Chapter 44

The Chiquerío Formation, southern Peru

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Abstract: The Chiquerío Formation (Fm.) is a thick glaciogenic succession deposited unconformably on gneisses of the Arequipa massif in southern Peru. It has undergone greenschist facies metamorphism during Early Palaeozoic orogeny. The Chiquerío Fm. consists of nearly 400 m of diamictite, sandstone, mudstone and carbonate, with a thin (11 m) cap dolostone at the top of the formation. It is overlain by the San Juan Fm., a 2 km-thick carbonate succession. The thick glacially influenced succession was deposited in deep marine conditions and consists mainly of massive diamictites (representing either ice-rafter debris or submarine debris flows) interbedded with turbiditic sandstones. Where internal lamination is present (e.g. bedding in the turbiditic packages), abundant dropstones can be recognized. There is no evidence of shallow marine reworking of the succession. No absolute age constraints on the depositional timing of the Chiquerío Fm. exist, because no volcanic tuffs have been identified. U–Pb dating of detrital zircons (U–Th–Pb SIMS) from the Chiquierío Fm. and the underlying San Juan Fm. suggest it is Neoproterozoic in age. The detrital zircon age spectra suggest derivation from the Amazonian craton. Detrital grains as young as c. 700 Ma have been documented in the post-glacial San Juan Fm. The sparse (chemo)stratigraphic data available for the Chiquerío Fm. exhibit patterns similar to those observed generally in Neoproterozoic post-glacial carbonate sequences. Palaeogeographic models for the deposition of the Chiquerío Fm. are critically dependent on the timing of the docking of the basement of the Arequipa massif with the South American craton (Amazonia). Presently there are no palaeomagnetic constraints. More research on the chronological and palaeogeographical constraints of this succession is required.

Supplementary material: Data are available at http://www.geolsoc.org.uk/SUP18479.

The Chiquerío Fm. crops out locally on the western coast of southern Peru (Fig. 44.1a). It is best exposed at its type locality 5 km SE of the town of San Juan (Fig. 44.1b, 75°8′W, 15°24′S, UTM 18L 482500 8301000). It rests unconformably on basement gneiss (Fig. 44.1b), termed the Arequipa massif (Cobbing & Pitcher 1972; Ramos 2008), and is cut by Early Palaeozoic intrusions (Loewy et al. 2004). The Chiquerío Fm. is overlain unconformably by Jurassic sedimentary rocks, although the oldest cover rocks at its type locality (Fig. 44.1b) are Neogene in age. There are very few data from other sections of the Chiquerío Fm. Caldas (1978) documents the presence of a well-exposed section of the Chiquerío Fm. in the Quebadra Jahuay (Fig. 44.1a, 74°51′W, 15°28′S), while sporadic outcrops are encountered overlying the Chiquerío massif basement in the vicinity of Marcona Mine (Fig. 44.1a, 75°7′W, 15°12′S).

The first detailed study of these rocks was undertaken by the Marcona Mining Company (1968). They defined the Marcona Fm. to include all the low-grade metasedimentary rock overlying the basement gneisses, and they considered the Marcona Fm. to be Carboniferous in age. The basal member of the Marcona Fm. was termed the Justa Member, and described as conglomerate with pebbles of gneissic basement, Wilson (1975) considered this stratigraphic position of the Chiquerío Fm. above the Precambrian basement gneiss and the Late Ordovician age for the cross-cutting San Nicolas batholith (Wilson 1975). Caldas (1978, 1979) considered the Marcona Fm. to be Late Precambrian–Early Palaeozoic in age.

Subsequent workers (Shackleton et al. 1979; Cobbing 1981) reinterpreted the terminology of the Marcona Mining Company (1968), with the Marcona Fm. representing all the low-grade metasedimentary rock overlying the basement gneiss including the basal glaciogenic strata. Shackleton et al. (1979) regarded the Marcona Fm. to be entirely Early Palaeozoic based on structural considerations. He traced deformation events from the Marcona Fm. into the underlying basement gneiss and established that the crystalline basement rocks had experienced an older deformation history. The glaciogenic rocks were described by Cobbing (1981) in the IGCP 38 volume on the Earth’s Pre-Pleistocene Glacial Record (Hambery & Harland 1981). Cobbing (1981) considered them to be Early Palaeozoic in age. Subsequently, Injoque & Romero (1986) described possible Precambrian stromatolites in the San Juan Fm.

Loewy et al. (2003, 2004) undertook whole-rock Pb and U–Pb zircon geochronological analyses on the Chiquerío Fm. and the underlying gneisses of the Arequipa massif. They used, with modifications, the stratigraphic terminology of Caldas (1978, 1979). The Chiquerío Fm. was defined as the basal, glaciogenic portion of the sequence and was considered to be Neoproterozoic in age. Loewy et al. (2003, 2004) were unable to find any significant differences between the San Juan and Marcona formations of Caldas (1978, 1979), and considered the San Juan Fm. to include all the low-grade metasedimentary rock overlying the Chiquerío Fm. at this locality. This stratigraphic nomenclature was adopted by Chew et al. (2007a) and is used in this chapter. Chew et al. (2007a) presented sedimentary observations, chronostratigraphic data and U–Pb detrital zircon analyses from the Chiquerío and San Juan formations. They considered the Chiquerío and San Juan formations Late Neoproterozoic in age, and to be autochthonous with respect to the Amazonian craton. These considerations...
Chew et al. (1978, 1979; Loewy et al. 2004). Late Neoproterozoic–Early Palaeozoic basin is uncertain. Juvenile extensional magmatism (dacite dykes) has been dated at 635 + 5 Ma in the basement of the Antofalla terrane in Northern Chile (Loewy et al. 2004). Late Neoproterozoic extension-related volcanism related to Rodinia break-up has been identified in the Puncoviscana fold belt of northwestern Argentina (Omarini et al. 1999), although the Puncoviscana Basin has a complex history of extension, compression and magmatism (Ramos 2008) that may not be directly comparable to the tectonic evolution of the basin where the sediments of the Chiquero and San Juan formations accumulated. Considering a Late Neoproterozoic age for the Chiquero and San Juan formations (e.g. Caldas 1978, 1979; Chew et al. 2007a; Loewy et al. 2003, 2004), an extensional basin setting is most likely.

Shackleton et al. (1979) proposed a structural evolution of the Chiquero and San Juan formations. Two deformation events are recognized within these rocks. Two earlier deformation events (D1 and D2) are restricted to the underlying Arequipa massif basement, so the deformation events affecting the Chiquero and San Juan formations are attributed to the regional D3 and D4 deformation events (Shackleton et al. 1979). The earlier event (D3) produced a bedding-parallel schistosity (S3) formed by fine-grained muscovite and biotite. Where suitable strain markers are present (such as in the conglomeratic portions of the Chiquero Fm.), a strong lineation is aligned along this foliation surface, plunging moderately to the south. The S3 schistosity is crenulated and folded by a second deformation (D4), which controls the large-scale distribution of the units. Peak metamorphic conditions were attained during the D3 event, and the muscovite and biotite assemblages present are indicative of the greenschist facies (Shackleton et al. 1979). Undeformed fine-grained granite dykes cut the F3 and F4 fold axial planes, and one such granite dyke has yielded a U–Pb zircon lower intercept age of between 468 and 440 Ma (Loewy et al. 2004). The regional D3 and D4 events are considered to be Early Palaeozoic in age (Loewy et al. 2004), and are probably coeval with Famatinian (Early Ordovician) metamorphism and subduction-related magmatism on the western Gondwanan margin (Chew et al. 2007b).

Structural framework

Very limited work has been published on the nature of the basin in which the sediments of the Chiquero and San Juan formations accumulated. The present-day outcrop distribution of the Chiquero and San Juan formations is restricted to a thin zone, 20 km wide, along a strike length of 200 km on the western margin of the Arequipa massif in southern Peru (Fig. 44.1a). However, the initial geometry and tectonic setting of this Late Neoproterozoic–Early Palaeozoic basin is uncertain. Juvenile extensional magmatism (dacite dykes) has been dated at 635 + 5 Ma in the basement of the Antofalla terrane in Northern Chile (Loewy et al. 2004). Late Neoproterozoic extension-related volcanism related to Rodinia break-up has been identified in the Puncoviscana fold belt of northwestern Argentina (Omarini et al. 1999), although the Puncoviscana Basin has a complex history of extension, compression and magmatism (Ramos 2008) that may not be directly comparable to the tectonic evolution of the basin where the sediments of the Chiquero and San Juan formations accumulated. Considering a Late Neoproterozoic age for the Chiquero and San Juan formations (e.g. Caldas 1978, 1979; Chew et al. 2007a; Loewy et al. 2003, 2004), an extensional basin setting is most likely.

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Stratigraphy

The Chiquero Fm. rests unconformably on gneisses of the Arequipa massif and consists of nearly 400 m of diamictic, sandstone, mudstone and carbonate, with a thin (11 m) finely laminated dolostone and dolomicrite unit at the top of the formation (Fig. 44.2, Chew et al. 2007a). It is overlain by the San Juan Fm., a 2-km-thick carbonate succession (Fig. 44.3). The San Juan Fm. consists of several hundred metres of massive beige dolomite, with subordinate thinly bedded limestone, black shale, graded pebbly dolostone and phyllite (Fig. 44.3, Chew et al. 2007a). No unconformities have been observed in either formation. At many localities, the San Juan Fm. rests directly on the basement gneiss (Caldas 1978).

Glaciogenic deposits and associated strata

The following description of the glaciogenic deposits of the Chiquero and San Juan formations is derived chiefly from Chew et al. (2007a), based on the well-exposed coastal section SE of the town of San Juan (Fig. 44.1b). The basal siliciclastic section of the Chiquero Fm. is 348 m thick (Fig. 44.2), and consists primarily of massive diamicite with poorly developed internal stratification. The matrix of the diamicite is a dark meta-siltstone, whereas the majority of the clasts are granitic gneiss that superficially resemble the underlying Arequipa massif basement (Loewy et al. 2004; Chew et al. 2007a). The clasts display no evidence of facetting or striation. Clast types include weakly foliated, K-feldspar rich granites, foliated grey-pink gneiss (sometimes megacrystic), fine-medium grained sandstone blocks and clasts of amphibolite. Some of the gneissic clasts are greater than 50 cm across. There is only very occasional evidence of stratification in the massive diamicite portion of the sequence. This stratification is present in the form of thin, discontinuous mudstone layers and occasional lenses, up to 3 m thick, of boulder conglomerate. These conglomeratic lenses are poorly sorted, and have a high concentration of clasts, approaching being clast supported.

Between 76 and 152 m above the basement contact there is a sequence of stratified diamicite interbedded with thin siltstone and graded sandstone beds. The stratification in the diamicite is
defined by either thin siltstone beds or mudstone lenses. This internal stratification is much more pronounced and more continuous than that seen in the underlying massive diamictite. The stratified diamictite contains abundant outsized clasts of granitic gneiss that deflect underlying lamina. A large angular megaclast of bedded sandstone, greater than 6 m across (Fig. 44.2) is also present within diamictite in this part of the sequence. It appears to pierce the crude lamination in the underlying diamictite.

The upper part of the Chiquerio Fm. and the overlying San Juan Fm. are predominantly carbonate, with a relatively abrupt switch (transitional over 1 m) to carbonate-dominated sedimentation occurring at 348 m (Fig. 44.2). The dominant lithology is a calcareous diamictite with white dolostone and limestone clasts, and only minor amounts of granitic gneiss. The carbonate clasts are...
strongly flattened and stretched along the main bedding-parallel tectonic fabric (S3). Overlying the carbonate diamictite are 11 m of finely laminated (0.2–5 cm), fine-grained pink dolomite and dark dolomictite in the upper Chiquerío Fm. (Chew et al. 2007a). This dolomictite unit shows no internal structure apart from prominent lamination; it has no evidence of outsized clasts. The San Juan Fm. overlies this fine-grained laminated dolostone–dolomictite unit. The basal portions of the formation consist of several hundred metres of predominantly massive beige dolomite (Fig. 44.3, Chew et al. 2007a). This is overlain by a lithologically varied unit of black shale, massive dolomite, and thinly bedded graded pebbly dolostone (950–1093 m; Fig. 44.3). The overlying unit is 170 m thick, and consists of thinly bedded limestone and dark micrite (Fig. 44.3). Above this unit, there is a thick (nearly 1 km) sequence of massive dolomite that is only briefly interrupted by the deposition of a thin package of graded pebbly dolostone and mudstone (1395–1487 m; Fig. 44.3).

**Boundary conditions with overlying and underlying non-glacial units**

The basal contact of the Chiquerío Fm. is an unconformity with gneissic rock of the Arequipa massif basement, best seen at low tide, along the coast, 5 km SE of San Juan. At the regional scale, it is unknown whether the unconformity surface is planar or has topography. At many other localities (e.g. Punta San Juan, 2 km west of the town of San Juan, Fig. 44.1b), the contact between the Chiquerío Fm. and the basement gneiss is a fault. In addition, the entire Chiquerío Fm. is frequently excised, with the overlying San Juan Fm. resting directly on the basement gneiss (Caldas 1978).

The upper contact of the Chiquerío Fm. has been placed at either the base (e.g. Caldas 1978) or at the top of the finely laminated, 11-m-thick unit of pink dolostones and dark dolomictites (e.g. Cobbing 1981; Chew et al. 2007a). The Chiquerío and San Juan formations are overlain unconformably by unmetamorphosed Mesozoic and Cenozoic sediments (Caldas 1978).

**Chemostratigraphy**

Chew et al. (2007a) presented C- and O-isotope data for the upper part of the Chiquerío Fm. and the overlying San Juan Fm. (Fig. 44.3). These are the only chemostatigraphic data presently available for the Chiquerío and San Juan formations. Diagenetic overprinting of the original seawater isotopic signatures is difficult to assess. Detailed textural evidence to evaluate diagenesis within the carbonate rocks is lacking as the rocks have undergone some recrystallization during greenschist-facies metamorphism, and there is no alternative complete section with which to compare lateral variations in the stable isotope profile. The beginning of carbonate-dominated sedimentation in the Chiquerío Fm. occurs at 348 m (Fig. 44.2), where the dominant lithology is a calcareous diamictite with white dolostone and limestone clasts. Both the clasts within the diamictite and the interbedded limestone beds yield δ13C values between 0‰ and +2‰ (VPDB) (Fig. 44.3). Finely laminated pink dolostone and dark dolomictite overlie the carbonate diamictite. This dolostone unit yields consistent negative δ13C values of ~2‰ (Fig. 44.3, Chew et al. 2007a).

The overlying San Juan Fm. exhibits a recovery in δ13C values to between +1‰ and +2‰ (Fig. 44.3). The basal portions of the formation consist of several hundred metres of predominantly massive beige dolomite. Between 1075 m and 1250 m, a thinly bedded limestone and dark micrite unit exhibits strongly negative δ13C values from ~5‰ to ~8‰ (five data points, Fig. 44.3, Chew et al. 2007a). Above this unit, there is a return to deposition of massive dolomite and the δ13C values range between +1‰ and +2.5‰. So far, no unequivocal glaciogenic strata nor significant sequence boundary associated with this younger, strongly negative (−5‰ to ~8‰) δ13C excursion have been identified (Chew et al. 2007a).

**Other characteristics (e.g. economic deposits, biomarkers)**

The Marcona deposit (20 km north of San Juan, Fig. 44.1a) and the associated Pampa de Pongo deposit (35 km east of San Juan) are the largest Fe accumulations, with associated copper and gold, along the western South America margin. The deposit substantially post-dates the deposition of the glaciogenic strata, and is considered to have formed during a phase of Mesozoic arc magmatism (Hawkes et al. 2002). Approximate resources include more than 1400 Mt of iron ore at Marcona and 1000 Mt of magnetite mineralization at Pampa de Pongo (Hawkes et al. 2002). The two deposits form part of a cluster of similar occurrences that together define the ‘Marcona Fe–Cu District’. The larger Fe bodies are located within the Chiquerío, San Juan and Marcona formations, and also by basaltic andesite, andesite and volcaniclastic rock of the Middle to Upper Jurassic Rio Grande Fm. (Hawkes et al. 2002).

There are no biostatigraphic data available for the Chiquerío Fm. ‘Stromatolite-like’ structures have been recorded in the overlying San Juan Fm. (Injoque & Romero 1986) and are correlated by the authors with late Neoproterozoic–Early Cambrian stromatolites.

**Palaeolatitude and palaeogeography**

Palaeolatitudinal and palaeogeographic constraints for the Chiquerío Fm. are sparse. There have been no palaeomagnetic studies on the Chiquerío Fm. Given that the Chiquierío and San Juan formations have experienced greenschist-facies metamorphism (Shackleton et al. 1979) and were subsequently intruded by Early Palaeozoic plutons (Loewy et al. 2004), remagnetization by Early Palaeozoic-age metamorphism is likely.

The detrital zircon data of Chew et al. (2007a) from the Chiquierío and San Juan formations are consistent with derivation from the Proto-Andean margin (Chew et al. 2007b). This would imply that both the glaciogenic strata and its underlying gneissic basement were proximal to the South American craton (Amazonia) during Late Neoproterozoic times (Chew et al. 2007a). This juxtaposition indicates that the Arequipa massif basement must have accreted earlier, probably during the 1.3–1.0 Ga Grenville–Sunsas Orogeny (Chew et al. 2007a) as first postulated by Loewy et al. (2004). Ramos (2008) and Loewy et al. (2004) provide a detailed synthesis on the tectonic evolution and docking history of the Arequipa massif and the Antofalla terrane.

An autochthonous origin for the Chiquerío Fm., with respect to cratonic South America, places crude palaeolatitudinal constraints on these rocks. There is presently only one palaeomagnetic pole for the Amazon craton in the Late Neoproterozoic (Töhver et al. 2006), derived from the palaeomagnetic study of the Neoproterozoic Puga cap carbonate (Trindade et al. 2003). The dolomite and limestone of the Puga Fm. from the SE Amazon craton preserve a dual-polarity component that is interpreted as a primary magnetization. This implies a low palaeolatitude of 22 ± 6° 5° for the Amazonian block just after deposition of the Puga diamictites. Although direct ages for the Puga Fm. are not yet available, 87Sr/86Sr ratios and δ13C results presented by de Alvarenga et al. (2004) suggest correlation with the c. 635 Ma (Hoffmann et al. 2004; Condon et al. 2005) post-glacial units of the Congo craton.

**Geochronological constraints**

To date, no tuffs have been recorded from the Chiquerío Fm. Existing age constraints include a minimum age of 468–440 Ma.
950–1300 Ma, with a prominent peak at c. 1200 Ma and a subsidiary peak at c. 1000 Ma (Chew et al. 2007a, Fig. 44.4). SJ-16 is a sample of diamictite matrix from the Chiquerío Formation. It is also characterized by a restricted age distribution from 950 to 1300 Ma, with a prominent peak at c. 1200 Ma and a subsidiary peak at c. 1000 Ma (Chew et al. 2007a, Fig. 44.4). The detrital zircon data from these Chiquerío Formation samples yield very minimal detritus, which could potentially be derived from the underlying basement (the Palaeoproterozoic Arequipa massif, 1790–2020 Ma; Loewy et al. 2004). Sample SJ-57 (55 grains) is from a coarse pebbly limestone bed from the San Juan Formation, 1412 m above the Chiquerío Formation–Arequipa massif basement contact and 178 m above the second negative C-isotope excursion (Fig. 44.4). The majority of grains from this sample also lie in the 950–1300 Ma range, with peaks at c. 1000 Ma and c. 1200 Ma. There are also minor peaks within the c. 1600–2000 Ma and c. 700–830 Ma intervals (Chew et al. 2007a, Fig. 44.4). A c. 700 Ma grain provides a maximum age constraint for the deposition of this portion of the San Juan Formation.

Discussion

The depositional environment of the Chiquerío Formation is most likely deep marine, based on the lithofacies and the lack of high-energy sedimentary structures. The stratified portion of the siliciclastic section (between 76 and 152 m above the basement contact, Fig. 44.2) contains abundant dropstones of granitic gneiss, which disrupt the laminations in graded turbiditic sandstone beds, thus suggesting a glaciﬂuenced marine environment (Caldas 1978; Cobbing 1981; Loewy et al. 2004; Chew et al. 2007a). The depositional environment of the massive diamictite portions straddling this stratified interval (Fig. 44.2) may represent ice-rafted debris and suspension settling of ﬁne grained sediment, or alternatively may have been produced by submarine debris ﬂows. There is no sedimentary evidence in the siliciclastic portion of the sequence (e.g. wave ripples, cross-bedding) of shallow-water conditions (Chew et al. 2007a). The San Juan Formation consists predominantly of massive beige dolomite with little internal structure. The possible Precambrian stromatolites described by Injouque & Romero (1986) would suggest a shallow marine or intertidal environment for portions of the San Juan Formation.

The laminated dolostone facies at the top of the Chiquerío Formation and its associated large negative δ¹³C excursion are characteristic of cap dolostone associated with Late Neoproterozoic glacialis (Kennedy et al. 1998; Hoffman & Schrag 2002; Halverson et al. 2005; Shields 2005), although negative anomalies in the late Neoproterozoic are not exclusively linked to ice ages (Le Guerroué et al. 2006). Chew et al. (2007a) considered the Chiquerío Formation and the pronounced negative C-isotope excursion in the San Juan Formation to represent two distinct glacial events correlated to a ‘Sturtian–Marinoan’ couplet elsewhere in the world. Although no unequivocal glaciogenic strata nor a signiﬁcant sequence boundary indicative of a glacial event have been identiﬁed with the second negative C-isotope excursion, it may correlate with the negative Trezona anomaly, which immediately preceded the Marinoan glaciation (Halverson et al. 2005). Alternatively, if Chiquerío Formation and the C-isotope excursion represent a Marinoan-age glacial event and the Shuram/Wonoka isotopic anomaly (Halverson et al. 2005; Le Guerroué et al. 2006), then a depositional age of c. 635 Ma for the Chiquerío Formation (Chew et al. 2007a) is inferred. In either case, a Late Neoproterozoic (<700 Ma) age is supported by the youngest detrital zircon population in the San Juan Formation. The Proto-Andean margin of Amazonia is characterized by abundant zircon detritus between 1300–900 Ma and 630–550 Ma (Chew 2007b). The absence of Late Neoproterozoic (700 Ma and younger) zircon in the Chiquerío Formation may simply reﬂect that these glaciogenic strata were too old to accumulate such detritus, or alternatively had a restricted sediment source, mainly derived from local basement.

Fig. 44.4. Zircon probability density distribution diagrams from the Chiquerío Formation (SJ-11, SJ-16) and the San Juan Formation (SJ-57) (Chew et al. 2007a). Light grey curves represent all ages from each sample, and the dark curves represent ages that are >90% concordant. The youngest detrital zircon age in each sample is shown within a black box.

Based on a loosely deﬁned U–Pb TIMS zircon lower intercept from the cross-cutting, post-tectonic San Juan granite of the San Nicolas batholith (Loewy et al. 2004), and maximum ages of 932 ± 28 Ma and 955 ± 18 Ma (the youngest detrital U–Pb SIMS zircon ages from the study of Chew et al. 2007a).

Loewy et al. (2004) also dated three clasts from the Chiquerío Formation SE of San Juan by U–Pb TIMS zircon. Two clasts of pink, weakly foliated, K-feldspar rich megacrystic granite yielded ages of 1168 ± 9/–6 Ma, 1162 ± 6 Ma, while a third clast of similar composition but with a gneissic foliation yielded a poorly constrained upper intercept of c. 1165 Ma. Chew et al. (2007a) undertook U–Th–Pb SIMS analyses of detrital zircons from three samples from the Chiquerío and San Juan formations. Combined age (probability-density distribution) plots and histograms for the three samples from that study are illustrated in Figure 44.4.

Sample SJ-11 is from a thin graded turbiditic sandstone bed from the Chiquerío Formation. It yields a restricted age distribution of 950–1300 Ma, with a prominent peak at c. 1200 Ma and a subsidiary peak at c. 1000 Ma (Chew et al. 2007a, Fig. 44.4). Light grey curves represent all ages from each sample, and the dark curves represent ages that are >90% concordant. The youngest detrital zircon age in each sample is shown within a black box.
Further global correlation of the Chiquirón Fm. and the pronounced negative C-isotope excursion in the San Juan Fm. are hampered by the lack of consensus on the temporal range of the ‘Sturian’ glacial episode (see Hoffman & Li 2009 for a review), the lack of absolute age constraints for the Chiquirón and San Juan formations, and the relatively low-resolution sampling employed for the stable isotope study. Further areas of research that might prove beneficial in the future include higher-resolution sampling for stable isotope analysis in the San Juan Fm. and a comprehensive search for tuffs in the glaciogenic strata.

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