARY

Flat-pebble conglomerate is an important component of carbonate deposits, particularly in Cambrian and Lower Ordovician strata (Sepkoski, 1982). Flat-pebble accumulations have been described from modern supratidal and beach environments (e.g. Roehl, 1967; Dionne, 1971; Sanderson & Donovan, 1974), but most authors have concluded that the vast majority of ancient flat-pebble conglomerate beds were deposited in subtidal environments below fairweather wave base (Kazmierczak & Goldring, 1978; Markello & Read, 1982; Sepkoski, 1982; Demicco, 1983; Wilson, 1985; Grotzinger, 1986; Lee & Kim, 1992; Mount & Kidder, 1993). Given that subaerial diagenetic processes were not responsible for lithification of the carbonate beds, it was concluded early on that submarine cementation or hardground formation was a necessary step in the formation of flat pebbles. Sepkoski (1982) argued that the evolution of metazoa at the base of the Cambrian resulted in abundant faecal pellets that were a presorted source of thin grainstone beds. The thin pelletal limestone beds were highly permeable and easily cemented so that the reworking of these early cemented beds was the source of flat pebbles. There has been much speculation concerning the processes by which such beds were reworked into flat-pebble conglomerate, but few detailed process-oriented sedimentological studies have been undertaken on flat-pebble facies.

Flat-pebble conglomerate beds of the Snowy Range Formation of northern Wyoming and southern Montana are shown here to be of variable origin and to occur stratigraphically within both non-cyclic and cyclic strata. Four types of flat-pebble beds are described. The first type described here is shown to have resulted from failure and mass movement of thickly laminated strata of carbonate sand shoreface deposits of the grainstone-dominated facies association. Such deformation resulted from either storm-generated or seismic waves. Buckling, rotation and disarticulation of cm-scale lamination within HCS grainstone led to the development of viscous flows dominated by laminar shear. The addition of coarse grainstone reduced friction in these flows and may have allowed them to move beyond the shoreface across the muddy bottom of the proximal near-shore zone. Many hypotheses have been offered over the years for the origin of flat-pebble conglomerate, including deposition from mass flows, but this study is the first to demonstrate a particular origin using deposits that show all stages of development of such beds.

The origins of the other three types of flat-pebble beds were derived from analysis of fully developed flat-pebble conglomerate beds. An anomalously thick amalgamated flat-pebble bed at one section (Cookstove Basin) can be interpreted straightforwardly as a beach deposit that is overlain by a thick shoreface deposit of amalgamated HCS grainstone, then a flooding surface and an overlying shale-rich unit. The interpretation of the flat-pebble bed, with an upper surface of wave-generated pebble rosettes, within this transgressive succession is relatively straightforward.

A third type of flat-pebble conglomerate beds occurs at the tops of metre-scale, subtidal to peritidal, shoaling cycles. Sedimentological analysis of the cycles indicates that the flat-pebble beds formed by wave and/or storm reworking of shoreline deposits during lowstand conditions or as a transgressive lag during the earliest stages of subsequent flooding at the base of the next cycle. A fourth type of pebble conglomerate, consisting of reworked carbonate nodules, occurs within enigmatic, shale-dominated, metre-scale cycles. Although it is unclear whether these represent upward-deepening or upward-shoaling cycles, the conglomerate beds are lags formed by the winnowing and reworking of shale with abundant carbonate nodules by wave and/or storm processes.

This study demonstrates the multiple origins of flat-pebble conglomerate beds within a single unit, the Upper Cambrian to Lower Ordovician strata of the Snowy Range Formation. The interpretation of flat-pebble conglomerate beds therefore requires careful analysis of their stratigraphic and sedimentological context. These must be understood within the history of secular changes in palaeogeography, biological evolution, oceanic chemistry and the geotechnical properties of sediment.

REFERENCES

Aigner, T. (1985) *Storm Depositional Systems*. Lecture Notes in Earth Sciences 3. Springer-Verlag, New York, 174 pp.

Aitken, J.D. (1978) Revised models for depositional Grand Cycles, Cambrian of the southern Rocky Mountains, Canada. *Can. Petrol. Geol. Bull.*, **25,** 515–542.

Blackwelder, E. (1918) New Geological formations in western Wyoming. *Washington Acad. Sci. J.*, **8,** 417–426.

Bottjer, D.J., Hagadorn, J.W. and **Dornbos, S.Q.** (2000) The Cambrian substrate revolution. *GSA Today*, **10,** 1–7.

Chow, N. (1986) *Sedimentology and diagenesis of middle and upper Cambrian platform carbonates and siliciclastics, Port au Port Peninsula, Western Newfoundland*. Unpubl. PhD Thesis. Memorial University, St John's, Newfoundland, 458 pp.

Chow, N. and **James, N.P.** (1987) Cambrian Grand Cycles: a northern Appalachian perspective. *Geol. Soc. Am. Bull.*, **98,** 418–429.

Clukey, E.C., Kulhawy, F.H., Liu, P.L.-F. and **Tate, G.B.** (1985) The impact of wave loads and pore-water pressure generation on initiation of sediment transport. *Geo-Mar. Lett.*, **5,** 177–183.

Deiss, C. (1936) Revision of type Cambrian formations and sections of Montana and Yellowstone National Park. *Geol. Soc. Am. Bull.*, **47,** 1257–1342.

Deiss, C.H. (1938) Cambrian formations and sections in part of Cordilleran Trough. *Geol. Soc. Am. Bull.*, **49,** 1067–1168.

Demicco, R.V. (1983) Wavy and lenticular-bedded carbonate ribbon rocks of the Upper Cambrian Conococheague Limestone, Central Appalachians. *J. Sed. Petrol.*, **53,** 1121–1132.

Dionne, J.C. (1971) Vertical packing of flat stones. *Can. J. Earth Sci.*, **8,** 1585–1591.

Dorf, E. and **Lochman, C.** (1940) Upper Cambrian formations in Southern Montana. *Geol. Soc. Am. Bull.*, **51,** 541–556.

Droser, M.L. and **Bottjer, D.J.** (1989) Ordovician increase in extent and depth of bioturbation: implications for understanding early Paleozoic ecospace utilization. *Geology*, **17,** 850–852.

Embry, A.F. and **Klovan, J.E.** (1971) A Late Devonian (*sic*) reef tract on Northeastern Banks Island, N.W.T. *Can. Petrol. Geol. Bull.*, **19,** 730–781.

Goodwin, P.W. (1961) *Fauna and stratigraphy of the Cambrian and Lower Ordovician of the Bighorn Mountains, Wyoming*. Unpubl. MSc. Thesis, University of Iowa, 73 pp.

Grant, R.E. (1965) Faunas and stratigraphy of the Snowy Range Formation (Upper Cambrian) in southwestern Montana and northwestern Wyoming. *Geol. Soc. Am. Mem.*, **96,** 171 pp.

Greensmith, J.T. and **Tucker, E.V.** (1968) Imbricate structures in Essex offshore shell banks. *Nature*, **220,** 1115–1116.

Greensmith, J.T. and **Tucker, E.V.** (1969) The origin of Holocene shell deposits in the chenier plain facies of Essex (Great Britain). *Mar. Geol.*, **7,** 403–425.

Grotzinger, J.P. (1986) Evolution of Early Proterozoic passive-margin carbonate platform, Rocknest Formation, Wopmay Orogen, Northwest Territories. *Can. J. Sed. Petrol.*, **56,** 831–847.

Henkel, D.J. (1970) The role of waves in causing submarine landslides. *Geotechnique*, **20,** 75–80.

James, N.P. (1984) Shallowing-upward sequences in carbonates. In: *Facies Models* (Ed. R.G. Walker), 2nd edn, pp. 213–228, Geological Association of Canada, Toronto.

Jansa, L.F. and **Fischbuch, N.R.** (1974) Evolution of a Middle and Upper Devonian sequence from a clastic coastal plain–deltaic complex into overlying carbonate reef complexes and banks, Sturgeon–Mitsue area, Alberta. *Geol. Surv. Can. Bull.*, **234,** 205 pp.

Kazmierczak, J. and **Goldring, R.** (1978) Subtidal flat-pebble conglomerate from the Upper Devonian of Poland: a multiprovenant high-energy product. *Geol. Mag.*, **115,** 359–366.

Koerschner, W.F. and **Read, J.F.** (1989) Field and modeling studies of Cambrian carbonate cycles, Virginia Appalachians. *J. Sed. Petrol.*, **59,** 654–687.

Kreisa, R.D. (1981) Storm-generated sedimentary structures in subtidal marine facies with examples from Middle and Upper Ordovician of southwestern Virginia. *J. Sed. Petrol.*, **51,** 823–848.

Lee, Y.I. and **Kim, J.C.** (1992) Storm-influenced siliciclastic and carbonate ramp deposits, the Lower Ordovician Dumugol Formation, South Korea. *Sedimentology*, **39,** 951–969.

Lochman-Balk, C. (1971) The Cambrian of the craton of the United States. In: *Cambrian of the New World* (Ed. C.H. Holland), pp. 79–168. John Wiley and Sons, New York.

McKee, E.D. (1945) *Cambrian History in the Grand Canyon Region. Carnegie Inst. Washington Publ.*, **1,** 230 pp.

Markello, J.R. and **Read, J.F.** (1982) Upper Cambrian intrashelf basin, Nolichucky Formation, southwest Virginia Appalachians. *AAPG Bull.*, **66,** 860–878.

Martin, W.D., Fischer, H.J., Keogh, R.J. and **Moore, K.** (1980) The petrology of the limestones of the Upper Gros Ventre and Gallatin Limestone Formations (Middle and Upper Cambrian) Northwestern Wind River Basin, Wyoming. *Wyoming Geol. Assoc. Guidebook*, **31,** 45–48.

Mills, N.K. (1956) Subsurface stratigraphy of the Pre-Niobrara Formations in the Big Horn Basin, Wyoming: Wyoming stratigraphy, Part 1. *Wyoming Geol. Assoc.*, pp. 9–22.

Molina, J.M., Alfaro, P., Moretti, M. and **Soria, J.M.** (1998) Soft-sediment deformation structures induced by cyclic stress of storm waves in tempestites (Miocene, Guadalquivir Basin, Spain). *Terra Nova*, **10,** 145–150.

Mount, J.F. and **Kidder, D.** (1993) Combined flow origin of edgewise intraclast conglomerates. Sellick Hill Formation (Lower Cambrian), South Australia. *Sedimentology*, **40,** 315–329.

Myrow, P.M. (1992) Bypass-zone tempestite facies model and proximality trends for an ancient muddy shoreline and shelf. *J. Sed. Petrol.*, **62,** 99–115.

Myrow, P.M., Taylor, J.F., Miller, J.F., Ethington, R.L., Ripperdan, R.L. and **Allen, J.** (2003) Fallen Arches: dispelling myths concerning Cambrian and Ordovician paleogeography of the Rocky Mountain Region. *Geol. Soc. Am. Bull.*, **115,** 695–713.

Obermeier, S.F. (1998) Liquefaction evidence for strong earthquakes of Holocene and latest Pleistocene ages in the states of Indiana and Illinois, USA. *Eng. Geol.*, **50,** 227–254.

Obermeier, S.F. and **Pond, E.C.** (1999) Issues in using liquefaction features for paleoseismic analysis. *Seismol. Res. Lett.*, **70,** 34–58.

Osleger, D. and **Read, J.F.** (1991) Relation of eustasy to stacking patterns of meter-scale carbonate cycles, Late Cambrian, USA. *J. Sed. Petrol.*, **61,** 1225–1252.

Osleger, D. and **Read, J.F.** (1993) Comparative analysis of methods used to define eustatic variations in outcrop: Late Cambrian interbasinal sequence development. *Am. J. Sci.*, **293,** 157–216.

Peale, A.C. (1890) *Tenth Annual Report of the United States Geological Survey of the Interior for 1888–1889.* Part 1, pp. 130–132.

Peale, A.C. (1893) Paleozoic section in the vicinity of Three Forks, Montana. *US Geol. Surv. Bull.*, **110,** 1–56.

Pope, M.C., Read, J.F., Bambach, R. and **Hofmann, J.J.** (1997) Late Middle to Late Ordovician seismites of Kentucky, southwest Ohio and Virginia: sedimentary recorders of earthquakes in the Appalachian basin. *Geol. Soc. Am. Bull.*, **109,** 489–503.

Prior, D.B. and **Coleman, J.M.** (1982) Active slides and flows in underconsolidated marine sediments on the slopes of the Mississippi delta. In: *Marine Slides and Other Mass Movements* (Eds S. Saxov and J.K. Nieuwenhuis), pp. 21–49. Plenum Press, New York.

Prior, D.B., Suhayda, J.N., Lu, N.-Z., Bornhold, B.D., Keller, G.H., Wiseman, W.J., Jr, Wright, L.D. and **Yang, Z.-S.** (1989) Storm wave reactivation of a submarine landslide. *Nature*, **341,** 47–50.

Roehl, P.O. (1967) Stony Mountain (Ordovician) and Interlake (Silurian) facies analogs of recent low-energy marine and subaerial carbonates, Bahamas. *AAPG Bull.*, **51,** 1979–2023.

Runkel, A.C. (1994) Deposition of the uppermost Cambrian (Croixan) Jordan Sandstone and the nature of the Cambrian–Ordovician boundary in the Upper Mississippi Valley. *Geol. Soc. Am. Bull.*, **106,** 492–506.

Saltzman, M.R. (1999) Upper Cambrian carbonate platform evolution, Elvinia and Taenicephalus Zones (Pterocephaliid–Ptychaspid biomere boundary), northwestern Wyoming. *J. Sed. Res.*, **69,** 926–938.

Sanderson, D. and **Donovan, R.N.** (1974) The vertical packing of shells and stones on some recent beaches. *J. Sed. Petrol.*, **44,** 680–688.

Sepkoski, J.J., Jr (1982) Flat-pebble conglomerates, storm deposits, and the Cambrian bottom fauna. In: *Cyclic Event and Stratification* (Eds G. Einsele and A. Seilacher), pp. 371–388. Springer-Verlag, Berlin.

Tucker, M.E. and **Wright, V.P.** (1990) *Carbonate Sedimentology*. Blackwell, Oxford, 482 pp.

Walker, R.G. (1984) Shelf and Shallow Marine Sands. In: *Facies Models* (Ed. R.G. Walker), 2nd edn, pp. 141–170. Geological Association of Canada, Toronto.

Wilson, M.D. (1985) Origin of Upper Cambrian flat pebble conglomerates in the Northern Powder River Basin, Wyoming. *7th SEPM Core Workshop*. Golden, CO, pp. 1–50.

Wright, V.P. (1984) Peritidal carbonate facies models: a review. *Geol. J.*, **19,** 309–325.

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