Sequence stratigraphy in Proterozoic successions

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ABSTRACT

Sedimentological logging and facies mapping have been used to identify depositional sequences bounded by subtle but regionally persistent unconformities in rocks of Proterozoic age in the western United States, South Australia, and northwestern Canada. We conclude from these studies that the sequence stratigraphic approach is of considerable importance for intrabasinal time correlation in the Proterozoic and for facies interpretation and basin analysis in Proterozoic rocks.

INTRODUCTION

Dating in sedimentary rocks of Proterozoic age is generally imprecise, and correlation is largely lithostratigraphic. Biostratigraphic and paleomagnetic techniques, for example, provide only limited age resolution (e.g., Elston and Bressler, 1980; Bertrand-Sarfati and Walter, 1981; Vidal and Knoll, 1983). Isotopic ages from Proterozoic rocks are commonly problematic because isotopic systems tend to be reset by younger thermal events, and detrital minerals may yield the age of source terranes rather than the time of deposition (Moorbath and Taylor, 1985).

Prominent angular unconformities have been recognized, but the limitations of existing dating have led Proterozoic strata to be widely regarded as relatively conformable, even in successions as much as several kilometres thick (e.g., Crittenden et al., 1971; Preiss and Forbes, 1981). Such conformity in thick sections is unusual in Phanerozoic deposits for which better age resolution is possible. Moreover, most unconformities have chronostratigraphic significance, and they have long been used to develop time correlation in the Phanerozoic (e.g., Sloss, 1963; Vail et al., 1977; Ramsbottom, 1979; Busch and Rollins, 1984; Ross and Ross, 1985; Haq et al., 1987; International Subcommission on Stratigraphic Classification, 1987; Christie-Blick et al., 1987). We present evidence that regionally traceable unconformities are more abundant in Proterozoic strata than generally thought and that they therefore provide an important tool for establishing intrabasinal time stratigraphy in the Proterozoic.

UNCONFORMITY-BOUNDED DEPOSITIONAL SEQUENCES

Depositional sequences are defined as relatively conformable successions of genetically related strata bounded by unconformities or their correlative conformities (Vail et al., 1977; Haq et al., 1987; van Wagoner et al., 1987; see also International Subcommission on Stratigraphic Classification, 1987). Such sequences exist at a range of scales (Ramsbottom, 1979; Ryer, 1983; Busch and Rollins, 1984; van Wagoner et al., 1987) and form in response to changes in depositional base level and sediment supply (see Christie-Blick et al., 1987). Figure 1 illustrates lithofacies organization (systems tracts) and chronostratigraphy for parts of three idealized sequences on the order of tens to hundreds of metres thick, as well as the conceptual framework for the examples described in this paper.

The downward shift in coastal onlap associated with each sequence boundary is a response to an increase in the rate of sea-level fall or to a decrease in the rate of subsidence. Although sequence boundaries formed in this way exhibit a continuum of characteristics, two main types exist (Haq et al., 1987; van Wagoner et al., 1987). Type 1 boundaries are associated with stream rejuvenation, bypassing of shelf areas, and deposition preferentially in adjacent basins (lowstand wedge systems tract, LSW in Fig. 1). Type 2 boundaries generally lack these features and are overlain with less pronounced hiatuses by shelf sediments (shelf-margin wedge systems tract, SMW in Fig. 1). Renewed coastal onlap against a sequence boundary results from a decrease in the rate of sea-level fall or from an increase in the rate of subsidence and, hence, a relative rise of base level.

Within the onlapping strata, the transgressive surface is the lowest significant marine-flooding surface within a sequence, corresponding to the time of peak regression, and separates progradational to aggradational facies assemblages (LSW and SMW) from retrogradational facies assemblages (transgressive systems tract, TST in Fig. 1). The condensed interval, stratigraphically above the transgressive surface, is characterized by thin pelagic and hemipelagic sediments. It forms when the rate of sea-level fall is near a minimum or the rate of subsidence is near a maximum, and passes upward into progradational to aggradational facies assemblages of the highstand systems tract (HST in Fig. 1).

Sequence stratigraphy differs from lithostratigraphy because the former is based on genetic units rather than conventional map units (Fig. 1). Although sequence boundaries and transgressive surfaces locally coincide with abrupt lithostratigraphic contacts, many lithostratigraphic boundaries are defined by arbitrary cutoff within facies transitions. On the other hand, sequence boundaries may be present even where lithostratigraphic contacts appear to be gradational (e.g., between formations D and E in Fig. 1). Sequence boundaries are important not for the degree of erosion involved, which is generally limited, but for their regional persistence.

PROTEROZOIC EXAMPLES

Regional sedimentological and stratigraphic studies in North America and Australia show

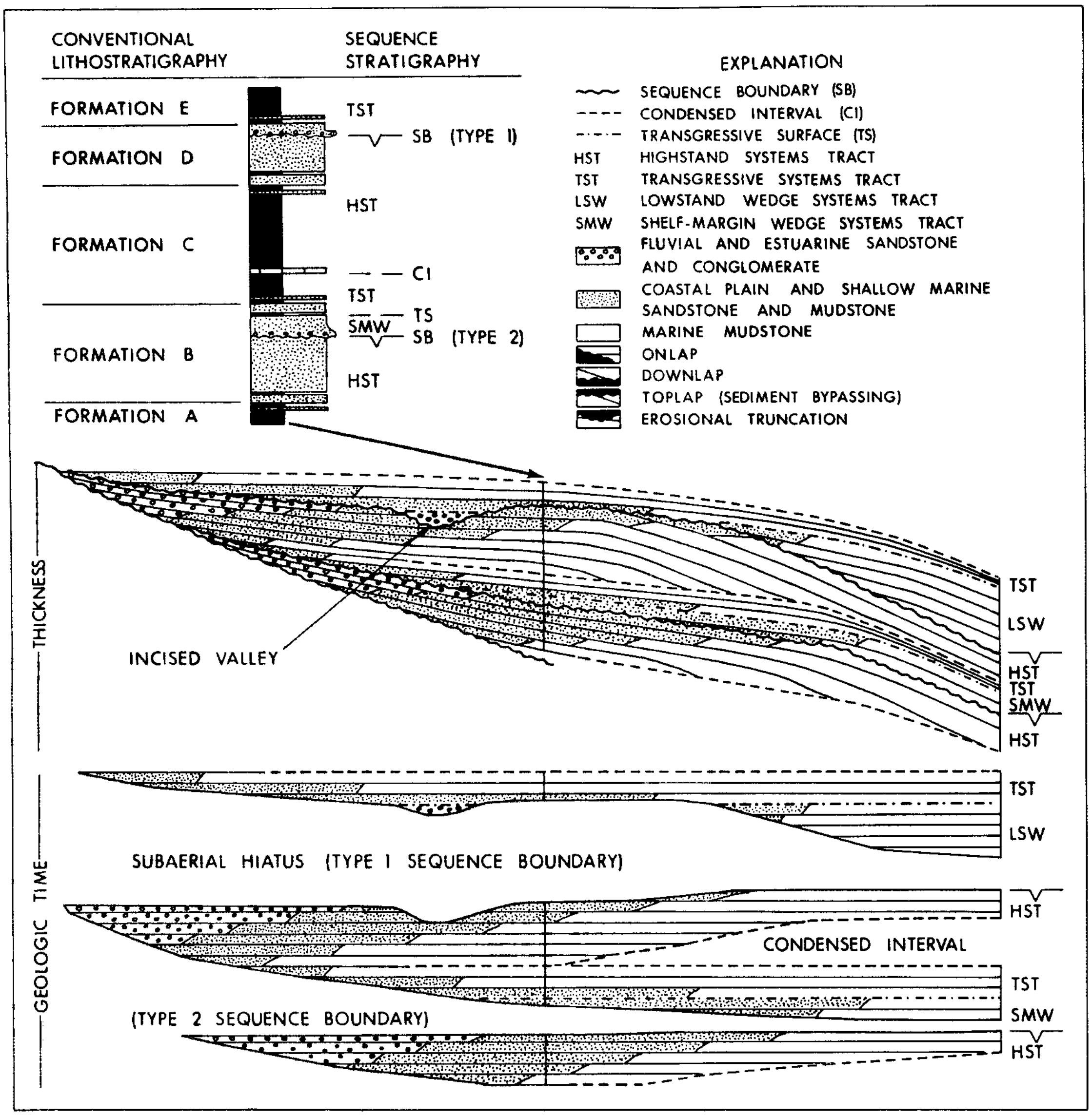

Figure 1. Conceptual cross sections showing lithofacies organization (systems tracts) and chronostratigraphy for parts of three sequences, and comparison of conventional lithostratigraphy and sequence stratigraphy for one locality (modified from Haq et al., 1987; van Wagoner et al., 1987). See text for further explanation.

that sequence stratigraphic concepts are applicable to the Proterozoic despite obvious difficulties in calibration and the detection of hiatuses. Here, we briefly discuss examples from three successions; additional details will be published elsewhere.

Kelley Canyon Formation and Brigham Group (Utah and Idaho)

The Brigham Group (Late Proterozoic to Early Cambrian age) of northern Utah and southeastern Idaho consists of about 2–4 km of shallow-marine and fluvial quartzite, and minor argillite, conglomerate, carbonate, and volcanic rocks (Fig. 2; Crittenden et al., 1971; Christie-Blick, 1982; Link et al., 1987). The underlying Kelley Canyon Formation (about 600 m thick) is predominantly marine argillite and minor carbonate and sandstone. The Kelley Canyon–Brigham succession was deposited partly in an extensional intracratonic basin and in part following development of the Paleozoic passive continental margin in western North America. The strata are divisible into four depositional sequences (Fig. 2), which can be traced as far as 500 km in a north-south direction and about 200 km east-west.

A regional cross section for the type 1 sequence boundary at or near the base of the Inkom Formation (Fig. 2) illustrates the methodology and the distinction between sequence stratigraphic and conventional lithostratigraphic approaches. As originally defined by Crittenden et al. (1971), the lithostratigraphic contact between the Inkom Formation (I in Fig. 2) and Caddy Canyon Quartzite (CC) ranges from sharp to gradational and is usually located at the top of the highest prominent quartzite (compare with Fig. 1). Sedimentological logging and facies mapping in the southern Sheeprock Mountains, northern Portneuf Range, and Huntsville area show that this apparently conformable transition conceals a regional unconformity characterized by subtle truncation of underlying strata, onlap of overlying strata, and a discontinuity in the facies succession. In the Sheeprock Mountains, pebbly and granular sandstone and pebble conglomerate with outsize clasts of argillite as large as 3.5 m (interpreted as fluvial deposits) fill a channel about 45 m deep and more than 100 m wide, cut into parallel stratified, texturally mature coarse- to fine-grained quartzite (marine). In the Portneuf Range, the uppermost part of the Caddy Canyon Quartzite (above horizon a in

Fig. 2) consists of lenticular, parallel stratified sandstone and argillite with abundant flaser bedding (marine). These units onlap horizon a, an erosion surface, with subtle discordance (inset cross section in Fig. 2). Beneath horizon a, channel-filling conglomerate and sandstone, with locally abundant argillite clasts, define well-developed fining-upward sequences 1–3 m thick and are interpreted as fluvial. At Huntsville, the upper part of the Caddy Canyon Quartzite consists of channelized, cross-stratified to parallel-laminated quartzite with fining-upward sequences (braided-fluvial or fluvially dominated shallow marine). These rocks are overlain with sharp contact by offshore marine shale of the Inkom Formation. The lower part of the shale contains bodies of lenticular sandstone with irregular wavy laminae here ascribed to wave activity in the shallow marine environment. The lenticular sandstones appear to onlap the contact along an erosion surface, which locally cuts out as much as 120 m of the Caddy Canyon Quartzite.

The facies discontinuity at or near the base of the Inkom Formation is most pronounced at localities near the eastern margin of the basin (e.g., Canyon Range and Huntsville in Fig. 2), where the sequence boundary is inferred to merge with the transgressive surface (compare with Fig. 1). In the Sheeprock Mountains, conglomeratic rocks assigned by Christie-Blick (1982) to the lower part of the Inkom Formation (Fig. 2) are interpreted as incised valley fill of the lowstand wedge systems tract (LSW in Fig. 1). Similar facies in the upper Caddy Canyon Quartzite of the Drum Mountains and Portneuf Range (Fig. 2) appear to pass gradationally downward into finer grained sandstones and, subject to continuing research, are interpreted as the upper part of a highstand systems tract (HST in Fig. 1).

Three other sequence boundaries have been identified in the succession (Fig. 2). In descending stratigraphic order these are at the base of the Geertsen Canyon Quartzite (and correlative

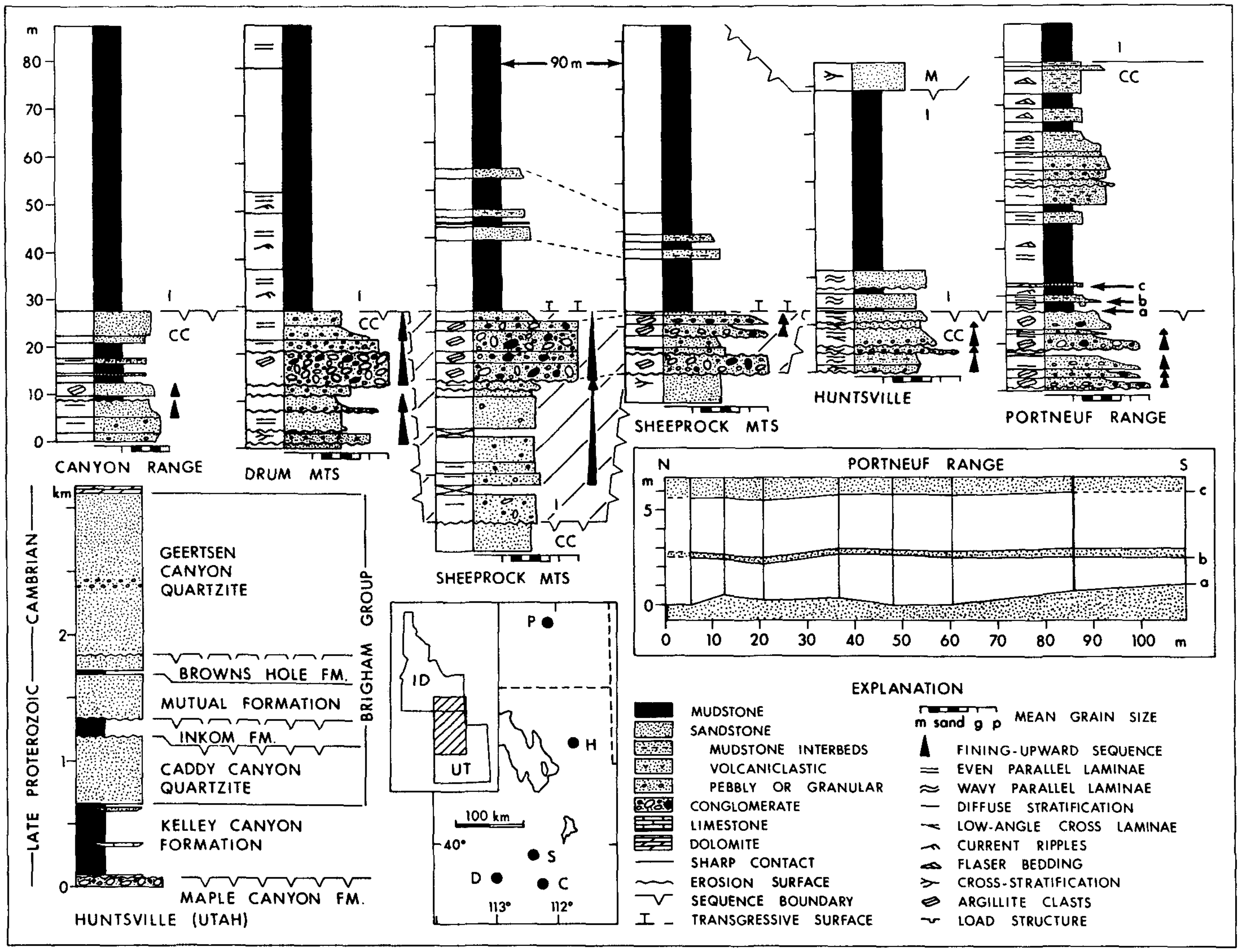

Figure 2. Regional cross section for type 1 sequence boundary at or near base of Inkom Formation (Late Proterozoic), northern Utah and southeastern Idaho, and sequence stratigraphy for strata of Late Proterozoic and Cambrian age in Huntsville area. Hachured part of cross section in columns for Sheeprock Mountains indicates strata interpreted as incised valley fill of lowstand wedge systems tract (see Fig. 1). Detailed cross section for Portneuf Range shows subtle onlap of marine strata against subaerial erosion surface (horizon a). Bold line on this section indicates location of stratigraphic log for Portneuf Range. Stratigraphic units: CC = Caddy Canyon Quartzite; I = Inkom Formation; M = Mutual Formation. Localities: C = Canyon Range; D = Drum Mountains; S = Sheeprock Mountains; H = Huntsville; P = Portneuf Range.

Camelback Mountain Quartzite in Idaho), at or near the base of the Mutual Formation, and at the base of the Kelley Canyon Formation. At Huntsville, the uppermost of these boundaries (type 1?) corresponds with an abrupt change in sandstone composition from quartz sandstone in the upper part of the Browns Hole Formation to feldspathic sandstone in the Geertsen Canyon Quartzite. In Idaho, the Camelback Mountain Quartzite fills a 40-m-deep channel in the upper part of the Mutual Formation (Link et al., 1987). The second boundary, also a type 1 boundary, in most places corresponds to a sharp contact between marine shale of the Inkom Formation and braided fluvial sandstone of the Mutual Formation. The existence of a sequence boundary is especially clear in the Sheeprock Mountains (see map in Fig. 2), where paleocurrents reverse at the contact from northeast-directed in the Inkom to southwest-directed in the Mutual. The lowest boundary is well defined at Huntsville, where laminated cherty dolomite at the base of the Kelley Canyon Formation overlies glacial-fluvial(?) conglomerate of the Maple Canyon Formation with sharp contact (type 2 sequence boundary?). We interpret the upward transition from dolomite to argillite as a response to deepening (transgressive systems tract).

The Kelley Canyon Formation is the only thick argillaceous unit in the succession and may contain evidence for a condensed interval. About 200 m above the base of the formation, carbonate reappears as lenses of concretionary argillaceous limestone. Crittenden et al. (1971) correlated the limestones with ooid and intraclast grainstones of the Blackrock Canyon Limestone of southeastern Idaho. An alternative working hypothesis is that the limestones represent a condensed interval and a relatively deep-water facies of the Kelley Canyon Formation.

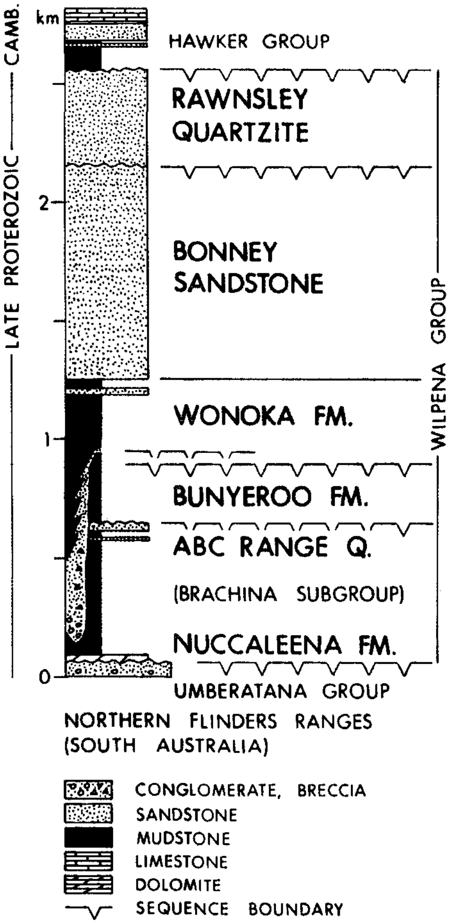

Figure 3. Sequence stratigraphy for strata of Late Proterozoic and Cambrian age in northern Flinders Ranges, South Australia (from von der Borch et al., 1987).

Wilpena Group (South Australia)

The Wilpena Group (Late Proterozoic) is composed of about 2.5 km of sandstone, argillite, and carbonate rocks, deposited in fluvial to relatively deep-marine environments in the upper part of the Adelaide "Geosyncline" (Preiss and Forbes, 1981). The complete succession includes both synrift and postrift strata, but the stratigraphic location of the transition is uncertain.

The Wilpena Group is divisible into four main sequences and many minor ones, particularly in the cyclically stratified shallow-marine and fluvial sandstones of the Bonney Sandstone (Fig. 3; von der Borch et al., 1987). The main sequences can be traced over 200 km in the northern and central Flinders Ranges of South Australia, and with less certainty over 2500 km across the Australian continent. Two closely spaced boundaries (type 1) are present at or near the base of the Wonoka Formation, which occupies erosional incisions cut as deeply as 1 km into the underlying Brachina Subgroup (von der Borch et al., 1985, 1987). Away from the incisions, the contact between siliciclastic argillite of the Bunyeroo Formation and argillite and calcarenite of the Wonoka is subtle and would probably be termed conformable by many stratigraphers. Incisions with less relief are also present locally at the base of both the Rawnsley Quartzite and the Hawker Group. Other contacts are, for the most part, concordant, and sequence boundaries are defined largely by facies discontinuities. Sequence boundaries at or near the base of the Nuccaleena Formation and Bunyeroo Formation closely resemble those at the base of the Kelley Canyon Formation and near the contact between the Caddy Canyon Quartzite and Inkom Formation in the western United States.

Bear Creek Group (Northwest Territories, Canada)

The Bear Creek Group (1.9 Ga) is composed of as much as 5 km of siliciclastic and carbonate rocks deposited in deep-marine, shallow-marine, and fluvial environments during development of a foreland basin along the eastern margin of Slave craton (Grotzinger and McCormick, 1988). The shelf deposits consist, for the most part, of interstratified units of relatively deep-water laminated mudstone and sandy mudstone, shallow-marine sandstone with hummocky cross stratification and polymodal paleocurrents patterns, and minor carbonate (intraclast/ooid grainstones and stromatolitic reefs). These facies are arranged into four main unconformity-bounded sequences, which generally coarsen and shallow upward (Fig. 4), and are laterally traceable for over 200 km.

An especially distinctive feature of the succession is diagenetic exposure fabrics developed

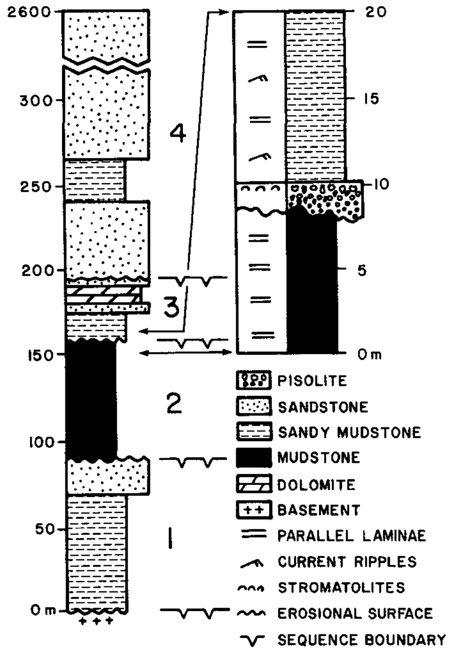

Figure 4. Sequence stratigraphy of Bear Creek Group (1.9 Ga), Kilohigok basin, Northwest Territories, Canada. Units 1 to 3 correspond to Hackett, Rifle, and Beechey Formations; unit 4 includes Link and Burnside Formations. Contact between sequences 2 and 3 is unusual because it superposes two relatively deep-water shelf sequences and is characterized by well-developed pisolitic paleosol. Extent of fabric development varies along strike from simple erosional surface associated with minor alteration to brecciated zones up to several metres thick with large, dislocated blocks, reverse-graded pisolite, and solution-enlarged karstic voids containing paleostalactites.

beneath several unconformities. The fabrics range from incipient alteration to brecciated zones up to several metres thick, with evidence of dissolution, karst development, and replacement. In advanced stages, paleosols are vertically zoned with well-developed pisolitic horizons. The existence of such pisolites between sequences 2 and 3 (Fig. 4) demonstrates the existence of a type 1 boundary even though deep-water mudstones and sandy mudstones are present both above and below the contact. In several cases, mapping indicates that the unconformities represent surfaces of toplap and/or erosion, against which there is onlap of the overlying strata.

SUMMARY AND DISCUSSION

Sequence boundaries can be recognized in Proterozoic rocks from a combination of sedimentological logging and facies mapping at local to regional scales, and they provide an important tool for intrabasinal time correlation. The principal criteria for identifying sequence boundaries are evidence for stratal discordance (onlap, downlap, toplap, and erosional truncation) and discontinuities in facies successions. Stratal discordance may be subtle, however, and the importance of a given boundary lies in its regional persistence, not in the amount of discordance observed. Subsidiary evidence for a sequence boundary includes marked changes in provenance, changes in paleocurrent trends, and diagenetic exposure fabrics.

Mapping indicates that discordant boundaries pass laterally into concordance with overlying and underlying strata, particularly away from basin margins, and in places boundaries become cryptic, but this does not necessarily prevent the sequence stratigraphic approach from being useful on a regional scale. The transgressive surface and other marine-flooding surfaces within a sequence are also characterized by prominent facies discontinuities. These surfaces can be distinguished from sequence boundaries involving a downward shift in onlap on the basis of facies geometry and stacking (see van Wagoner et al., 1987) and absence of evidence for appreciable erosion.

The origin of sequence boundaries is controversial even in better dated Phanerozoic strata (summarized in Christie-Blick et al., 1987), but some regionally persistent boundaries of Proterozoic age may be eustatic. In the Bear Creek foreland basin, for example, sequences can be correlated from the inner side of the basin far onto the craton beyond the peripheral flexural bulge (Grotzinger and McCormick, 1988) and are therefore unlikely to be of local tectonic origin. As numerical age calibration improves and a eustatic origin for individual boundaries becomes more firmly established, it may be possible to undertake intercontinental correlations between coeval Proterozoic sequences such as those of Late Proterozoic age in the western United States and South Australia.

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