Received: 20 December 2017 | Revised: 8 June 2018 | Accepted: 18 June 2018

DOI: 10.1002/dep2.46

ORIGINAL RESEARCH ARTICLE

WILEY The Depositional Record Open Access
The journal of the International Association of Seidmentologisits

New perspectives on the Luoquan Glaciation (Ediacaran-Cambrian) of North China

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Funding information
National Natural Science Foundation of China, Grant/Award Number: 41472103; National Science and Technology Major Project, Grant/Award Number: 2016ZX05004001; Kirsty Brown Memorial Fund, Ian Gass Bursary (Open University); London NERC DTP

Abstract

The Luoquan Formation provides a record of the Ediacaran-Cambrian glaciation in the North China Craton. The sedimentary record is well expressed in the Henan Province along the central China orogen, and includes a rich archive of striated pavements, diamictites, and dropstone-bearing laminites. A reappraisal of the sedimentological evolution of the Luoquan Formation notes the following features. First, striated pavements with crosscutting striations do not necessarily record multiple phases of glacial (re)advance, but more likely originate through the development of sticky spots in a palaeo-ice stream setting. The development of obstacles, basal adfreezing, or porosity variations in the subglacial substrate resulted in curvilinear and bifurcating striae, which can superficially be mistaken for crosscutting striae in isolated sections. Second, "massive" diamictites as previously described are in fact commonly weakly stratified, and there is a continuum from dropstone-bearing rhythmically bedded shales and siltstones, through stratified diamictites to massive diamictites. This continuum is believed indicative of deposition by rain out from debris rich ice for those diamictites with less pronounced stratification, in contrast to the mass flow hypothesis previously suggested. Third, the presence of large-scale, recumbent folds with associated thrusts is described at the type section. The suite of large-scale deformation structures, measuring >30 m in amplitude, is sealed by undeformed diamictites. The deformation structures are interpreted to reflect soft-sediment deformation produced through ice bulldozing. Integrating these observations, it is proposed that the Luoquan Formation was deposited in a large proglacial lake setting, with a range of ice contact to ice distal environments recognized.

KEYWORDS
cambrian, China, Ediacaran, glacial, glaciation

1 | INTRODUCTION

The Neoproterozoic is arguably most famous for its severe glacial episodes which dominated the Cryogenian interval, and which may have been global in extent (Evans & Raub, 2011; Hoffman, Kaufman, Halverson, & Schrag, 1998; Li, Evans, & Halverson, 2013). Most focus has been on the Sturtian (*ca* 717–660 Ma) and the Marinoan (*ca* 651–635 Ma) glaciations (Evans & Raub, 2011; Fairchild & Kennedy, 2007; Hoffman & Li, 2009;

Hoffman et al., 1998, 2017; Li et al., 2013; Rooney, Strauss, Brandon, & Macdonald, 2015; Zhao & Zheng, 2010; Zhou et al., 2004). Many workers consider these to be discrete global Snowball Earth glaciations, although poor global age control equally allows them to be viewed as diachronous (Spence, Le Heron, & Fairchild, 2016). Two other glaciations (Kaigas, *ca* 757–741 Ma, and Gaskiers, *ca* 590–582 Ma) are also recognized but considered to represent non-Snowball Earth conditions (Gao et al., 2013; Li et al., 2013; Pu et al., 2016). In the absence of other age constraints, diamictites of presumed glacial origin are widely used in the correlation of glacial cycles and palaeoclimate in the Neoproterozoic (Eyles & Eyles, 1983; Le Heron, Tofaif, Vandyk, & Ali, 2017). The Gaskiers glaciation of north east North America is an example of an increasingly tightly constrained glaciation, likely ≤340 Ka in duration, which was posited to have occurred <9.5 Myr prior to the advent of the Ediacaran biota (Pu et al., 2016). In spite of the emerging view that the Gaskiers glaciation is of regional, rather than global extent (Pu et al., 2016; Spence et al., 2016), glacial deposits of broadly similar age are recognized on other continents (Li et al., 2013). In China, these include the deposits of the Tarim Craton in the north-west, and those of the North China Craton (NCC). The latter are the focus of this paper.

The NCC, together with the South China Block and the Tarim Craton, are major Precambrian cratonic blocks (Zhao & Cawood, 2012) (Figure 1a). In the Tarim craton, there are four possible glaciations, ranging in broad age from late Tonian to Ediacaran; this compares to two Cryogenian glaciations in the South China craton and only one, the Luoquan glaciation, of Ediacaran to early Cambrian age in the NCC (Gao et al., 2013; Xu, Zou, Chen, He, & Wang, 2013). In contrast to the well-studied, but older, Cryogenian glacial diamictites of the South China Block (Arnaud, Halverson, & Shields-Zhou, 2011 and refs therein), the Luoquan diamictite has been subject to substantially less investigation. Debates revolve around whether the Luoquan Formation is glacial (Guan, Wu, Hambrey, & Geng, 1986; Mou, 1983; Mu, 1981; Yang & Wu, 1994) or of mass flow origin (Hong, 1984; Li, Li, & Zheng, 1990; Zhou, Xu, & Long, 2010).

Given the value of diamictite-bearing deposits in revealing insights into past climates, including both the severity of glaciations in the context of snowball Earth (Spence et al., 2016), new perspectives and a re-evaluation of the Luoquan Formation is long overdue. The aim of this paper was thus to present new data and fresh perspectives on both well-known (although not well published on) sections and lesser known sections, with high quality, high resolution sedimentary logs (Figure 2), soft-sediment deformation structures, and striated surfaces all considered. The new work forms the framework for future investigations, across the southern flank of the NCC.

2 | BACKGROUND

2.1 | Tectonic setting

The Luoquan Formation, and its equivalents, extend over 2,000 km across the Central China Orogen and its type section was established at Luoquan village in 1961 (34° 00.27′ N, 112° 44.73′ E) (Guan et al., 1986; Mou, 1983; Mu, 1981; Yin et al., 2015). The southern NCC includes a range of Archean to early Palaeoproterozoic basement rocks that are mantled by late Palaeoproterozoic to Phanerozoic cover sequences (Deng, Zhao, & Peng, 2016; Yin et al., 2015). The basement mostly comprises Neoarchean-Palaeoproterozoic metamorphic rocks that include graphite-bearing gneisses, greenstones, biotite gneisses, marbles and banded iron formations (Yin et al., 2015). Locally, these rocks are unconformably overlain by Palaeoproterozoic quartzites, which are in turn overlain by Meso-Neoproterozoic sedimentary rocks (Yin et al., 2015).

The Luoquan Formation was deposited upon the southern to south-western margin of the NCC, which had assembled over a billion years earlier (*ca* 1.85 Ga; Zhao & Zhai, 2013; Zheng, Xiao, & Zhao, 2013) and was likely at low latitudes during Luoquan deposition (Huang, Yang, Otofuji, & Zhu, 1999; Zhang, Li, Wu, & Wang, 2000). The Tonian to earliest Cambrian position of the NCC relative to other palaeocontinents remains contentious, with several workers tentatively placing it alongside Siberia (Li et al., 2008; Merdith et al., 2017). The South China Block and Tarim Craton were not joined with the NCC during Luoquan Fm deposition (Merdith et al., 2017; Song, Niu, Su, & Xia, 2013; Wen, Evans, & Li, 2017; Wu & Zheng, 2013). Moreover, the Kuanping unit, which today borders the NCC immediately south of the Luouqan Formation, did not accrete until 440 to 400 Ma, by subduction beneath the Kuanping unit (Wang, Deng, Bagas, & Wang, 2017 and references therein).

2.2 | Age and stratigraphy

The Luoquan Formation unconformably rests upon various units, the youngest of which is the Dongjia Fm, and is conformably overlain by the Dong Po Formation (Guan et al., 1986). The former consists of carbonaceous shale, siltstones and glauconitic sandstone overlain by argillaceous dolostones, which are interpreted as marine. Acritarchs in the Dongjia Formation are dominated by non-spinose varieties suggesting an early Neoproterozoic age (Yin & Guan, 1999). The deposits of the Dong Po Formation, meanwhile, include glauconitic siltstone and fine-grained sandstone,

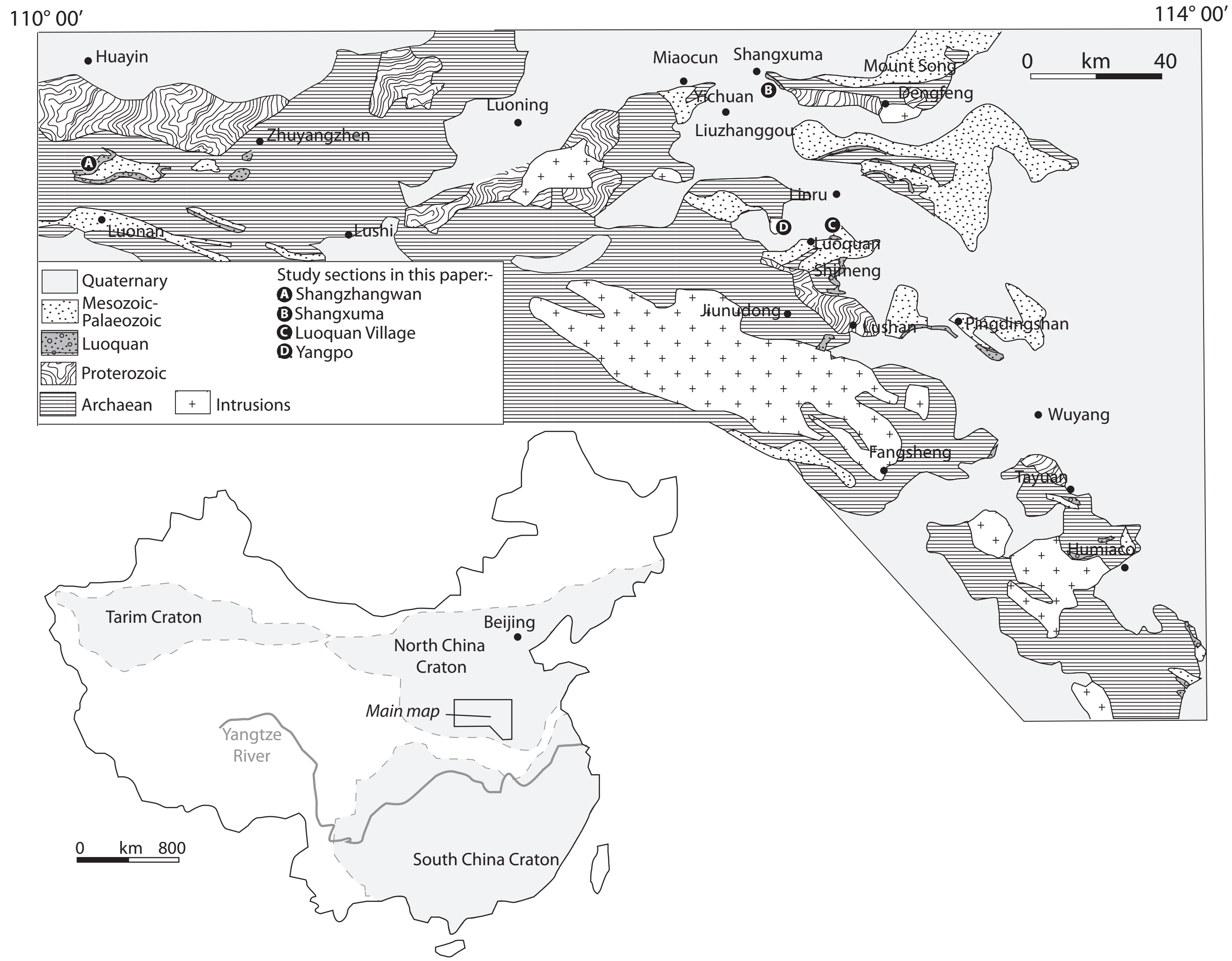


FIGURE 1 Simple geological overview map of the southern margin of the North China Craton showing the distribution of the Luoquan Formation. The principal study areas in this paper (Shangzhangwan, Shangxuma, Luoquan Village, Yang Po and Xunjan) are shown. Map redrafted and slightly modified after Guan et al. (1986)

also interpreted as marine (Yin & Guan, 1999). Yin and Guan (1999) examined the boundary between the Luoquan and overlying Dong Po Formation and reported small spinose *Micrhystridium*-like acritarchs from both formations. *Micrhystridium* has subsequently been renamed and subdivided into *Asteridium* and *Heliosphaeridiu* (Yao, Xiao, Yin, Li, & Yuan, 2005), which on other palaeocontinents form part of the *Asteridium–Heliosphaeridium–Comasphaeridium* (AHC) assemblage. The first appearance datum for the AHC is the lowermost Cambrian in Avalonia, South China, Spain, Tarim, India and South Australia (Ahn & Zhu, 2017, p. 1218 and references therein). In addition, Guan et al. (1986) reported *Trachysphaeridium, Taeniatum, Lophosphaeridium and Tasmanites* from the Luoquan Formation. The latter two are elsewhere found in association with the *Asteridium–Comasphaeridium* assemblage and linked to the Ediacaran-Cambrian transition (Högström, Jensen, Palacios, & Ebbestad, 2013 and refs therein). Further up section, the Xinji Formation unconformably overlies the Dong Po Formation, and contains a diverse fossil assemblage compatible with Series 2 of the Cambrian (*ca* 521–509 Ma) (Yun, Zhang, Li, Zhang, & Liu, 2016).

A shale Rb-Sr age of 528 (±23) Ma from the Dong Po Formation and glauconite K-Ar date of 650 Ma (±33) from the Dongjia Formation are compatible with an Ediacaran-Cambrian interpretation for the Luoquan Formation (see Zhang et al., 2000). In addition, Guan et al. (1986, table 2) noted a previously obtained glauconite K-Ar age of 503 Ma from the Dong Po Fm, but did not state their source. In contrast, a shale Rb-Sr age of 722 Ma (Li, Yang, & Jia, 1985; see Zhang et al., 2000) from the Luoquan Formation is inconsistent with bracketing radiometric ages and palaeontological constraint, likely resulting from inheritance (e.g. Bowring et al., 1993; Compston, Williams,

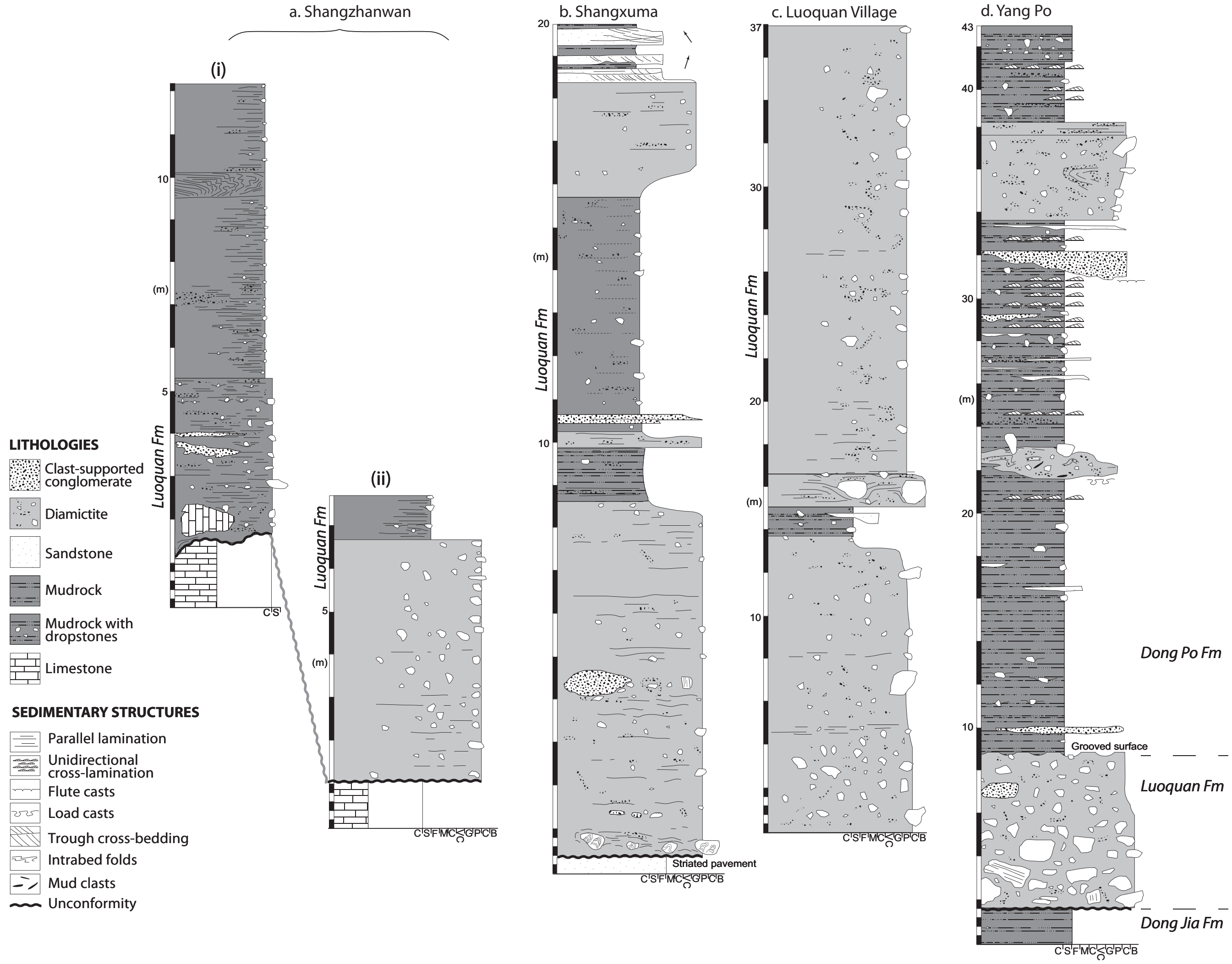


FIGURE 2 Detailed sedimentary logs from the key study areas, locations of which are shown on Figure 1. GPS co-ordinates for sections are as follows. (a) Shangzhangwan: 34°15.254′N 110°08.143′E; (b) Shangxuma: 34°31.550′N 112°33.514′E; (c) Luoquan Village: 34°00.266′N 112°44.733′E; (d) Yang Po: 35°03.174′N 112°35.448′E (lower part); 34°03.124′N 112°35.429′E (upper part)

Kirschvink, Zichao, & Guogan, 1992). In summary, the palaeontological data provide a more robust and consistent chronostratigraphic constraint than the radiometric data and support the earlier suggestion of Guan et al. (1986) and Yin and Guan (1999) that the Luoquan glaciation occurred during the late Ediacaran to early Cambrian.

2.3 | Previous sedimentological work

While the international literature of the Luoquan Formation is extremely scant, arguably restricted to the paper of Guan et al. (1986), there are a handful of papers published in Mandarin in regional journals and university periodicals in which two schools of thought emerge. On the one hand, a loose collective of scientists view the Luoquan as predominantly a mass flow succession, whereas on the other hand the strong influence of ice masses is emphasized. In the "mass flow" school, Hong (1984) suggested a gravity flow origin for the Luoquan Formation. Developing this idea, Li et al. (1990) interpreted it as a subaqueous fan characterized by gravity flows accumulating in an "offshore slope" setting, rather than a succession of glacial origin. Wang (1996) held a similar view (mass flows in a marine basin), and suspected that the Luoquan Formation was regionally diachronous, varying in age between Sinian (i.e. Ediacaran) and Cambrian across the southern fringes of the NCC. In the context of mass flows, Lin (2001) referred to the Luoquan Formation as "molasse" derived from a phase of mountain building at the southern fringes of the craton (the so-called Tianqin Movement commencing at about

700 Ma). Zhou et al. (2010) argues that a thin set of dolostones in the Luoquan Formation were the deposits of coastal tractional currents rather than from glaciation.

Guan et al. (1986) presented good quality sedimentary logs of the Luoquan Formation in its type area and in locations such as Shangxuma, where a high quality striated pavement is preserved. Attempts to correlate between sections were undertaken, and, on the basis of striation orientations measured from multiple examples of striated pavements, two principal ice-flow directions (from the north and from the northwest) were inferred. Yang and Wu (1994) likewise argued for a glacial origin. Consistent with the model of Guan et al. (1986), these studies envisaged an overall continental glacial environment, in which glaciers delivered material to lacustrine environments, as evidenced by an abundance of ice-rafted debris (IRD) in the formation. These workers also proposed a significant role for gravity reworking to explain the intercalation of thick diamictite accumulations with dropstone-bearing shales. Later, Ge and Cui (1994) described structures akin to cross-strata which were developed in diamictite oblique to bed boundaries. Recognizing that cross-beds form through tractive processes which sort and winnow material (in stark contrast to the unsorted texture of a diamictite), those workers instead proposed that the bedding-oblique structures formed through basal melt-out. Huang (1988) took a novel approach to test the glacial affinity of the Luoquan Formation, focussing on the concept of "terminal grade" for glacial deposits, which was initially proposed by Dreimanis and Vagners (1971) for Quaternary sediments. This concept proposes that phi 4–5 is the likely minimum grain-size in clasts produced by glacial abrasion and is explained through Griffiths crack theory (Benn & Evans, 2010). The terminal grade is also very much material dependant, and hence micas and feldspars may be expected to have smaller terminal grades than quartz for example (Haldorsen, 1983). Because a peak or bulge ("characteristic crest") is thus expected on a grain-size curve at phi 4 to 5, and is also present in the Luoquan Formation, Huang (1988) was able to confirm its glacial origins. Wu and Guan (1988) presented a couple of additional logs, developing the facies analysis presented in their earlier paper (Guan et al., 1986). While remaining in strong support of a glacial origin, they argued for a significant role of gravitational reworking to explain the abundant diamictites.

Apart from a single publication of Wang and Wang (2015) which presented a similar model with Wu and Guan (1988), there has been no substantial work on the Luoquan Formation in 25 years. Since then, however, there has been a paradigm shift in glacial sedimentology whereby ice streams are viewed as the principal agents of subglacial erosion and sediment transport (Bennett, 2003; Eyles, Putkinen, Sookhan, & Arbelaez-Moreno, 2016; Krabbendam, Eyles, Putkinen, Bradwell, & Arbelaez-Moreno, 2016; Le Heron, 2018; Stokes & Clark, 1999, 2001; Winsborrow, Clark, & Stokes, 2010). The rapid advancement of glaciology and glacial sedimentology means that it is thus timely and important to re-evaluate the true palaeoglaciological context of the Luoquan Formation. Given the question marks surrounding the precise tectonic setting, the nature of ice masses that deposited the Luoquan Formation deserves attention. The significance of the striated pavements, whether they represent the product of single or multiple glacial cycles, whether they represent the erosion of isolated valley glaciers or palaeo-ice stream pathways, merits re-appraisal. Furthermore, the relationship between diamictites and delicately laminated facies needs to be properly established to determine whether the former are ice-contact deposits or alternatively the products of slope collapse (either in a marine or lacustrine environment). The ultimate aim of this paper, therefore, is to shed light on these issues, by presenting new data from five key sections to deliver an updated, regional scale sedimentary model for the Luoquan Formation.

3 | DATA DESCRIPTION

This paper presents descriptions from five key sections which are shown on the overview geological map of the Hunan province/Xi'an area (Figure 1). Both these and the associated interpretations are presented on a geographic basis and then integrated to produce a new depositional model for the Luoquan Formation and associated strata.

3.1 | Luoquan Village section

This exposure represents the type section of the Luoquan Formation (Figure 2c). Mou (1983) reported the full thickness of the formation to be *ca* 190 m. This study, undertaken in September 2017, measured a 40 m thick succession similar to Wang and Wang's (2015), and corresponding to the basal part of Wu and Guan's (1988) section (Figure 3a–c): the nature of the exposure on the hillslope for the remaining 150 m is very patchy and intermittent, as the outcrop is almost entirely concealed by vegetation. Nevertheless, the lower 40 m of the formation comprises high quality exposure. The section is dominated by massive diamictite at the base, and massive to stratified diamictite (Figure 3a) at the top. A crudely defined fining upward motif characterizes the lowermost 10 m of the formation. In this motif, a brown to maroon coloured massive diamictite, bearing clasts of sandstone, quartzite and occasional carbonate, fines upward in terms of maximum clast size (from boulders at the base to granules and pebbles at the top). The fining upward profile (Figure 2c) culminates in a

1 m thick green shale bearing abundant lonestones, which sits in gradational contact on the underlying diamictite. Approximately 100 m along strike across the exposure, metre-scale lenses of sandstone are observed within the shale package. At the same stratigraphic level, discordant, boudin-like packages of sandstone crosscut the shale and penetrate the underlying diamictite (Figure 3b). Upsection, the shale exhibits a gradational upper contact into stratified muddy diamictite, which is characterized by pebble to boulder-sized lonestones (Figure 3d).

In spite of the layer-cake appearance of the outcrop at the type section, and in contrast to the simple stratigraphy in previous publications (Wu & Guan, 1988), evidence for impressive intraformational folding was observed in a roadside section <1 km from the village (Figure 4a,a'). Deformation is complex and comprises a large, recumbent antiform with associated disharmonic folds in adjacent layers, and low angle, abrupt discontinuities which truncate underlying beds (Figure 4a,a'). The entire outcrop is mantled by a comparatively less deformed interval which steepens progressively from the south-west to the north-west. The top of the measured section at Luoquan Village displays similar characteristics, with an isoclinal fold, possibly truncated by a thrust at the top (Figure 4b,b').

3.2 | Yang Po section

The Yang Po section has not previously been subject to detailed study, although two formations have been recognized through regional mapping, namely the Luoquan Formation and the overlying Dong Po Formation (Zhang, Du, Zuo, & Zhou, 2008). At Yang Po, the Luoquan Formation sits unconformably upon light grey silty dolomite of the Dongjia Formation (Figure 5a). At Yang Po, the Luoquan Formation is 4 m thick and consists of structureless, carbonate-rich, clast-rich diamictite (Figure 5b). Intraformational clasts of carbonate breccia (Figure 5c) and sandstone (Figure 5d) are also common. These, together with clasts of microbial carbonates, laminites, grey sandstones and cherty carbonate sit within a red matrix. Diamictites are dominated by angular to sub-angular clasts; an overall fining upward motif is apparent throughout the formation in terms of maximum clast size from boulders at the base to cobbles and pebbles at the top. The upper surface of the Luoquan Formation exhibits a ridge-groove morphology that is onlapped by undeformed red shales of the basal Dong Po Formation (Figure 6a,b).

The Dong Po Formation measures 33 m thick at the Yang Po section, and is characterized by blood red, lonestone bearing shales, with subordinate sandstones, conglomerates and diamictites (Figure 6c–k). Sandstones and conglomerates are developed in spectacular lenticular geometries measuring up to 10 m in width and up to 1 m thick. These lenticular-shaped bodies are characterized by highly irregular lower contacts which crosscut laminae in underlying shale, but typically have flat upper contacts (Figure 6c,d). Diamictite deposits substitute laterally for shales, and have two modes of occurrence. The first is a highly irregular facies, typified by feather-edges, intrabed folds, irregularly shaped clasts and its highly restricted lateral continuity (2 m thick beds die out laterally over a few metres) (Figure 6e). The second type is continuous over several tens of metres, and characterized by very gradational (imperceptible) lateral contacts with the lonestone-bearing shales and by its weakly stratified character. At the decimetre scale, interbedding of these weakly stratified diamictites and shales occurs.

From the basal contact with the underlying Luoquan Formation upward, the red shales intercalate with rippled sandstones (Figure 6f) and yield abundant lonestones throughout the formation (Figure 6g–j). At many intervals, these can be demonstrated to deflect and deform shale laminae (e.g. Figure 6i). Interestingly, red dolostone clasts (Figure 6j) yield tubestone textures, which are well-known sedimentary structures in Marinoan cap carbonates (Creveling, Bergmann, & Grotzinger, 2016). Sandstone and diamictite intervals occur more commonly upwards; with two exceptions, the lower 12 m are dominated by lonestone-bearing shales. Abundant unidirectional cross-laminae punctuate the lonestone-bearing shales in the upper third of the formation. Some of the lonestones in the red shales show evidence of facetted and striated surfaces (Figure 6k).

3.3 | Shangxuma section

The Shangxuma section (Figure 2b) was described briefly in Guan et al. (1986) and in Wu and Guan (1988) with special emphasis on its striated pavement. The striated pavement at Shangxuma is developed on fine-grained sandstones and is immediately overlain by blood-red diamictites correlated with the Luoquan Formation (Wu & Guan, 1988), but which more closely resemble the Dong Po Formation. Guan et al. (1986) interpreted the striated pavement to have formed beneath a grounded ice sheet that was flowing to the south east. However, Wu and Guan (1988) recognized cross-cutting striations, which they interpreted to represent two successive subglacial erosion events (i.e. two consecutive glacial cycles). Significantly, Guan et al. (1986) interpreted the presence of so-called "p-forms"—i.e. landforms developed through the plastic sculpting effects of ice.

A high resolution scaled drawing of the striated pavement has been produced based on >70 striation measurements, reconstructing the surface topography of ridges and grooves and the striations superimposed upon them

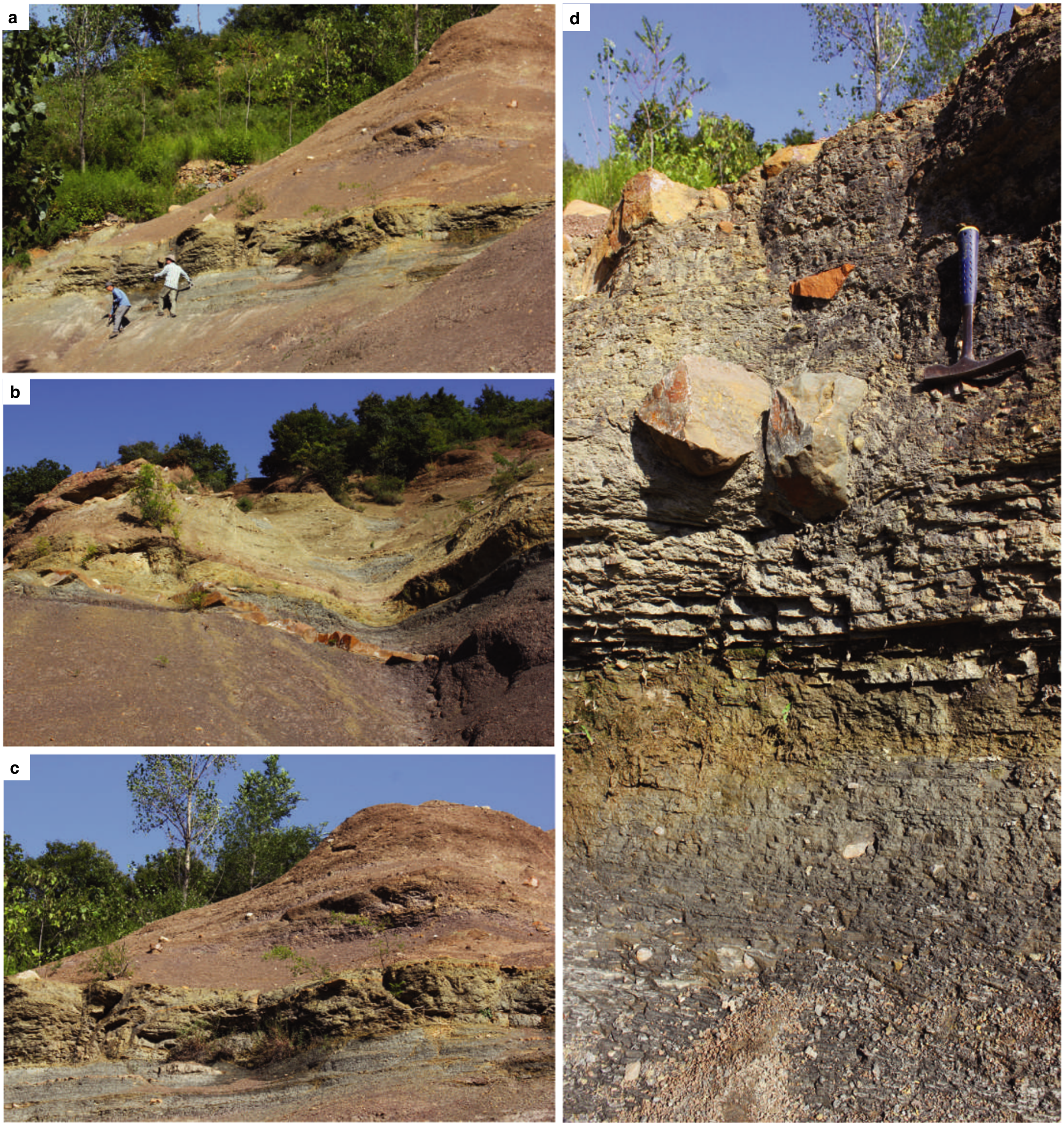


FIGURE 3 Typical sedimentary facies at Luoquan Village. (a) Interval of lonestone-bearing shale within an otherwise diamictite-rich succession. The geologist on the right has his feet on deposits shown at 14 m on Figure 2c. (b) Injectite structure/dyke extending from above the lonestone-bearing shale interval down into underlying diamictite. (c) Complete view of the upper part of the succession from the lonestone-bearing shale upward. (d) Detail of the lonestone-bearing shale (bottom part of photograph) and its gradual vertical transition into stratified diamictite that yields cobble- to boulder-sized clasts

(Figure 7a). While a dominant striation orientation at about 150° is recognized across the pavement, some striations show curvature, with end member measurements at about 142° and 159° (Figure 7a). The striated pavement is directly overlain by clast-poor diamictite (Figure 7b). Inspection of isolated areas of the striated pavement reveals crosscutting striations (Figure 7c). However, in at least two cases (Figure 7d,e), striations can be demonstrated to be curvilinear, producing apparent cross-cutting relationships as striations show local, lateral, diversions from a trough

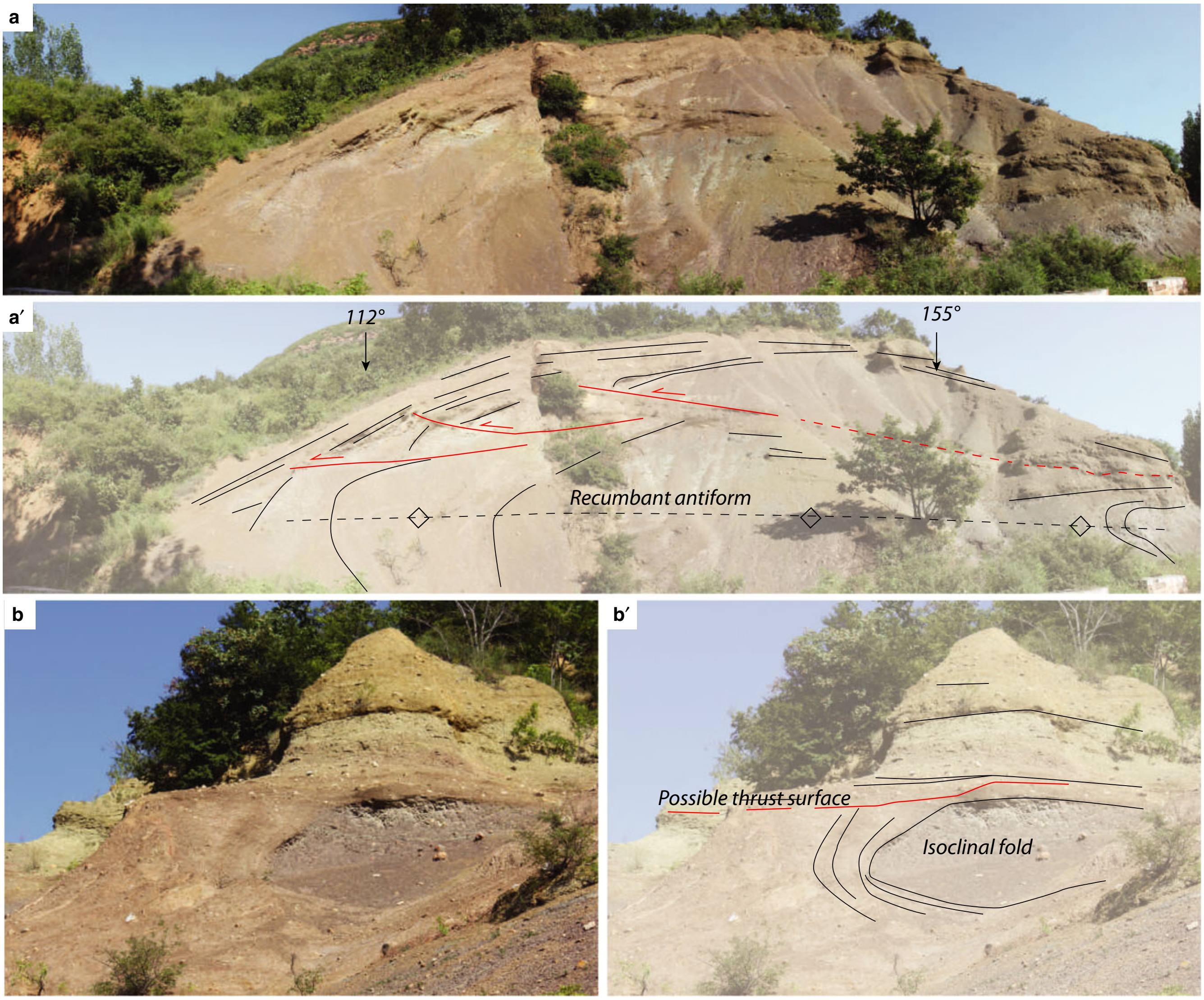


FIGURE 4 Large-scale soft-sediment deformation structures in the Luoquan Formation in the vicinity of the type section at Luoquan Village. (a and a′) 30 m amplitude recumbent antiform. Evidence of breaching by low angle thrusts and mantled by comparatively less deformed beds. (b and b′) Smaller scale isoclinal fold, truncated by a possible thrust surface, and overlain by undeformed subhorizontal diamictite. These soft-sediment deformation structures are interpreted as the products of glaciotectonism

onto the adjacent ridge. The striated surface expresses a well-developed polish, and striations locally affect the basal few millimetres of the overlying diamictite (Figure 7f). At the macro-scale, the striated pavement exhibits a stepped topography, with ridges and grooves in the upper step occurring *ca* 20 cm above their lower counterparts.

The regional dip of the striated pavement is parallel to the dip of the overlying strata, which comprises 19.5 m of red, locally stratified diamictite that is punctuated by a distinctive lonestone-bearing shale interval (Figure 2b). Basal diamictites above the striated pavement contain a train of four large stromatolite boulders (Figure 8a,b). The distinctive, lonestone-bearing shale interval exhibits sub-rounded clasts of sandstone and carbonate (Figure 8). The diamictite deposits are unconformably overlain by Cambrian cross-stratified sandstones (Figure 2b).

3.4 | Shangzhangwan section

Although this section has been well-known for many years (Gao, Wang, & Zhang, 2010; Yin et al., 2015), with a riverside outcrop exposing outstanding examples of stratified diamictite, no detailed descriptions or sedimentary logs have been forthcoming. Here, the Luoquan Formation rests in angular unconformity upon pre-glacial carbonates, with a locally developed and undulose topography of several metres (Figure 9a). Two sedimentary logs were measured, spaced 150 m apart (Figure 2a). One of these, to the west

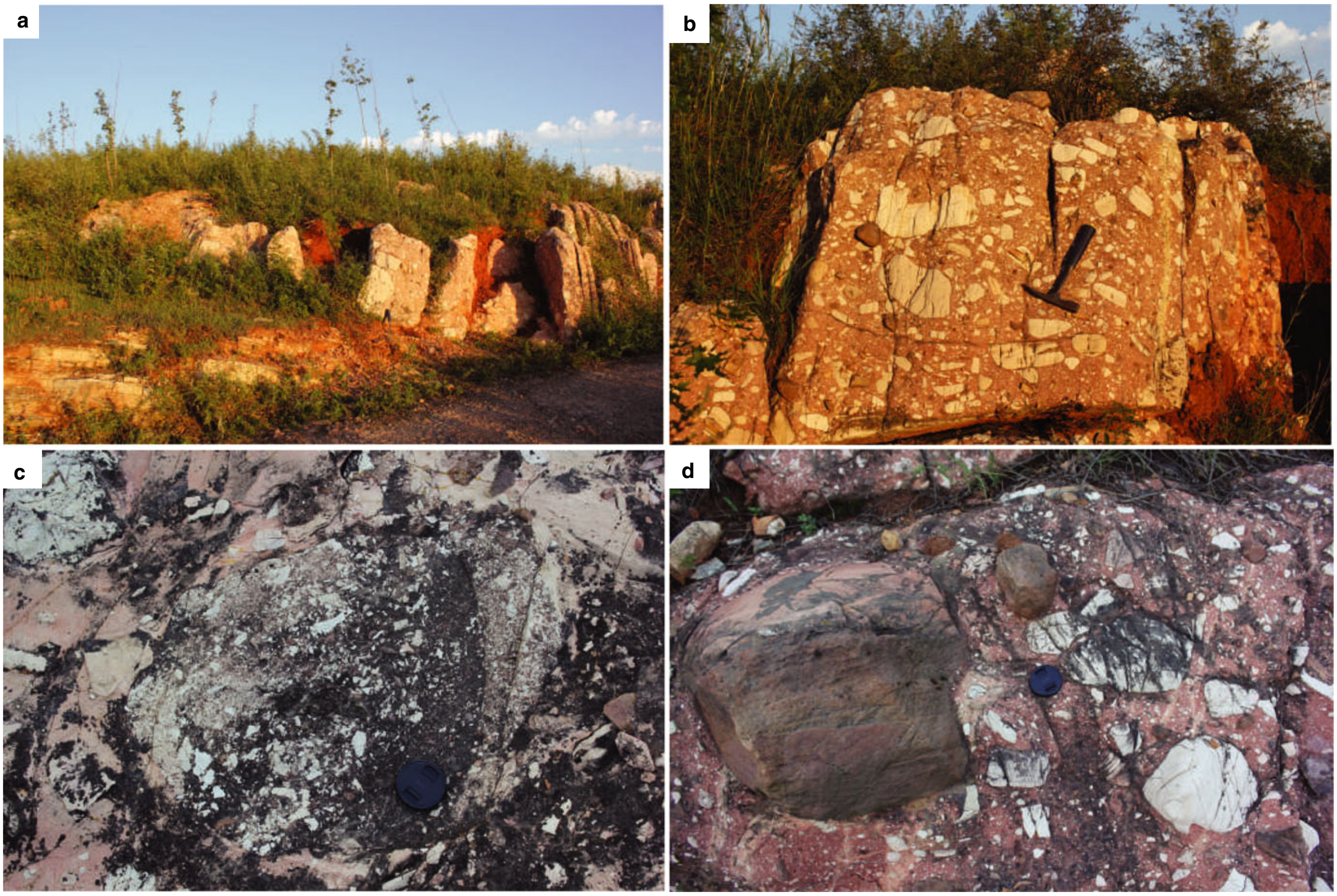
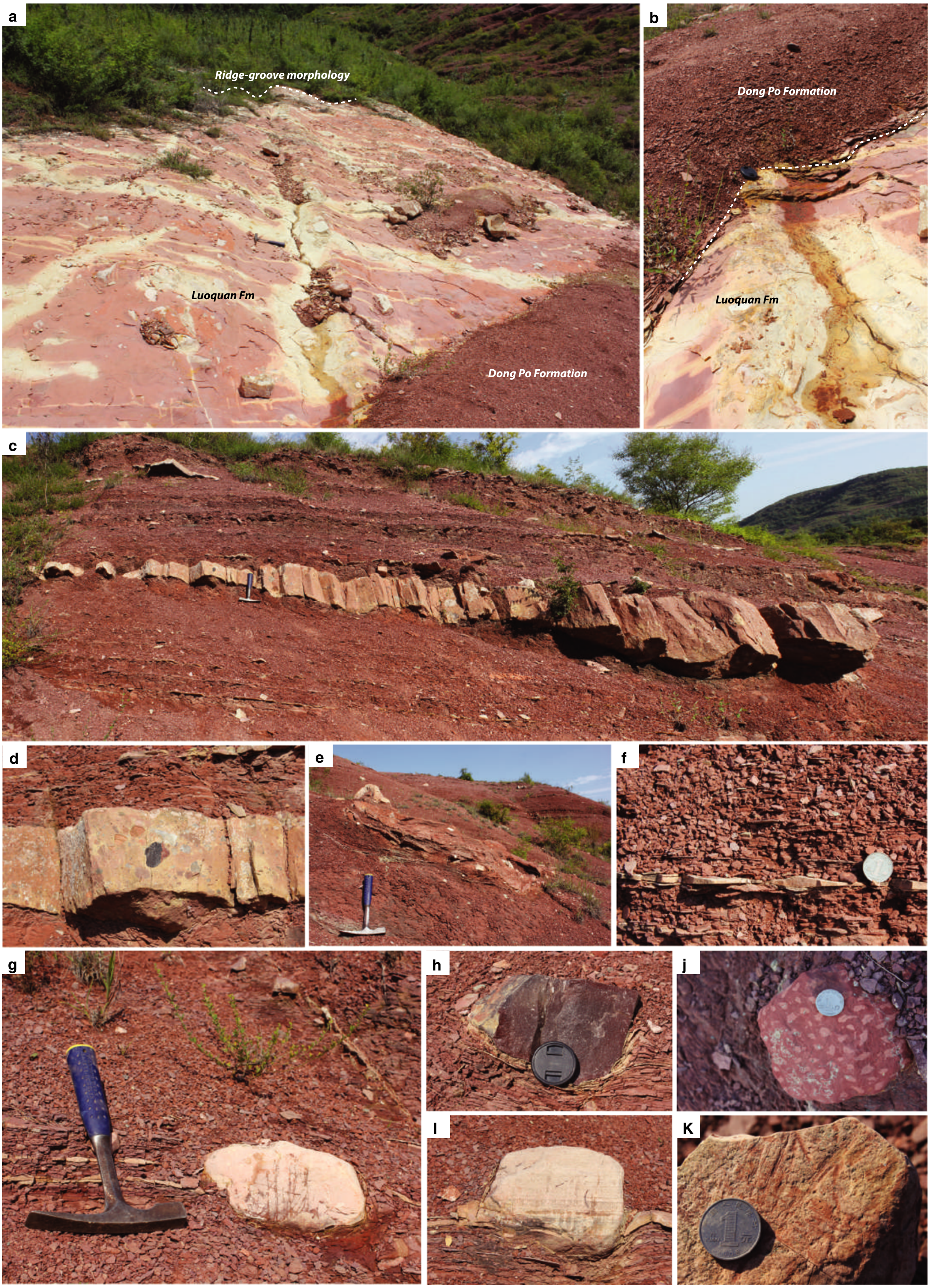


FIGURE 5 Basal diamictites of the Luoquan Formation at Yang Po and their basal contact on the Dong Jia Formation below. (a) Contact between the Dong Jia and overlying Luoquan formations. The contact represents a hiatus of likely >1 Ga duration (Prof. Yongqing Liu, *pers. comm.*). (b) Typical outcrop expression of the Luoquan Formation at Yang Po. Diamictites are almost monomictic with respect to clast composition (carbonates), although chert and sandstone clasts also occur locally. (c) Example of an intraformational clast of carbonate-rich diamictite. (d) Example of a sandstone boulder (to the left of the photograph) within the Luoquan strata

of a small river valley, exhibits a massive basal diamictite up to 6 m thick: this section of diamictite is absent in the eastern section (Figure 2a). The majority of the succession comprises 20 m of stratified, pebbly and granule-rich pebbly siltstones and shales (Figure 9b,c). Laterally, gradational facies transitions into stratified substitute for pebbly and granule-rich and siltstones both laterally and vertically. In both end-member facies, outsized clasts incorporate quartz grains, lithic fragments and carbonate debris. In several examples, these clasts disrupt and puncture underlying laminations, but are draped by undisturbed laminations (Figure 9c). Decimetre-scale folds occur within more silt-rich intervals, comprising isoclinal to recumbent antiforms (Figure 2a, 10 m; Figure 9d) which are overlain and draped by undeformed strata. In contrast to the delicate organization of the stratified diamictite, the massive basal diamictite comprises very thickly bedded, and largely structureless, deposits (Figure 9e,f). Texturally, these deposits closely resemble the Luoquan diamictites at Yang Po (Figure 9g) with angular to sub-angular carbonate clasts dominating.

FIGURE 6 The Dong Po Formation at Yang Po. This is a locally recognized formation, which sits concordantly above the Luoquan Formation in this area. (a and b) Grooves developed on the upper part of the Luoquan Formation (9 m on Figure 2d), draped by blood-red shales of the Dong Po Formation above. (c) Large channel of conglomerate punctuating the red shales. (d) Detail of the channel body, illustrating a clast-supported conglomerate. (e) Diamictite lens (22 to 23 m on Figure 2d) with carbonate boulders confined to the top of the deposit. (f) Lens of rippled sandstone within red shale. (g through j) examples of lonestones within red shale. (g) and (h) show excellent evidence for truncation of the laminations by the clasts, and in the case of h and i deflection of the laminations beneath the edges of the clasts is also evident. These characteristics are strongly supportive of a dropstone interpretation for these textures. While (j) does not show these characteristics, the red dolostone clast exhibits structures akin to tubestones in Marinoan cap-carbonates (Creveling et al., 2016). This is one line of evidence that the Dong Po could be younger than Ediacaran in age. k: Striated clast


a
Ridge-groove morphology
Luoquan Fm
Dong Po Formation
b
Dong Po Formation
Luoquan Fm
c
d
e
f
g
h
j
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K

4 | DATA INTERPRETATIONS

4.1 | Luoquan Village section

The Luoquan section is notable for alternating crudely stratified and massive diamictites which are well represented on the measured section (Figure 2). Significant vertical transitions from stratified diamictite to dropstone-bearing shale also occur (12–15 m, log C, Figure 2). These transitions imply a genetic connection between stratified diamictite and shale lithofacies, allowing them to be viewed as IRD-rich end members. In the context of a sub-ice shelf setting, it is possible that the comparatively drop-stone-poor shale corresponds to a "null zone" beneath an ice sheet, that is, an interval representing deposition beneath debris-poor ice (Domack & Harris, 1998; Domack, Jacobson, Shipp, & Anderson, 1999). However, in those sub-ice shelf models, dropstone-free intervals are predicted: by contrast IRD is distributed throughout the shales at Luoquan Village (Figure 3d). Given the excellent evidence for IRD in the shale (abundant dropstones), the entire succession is interpreted as recording subaqueous diamictite deposition. Specifically, given the presence of finely laminated textures (Figure 3), resembling varves in Quaternary systems (Bendle, Palmer, Thorndycraft, & Matthews, 2017; Palmer, Lowe, Rose, & Walker, 2008), it is suggested that the Luoquan Village section records the oscillation of an ice mass at the margins of a proglacial lake. The large-scale deformation structures (Figure 4) are interpreted as glacitectonized zones perhaps akin to push moraines in an ice-marginal environment (Aber & Ber, 2007 and refs therein). Although small-scale deformation structures have been described before in the Luoquan Formation (Yang & Wu, 1994), large-scale deformation structures such as those described herein provide a valuable new window into ice sheet dynamics.

4.2 | Yang Po section

The Yangpo section (Figure 2, log D) is interpreted to record deposition of a basal ice-contact diamictite during initial transgression to establish a stable, ice-contact lake in which sediments were delivered via iceberg rafting, mass flows and rhythmic, varve-like processes. The presence of highly convoluted diamictite beds within otherwise delicately bedded shales testifies to slope collapse, perhaps triggered by high sedimentation rates at the lake margin. The pronounced, linear grooves on the top of the basal diamictite (Figure 2, log D, 9 m; Figure 6a,b) are interpreted as iceberg keel scour marks (Linch & Dowdeswell, 2016; Woodworth-Lynas & Dowdeswell, 1994), or alternatively pressure ridges beneath shorefast ice. In either case, their presence is compatible with a transgressive regime whereupon floating ice, in a glacilacustrine environment, could become established. The apparently random orientation of ripples, notwithstanding the relatively limited dataset, does not lend any strong support to a regional palaeoslope driving both dilute flows (the ripple cross-laminae) and the denser flows (deformed diamictite beds). This is tentatively cited as further support for a lacustrine, rather than marine, setting on account of the better defined regional slopes which would be expected in a marine setting. The presence of tubestone structures in dolostone clasts may be significant: given that these structures are characteristic of Marinoan cap carbonates (Creveling et al., 2016), they may place a maximum age constraint on the deposits. This suggestion is tentative, however, and requires further investigation and substantiation.

4.3 | Shangxuma section

Analysis of the striated pavement at Shangxuma (Figure 7) has suggested that apparently crosscutting striations may be related to the same phase of subglacial erosion. This interpretation builds significantly upon the work of Guan et al. (1986), who recognized the crosscutting relationships but did not offer an explanation. It is proposed that the grooves, ridges and striations formed as a continuum of subglacial structures as is widely recognized in younger deposits (Ely et al., 2016). The curved trajectory of striations from grooves onto adjacent ridges is explained by the ploughing objects experiencing an obstacle immediately downglacier, or alternatively point to "sticky spots" at the base of the ice sheet. It has long been recognized that ice streams experience locally dramatic deceleration owing to factors such as till-free areas, bedrock bumps, a well-drained substrate or basal freeze on of meltwater (Stokes, Clark, Lian, & Tulaczyk, 2007). Thus, in clear distinction

FIGURE 7 The striated pavement and associated structures at Shangxuma. (a) Scale drawing of the striated pavement together with measurements of 72 striations. Note the relationship between apparently crosscutting striation sets on the scale drawing. (b) Contact between striated pavement and diamictites lying directly on the contact. (c) View of an area of cross-cutting striae: a simple interpretation, without considering the wider geomorphic evidence, would be that these represent two phases of subglacial abrasion in central China. (d and e) Two views of the curvilinear nature of some striations at the outcrop scale, as shown in a. (f) Striated pavement draped by diamictite. Some striations are also developed in the very basal deposits (i.e. over a few mm) in this diamictite. (g) Organization of the striated pavement into an upper and a lower step, as also shown in a

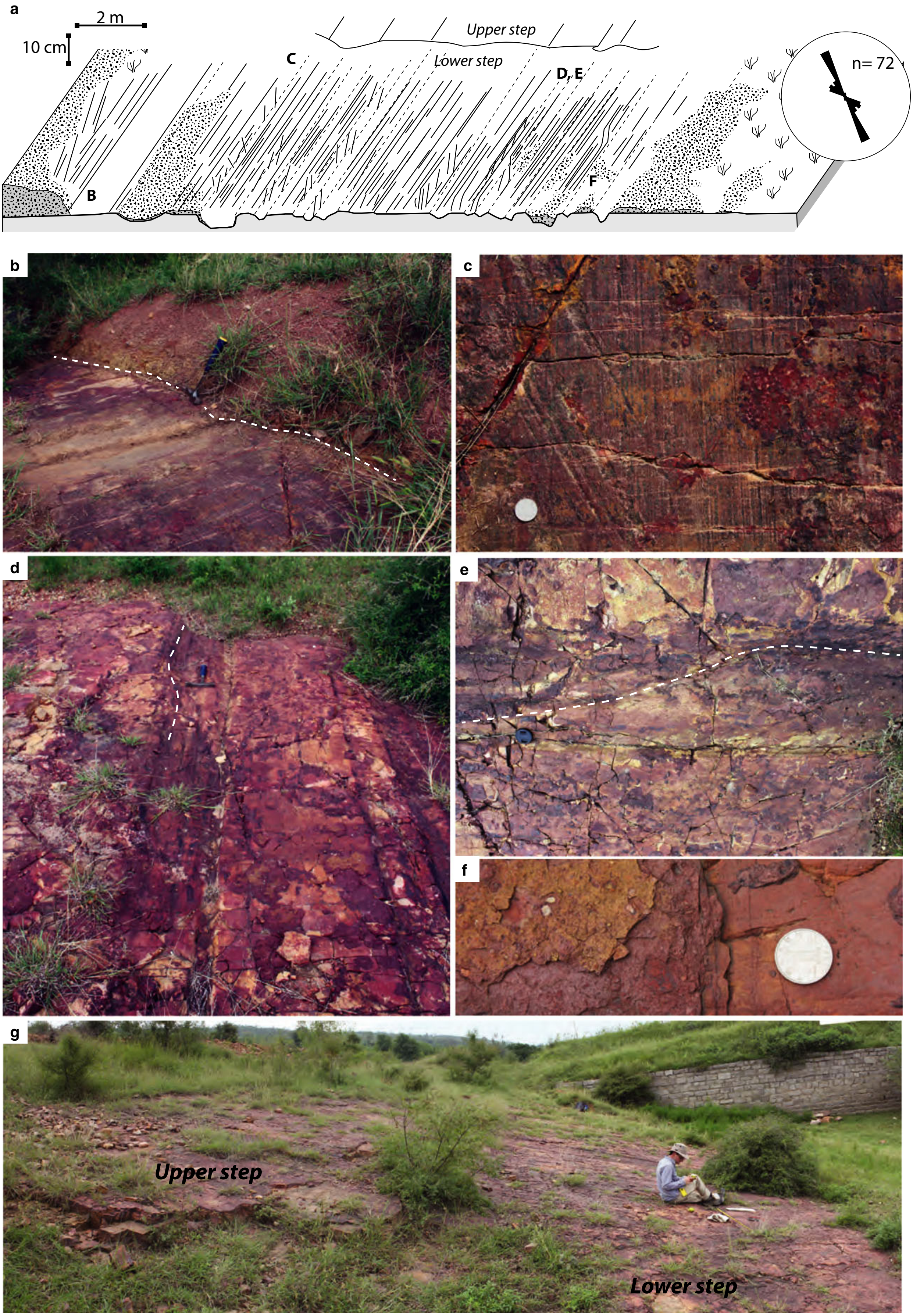

a
2 m
10 cm
Upper step
Lower step
C
D, E
B
F
n= 72
b
c
d
e
f
g
Upper step
Lower step

FIGURE 8 Deposits above the striated pavement at Shangxuma. (a) Overall outcrop character, with the geologist sitting above a train of large carbonate boulders towards the bottom of the photograph, corresponding to 0.5 m on Figure 2b. (b) Detail of one such boulder, comprising a stromatolitic limestone. (c) Scattered lonestones in silty shale, shown at 8.5 to 10 m on Figure 2b. (d) Sharp contact between diamictites and overlying Cambrian cross-bedded sandstones commencing at 18.5 m on Figure 2b

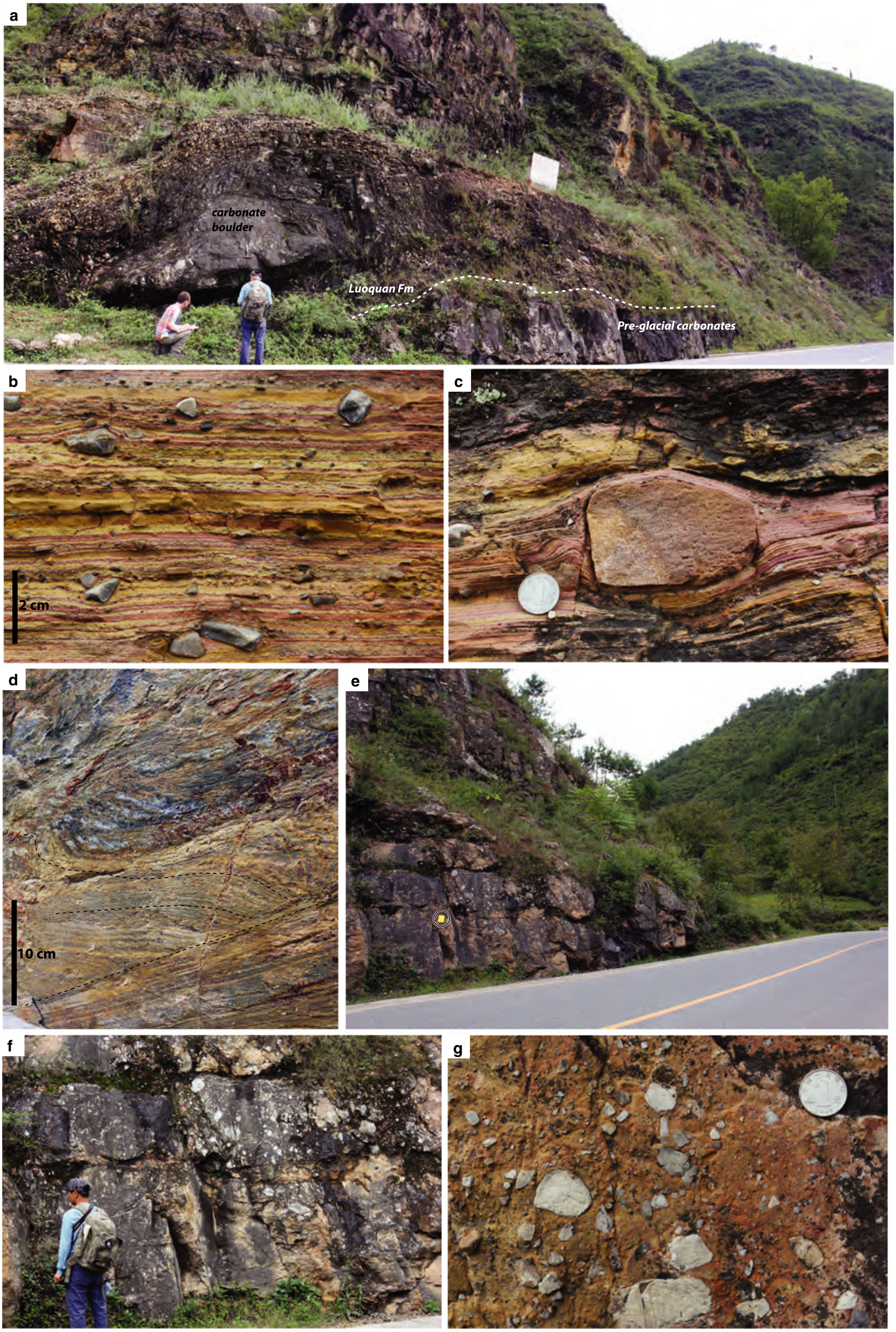
to any interpretation of cross-cutting striations implying successive phases of ice flow, only one phase of subglacial deformation was identified in the Shangxuma section.

There are three lines of evidence to support that the striated surface was produced by an overriding ice sheet rather than by iceberg keel plough marks (Linch & Dowdeswell, 2016; Woodworth-Lynas & Dowdeswell, 1994). First, polish on striated surfaces is interpreted to record accretion of a thin film of material subglacially through the application of a basal shear stress over wide areas, and which can only occur in a subglacial context (Siman-Tov, Stock, Brodsky, & White, 2017). Second, there are rare occurrences of striations traversing the very basal layers of the overlying diamictites which add credence to this hypothesis. Third, the occurrence of four large boulders of carbonate towards the base of the overlying diamictite may record a subglacial boulder pavement. While other plausible explanations have been offered for boulder pavements in other diamicton/diamictite successions (Eyles, 1988; McCabe & Haynes, 1996), there is no evidence for winnowing of the boulder pavement (e.g. an interval devoid of mudstone/diamictite, or cross-strata). Thus, a subglacial explanation is considered the most likely.

4.4 | Shangzhangwan section

The Shangzhangwan strata are interpreted as the glacilacustrine sediments deposited in a range of proximal to medial

FIGURE 9 The Luoquan Formation at Shangzhangwan. (a) Undulose basal contact onto underlying preglacial carbonates. Lower levels of the Luoquan Formation include a large boulder of the preglacial substrate (indicated). The field of view approximately equates to the entirety of Figure 2a log (i). (b) Stratified pebbly mudstone with well-expressed intercalations of silty and clay-rich laminae. (c) Evidence for impact structures beneath lonestones in the same deposit, testifying to an abundance of IRD at Shangzhangwan. (d) Intense soft-sediment deformation (Figure 2a, log (i), 10 m); structures are underlain and overlain by undeformed, laminated sediment. (e) Outcrop view of the section shown as Figure 2a, log (ii). (f) Detail of the lower part of the section shown in e, illustrating the outcrop character of the massive, basal diamictite of the Luoquan Formation. (g) Abundance of carbonate stones within the diamictite, closely resembling the Yang Po outcrop (cf. Figure 5b)


a
carbonate boulder
Luoquan Fm
Pre-glacial carbonates
b
2 cm
c
d
10 cm
e
f
g

settings with respect to the sediment input point at the lake margin. "Varve-like" textures were noted by Mu (1981) and Guan et al. (1986) from other sections, yet the Shangzhangwan section is dominated by stratified diamictite. The lateral passage of stratified diamictite into pebbly shale with silt laminae highlights sedimentation in a standing body of water such as a glacial lake (Palmer et al., 2008). The lake most probably experienced gravitational collapse at its margins, generating significant basin floor topography. The possible occurrence of minor extensional faulting is invoked to explain the abrupt lateral disappearance of the basal diamictite between measured sections (Figure 2a). In this context, it is suggested that iceberg delivery was prodigious, delivering IRD and producing dropstones, yet at the same time suppressing evidence for any reworking or sediment redistribution processes that may have occurred. The lateral and vertical transition of these deposits into IRD-bearing shales suggests an abundance of clay advected into the lake, probably from hypopycnal flows. In addition to the well-organized, stratified nature of the deposits, the <1 mm alternations of silt and clay rich laminae in the finer-grained facies compare favourably to Quaternary rhythmites (Bendle et al., 2017) produced through either seasonal or biannual variations in meltwater flux.

5 | DEPOSITIONAL MODEL AND DISCUSSION

Analysis thus far highlights a clear glacial control on sedimentation, amplifying the high quality, early work of Guan et al. (1986). Integrating the observations and interpretations from each of the study sections, a general depositional model is presented for the Luoquan Formation (Figure 10). It is proposed that the ice masses feeding the Luoquan basin were warm-based, and given the wide spatial distribution of striated pavements across the Henan Province (Guan et al., 1986), it is proposed that the region was covered by an ice sheet rather than small valley glaciers. In this context, it is suggested that the Luoquan lake basin was fed by ice streams in the hinterland, replete with sticky spots. Oscillation of the ice front produced substantial push moraine structures, locally duplicating the stratigraphy and producing a glaciotectonically thickened sequence. Interestingly, this finding also seems to account for the previously reported thickness variations (a few metres to 200 m) measured by Guan et al. (1986), and which were cited as evidence for a highly undulose subglacial topography. In contrast to previous workers, strong evidence that the Luoquan Formation was deposited by a series of turbidity currents was not found (Wang, 1996), although in general the gravitational reworking of glacial deposits to produce diamictites of mass flow origin is a sensible hypothesis (Wu & Guan, 1988). In spite of this, however, well-developed vertical transitions from dropstone-bearing shale, via well stratified to weakly stratified diamictite are evident, notably at the Luoquan Village type section. These relationships suggest that the majority of the diamictites may be of primary origin, rather than slope-reworked deposits. In the latter case, the intercalation of turbidites, hyperconcentrated flow deposits, and debrites would be expected (Busfield & Le Heron, 2016).

Internal correlation of the Luoquan Formation between the widely spaced individual sections (Figure 2) is not attempted in this contribution owing to the absence of good marker horizons. This compares starkly with the work of Guan et al. (1986) who separated the Luoquan Formation into three members, although the basis for the subdivision was not explained. Nevertheless, these workers envisaged an upsection evolution from a till plain with braided streams (the basal diamictite) evolving upsection into a lake fed by a delta, and ice re-advance producing a lodgement till at a lake margin in a third phase. Broadly, many of these sub-environments are recognized herein, although evidence for a delta system was not identified in this dataset.

Reappraisal of the significance of striated pavements is possible in terms of ice sheet dynamics. Both Mu (1981) and Guan et al. (1986) published regional data for striation orientations. The former author recognized striations oriented from 280 to 360° from seven localities, from which flow towards the S and SSE were determined from nailhead striae at Lushan (Mu, 1981, table 1). Mu also noted similarly orientation striation in equivalent strata at the far west and east of the NCC. Guan et al. (1986) found similar ice-flow directions from four localities and the opposite direction, northwards, at Shimengou. The latter northward flow is supported by the subglacial thrust structures interpreted by Ge and Cui (1994). Given the palaeo-ice stream paradigm, noting that ice streams account for about 90% of an ice sheet's flux when compared to slow moving or stagnant ice around it (Bennett, 2003), it is tentatively suggested that the suite of striated pavements underlying the Luoquan Formation in central China (Guan et al., 1986; Mu, 1981) might record the passage of palaeo-ice stream(s) across the region. Based on recent results from Quaternary striated pavements, the glacial polish that is both reported in the literature (Mou, 1983; Mu, 1981), and which is well expressed at Shangxuma, may have formed through a combination of micrometre-scale accretion and deposition by siliceous or argillaceous gels beneath fast flowing ice (Siman-Tov et al., 2017). Thus, with detailed and systematic analysis, a palaeo-ice sheet reconstruction may be possible.

In the context of Neoproterozoic glaciations, the question of the global significance of the Luoquan Formation remains. It is plausible that a correlation between the Luoquan Formation and Ediacaran glacial records elsewhere remains possible, although this is by no means certain. Based on U-Pb geochronology of tuff intervals, recent work has shown that the Gaskiers Formation in Newfoundland was deposited in the window 580.90 ± 0.40 and 579.88 ± 0.44 Ma (Pu et al., 2016). The same work has emphasized that the Gaskiers glaciation is considered to have been of local, rather than global, extent, and thus any attempt to correlate the Luoquan rocks with this event should be treated with scepticism until further age constraints are forthcoming. In the large 2011 compendium, the Geological Record of Neoproterozoic Glaciations, only two papers were offered on glaciations in China, notably in the Tarim Block (Zhu & Wang, 2011) and in the Yangtze region (Zhang, Chu, & Feng, 2011). Thus, there have been no further geochronological advances since the mid-1980s when Guan et al. (1986) suggested that the Luoquan is "believed to have formed close to the Cambrian-Precambrian boundary". The geochronology, for the sake of regional and global comparisons and understanding the true extent of syn-Luoquan ice sheets, requires major work. Indeed, a summary by Mu (1981) is equally relevant in 2017: "at present there are different ideas as to the age of the Luoquan Formation. One is to assign it to the Early Cambrian period and the other is to consider it as belonging to the Sinian System". Potentially, direct dating of the striated pavements may be possible (Siman-Tov et al., 2017), although to the authors' knowledge this has not successfully been attempted.

6 | CONCLUSIONS

- Reappraisal of the Luoquan Formation in central China adds credence to earlier work for a strong glacial influence upon sedimentation. A new analysis of famous sections, including that at Luoquan Village, reveals the presence of large-scale deformation structures measuring many tens of metres in amplitude. These are interpreted as ice marginal fold-thrust belts (push moraines) which record ice bulldozing. The recognition of these structures within otherwise stratiform diamictites suggests that previous measured sections may have published over-estimates of formation thickness, but more importantly place the Luoquan in a better palaeogeographic context.
- Analysis of a famous striated pavement at Shangxuma suggests that the origin of crosscutting striations should be re-evaluated. Rather than indicating two phases of ice sheet overriding, the preferred model views these as end members of a continuum of curvilinear striations that developed in response to sticky spots at the ice sheet bed. At a wider scale, given the abundance of striated surfaces and the general uniformity in their orientation of striae across central China from previous work (Guan et al., 1986; Mu, 1981), it is tentatively proposed that these record the passage of multiple ice streams draining a fairly substantial ice mass, rather than a series of isolated valley glaciers. These considerations have important palaeogeographic implications even if the age of the formation remains unclear;

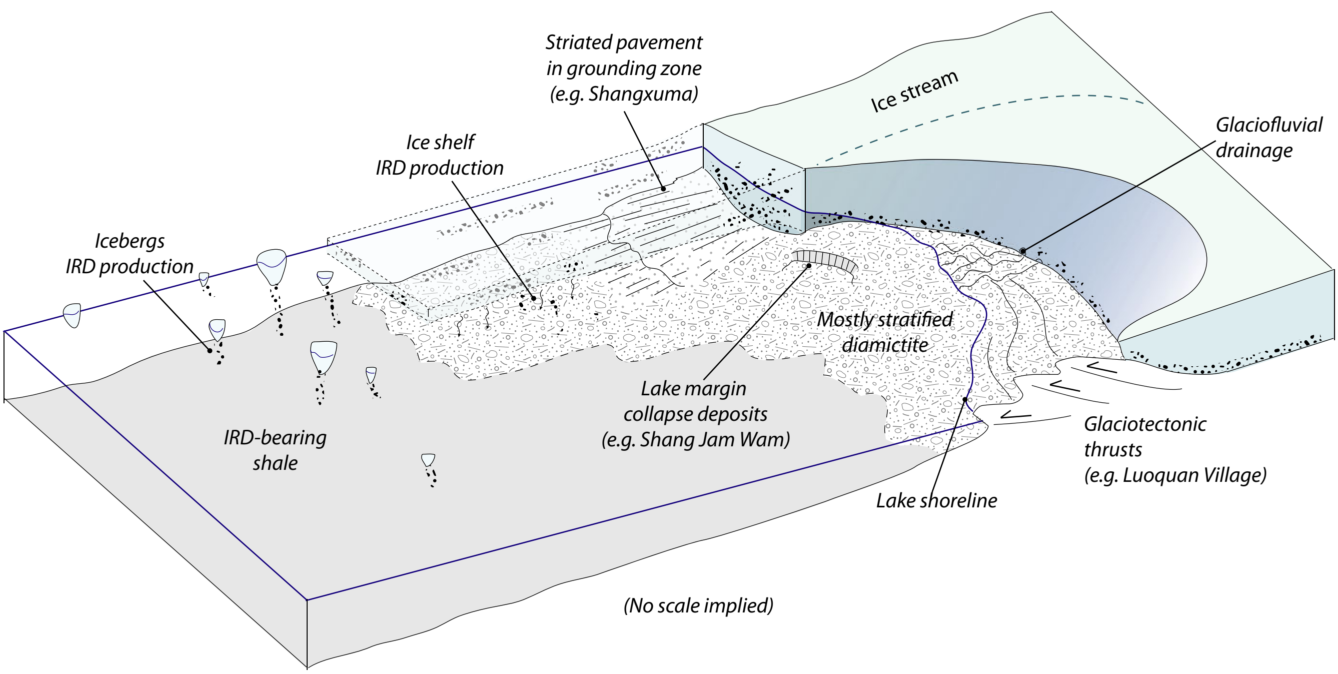


FIGURE 10 Simple depositional model integrating observations and interpretations from each of the study sections

- In contrast to previous workers, and in spite of detailed measured sections, based on the findings presented in this paper, it is believed that creating a stratigraphic framework that subdivides the Luoquan into individual members would be premature. Nevertheless, by integrating data from each of the studied sections, it is proposed that the Luoquan was deposited in an ice contact to immediately proglacial lake. Rather than viewing many of the diamictites as mass flow deposits, by observing transitional vertical relationships from dropstone-bearing shale through well-stratified diamictite to weakly stratified diamictite, ice rafting is suggested as the principal means of sediment delivery to the lake basin. In more "proximal" settings, that is,, closer to the shoreline, sediment delivery obscured rhythmite accumulation altogether. At the opposite end of the spectrum, dropstone-bearing shales and siltstones, with rhythmite characteristics, accumulated further from the sediment source.

ACKNOWLEDGEMENTS

This study has been partly supported by National Natural Science Foundation of China (grant no. 41472103) and National Science and Technology Major Project (2016ZX05004001). T.M.V. received funding towards this research from the Kirsty Brown Memorial Fund, Ian Gass Bursary (Open University) and the London NERC DTP. The authors are very grateful to Professor L Q Liu and to Professor Hong-Wei Kwang who helped us gain access to the sections with detailed instructions. The authors are grateful for the reviews of P.F. Hoffman and Anonymous, and the editorial work of Elias Samankassou and Peter Swart.

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How to cite this article: Le Heron DP, Vandyk TM, Wu G, Li M. New perspectives on the Luoquan Glaciation (Ediacaran-Cambrian) of North China. *Depositional Rec*. 2018;4:274–292. https://doi.org/10.1002/dep2.46