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 orogenesis. 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-rafted 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 yet been identified. U–Pb dating of detrital zircons (U–Th–Pb SIMS) from the Chiquerío Fm. and the overlying San Juan Fm. suggest it is autochthonous with respect to Amazonia, as 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 Arequipa 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) obtained four K–Ar ages for the San Nicolas batholith, which cross-cuts the low-grade metasedimentary rocks in the region. The ages obtained (K–Ar hornblende ages of 442 ± 10 Ma and 438 ± 9 Ma and K–Ar biotite ages of 428 ± 12 Ma and 421 ± 11 Ma) demonstrated that the Marcona Fm. must be pre-Late Ordovician in age.

Caldas (1978), in the course of a regional mapping programme, reinterpreted the stratigraphy of the Marcona Mining Company (1968). The basal Justa Member of the Marcona Fm. was termed the Chiquerío Fm., and the glaciogenic nature of this part of the sequence was recognized for the first time (Caldas 1978, 1979). The overlying dolomitic rocks were also assigned to a new formation, the San Juan Fm. The Marcona Fm. was redefined to represent the phyllitic, siliciclastic unit lying above the San Juan Fm. Caldas (1978, 1979) inferred a Late Precambrian age for the Chiquerío Fm. and the overlying dolomitic San Juan Fm. based on the 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) resurrected 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* (Hambrey & 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.* (2007*a*) and is used in this chapter. Chew *et al.* (2007*a*) presented sedimentary observations, chemostratigraphic 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

From: Arnaud, E., Halverson, G. P. & Shields-Zhou, G. (eds) *The Geological Record of Neoproterozoic Glaciations*. Geological Society, London, Memoirs, **36**, 481–486. 0435-4052/11/$15.00 © The Geological Society of London 2011. DOI: 10.1144/M36.44

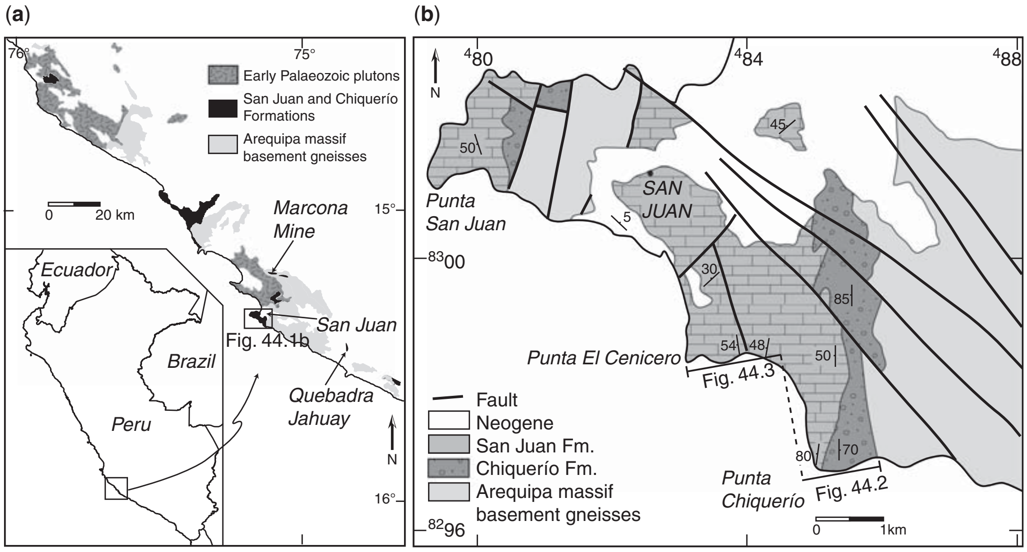

Fig. 44.1. (**a**) Location map and geological map of the western coast of southern Peru. (**b**) Geological map of the region around San Juan, modified from Caldas (1978, 1979).

also constrained the docking history of the underlying Arequipa massif to be Late Neoproterozoic or older in age, most likely juxtaposing during the 1.3–1.0 Ga Grenville–Sunsas orogeny (Chew *et al.* 2007*a*), as first postulated by Loewy *et al.* (2004).

Structural framework

Very limited work has been published on the nature of the basin in which the sediments of the Chiquerío and San Juan formations accumulated. The present-day outcrop distribution of the Chiquerío 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 Chiquerío and San Juan formations accumulated. Considering a Late Neoproterozoic age for the Chiquerío and San Juan formations (e.g. Caldas 1978, 1979; Chew *et al.* 2007*a*; Loewy *et al.* 2003, 2004), an extensional basin setting is most likely.

Shackleton *et al.* (1979) proposed a structural evolution of the Chiquerío 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 Chiquerío 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 Chiquerío 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.* 2007*b*).

Stratigraphy

The Chiquerío Fm. rests unconformably on gneisses of the Arequipa massif and consists of nearly 400 m of diamictite, 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.* 2007*a*). 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.* 2007*a*). 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 Chiquerío and San Juan formations is derived chiefly from Chew *et al.* (2007*a*), based on the well-exposed coastal section SE of the town of San Juan (Fig. 44.1b). The basal siliciclastic section of the Chiquerío Fm. is 348 m thick (Fig. 44.2), and consists primarily of massive diamictite with poorly developed internal stratification. The matrix of the diamictite 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.* 2007*a*). The clasts display no evidence of faceting 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 diamictite 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 diamictite interbedded with thin siltstone and graded sandstone beds. The stratification in the diamictite is

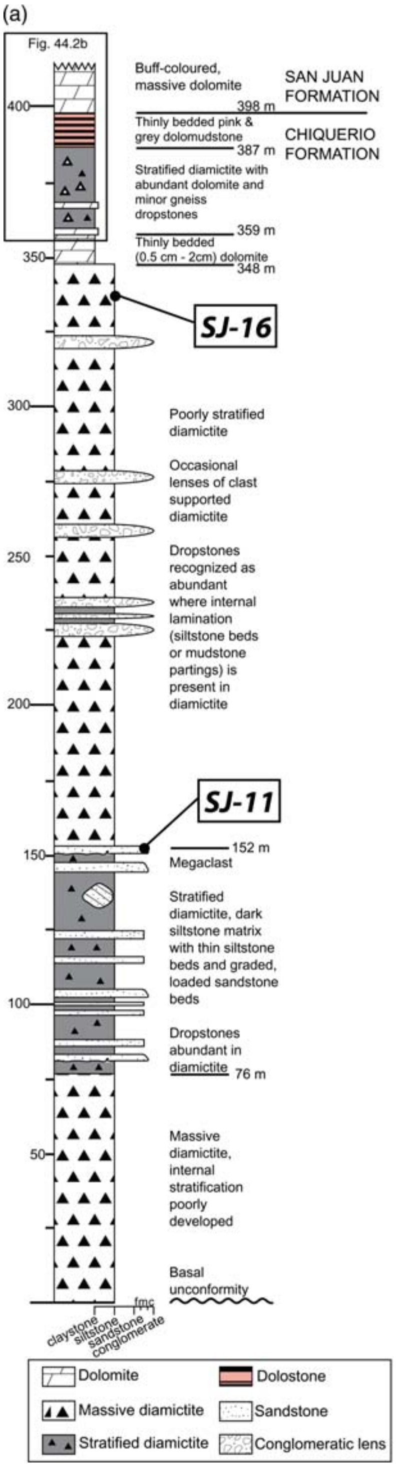

Fig. 44.2. (**a**) Stratigraphic section of the Chiquerío Fm. and the basal portion of the San Juan Fm. The line of section is illustrated in Figure 44.1b. (**b**) Log of the carbonate portion of the upper Chiquerío Fm. This section (359–410 m) is indicated by a box in (a).

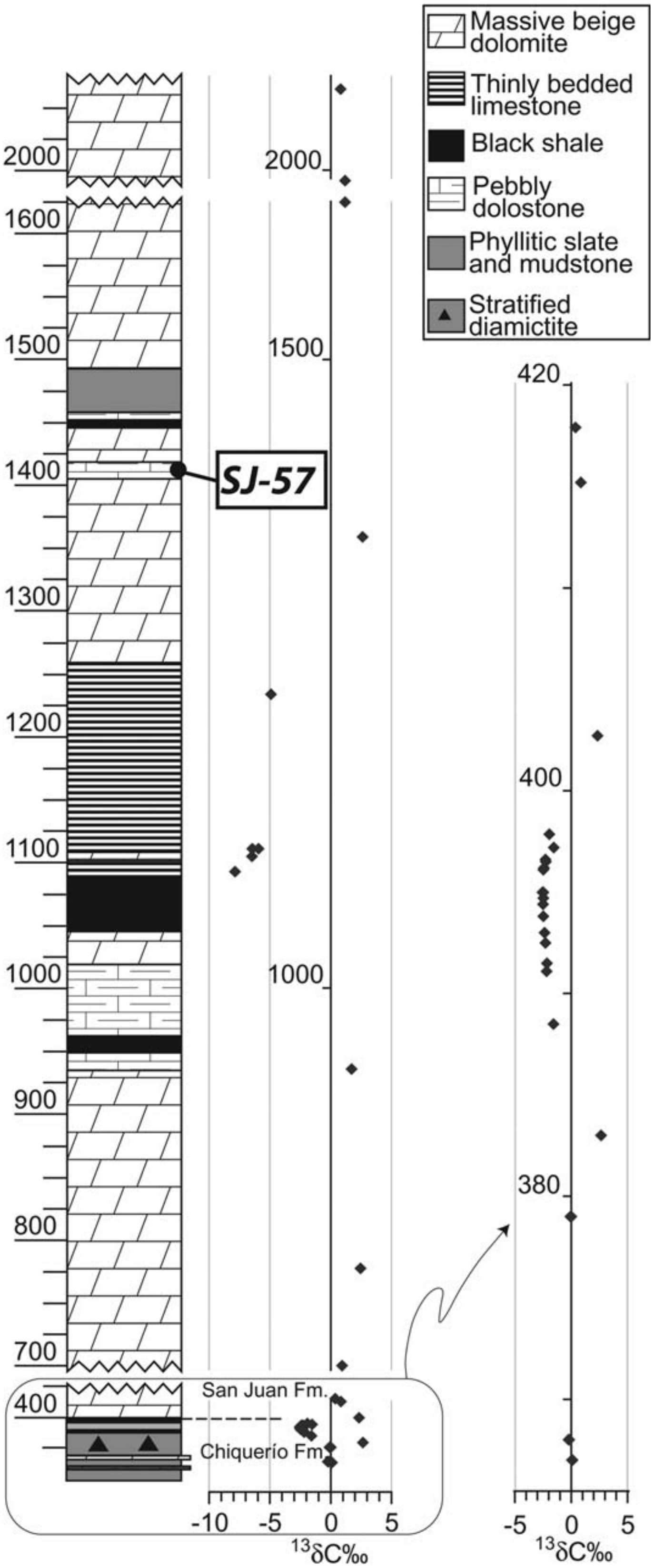

Fig. 44.3. Stratigraphic section and C-isotopic trends through the upper part of the Chiquerío Fm. and the San Juan Fm. Stratigraphic heights are in metres above the Chiquerío Fm.–Arequipa massif basement contact. The line of the section is illustrated in Figure 44.1b.

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 Chiquerío 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 dolostone and dark dolomicrite in the upper Chiquerío Fm. (Chew *et al.* 2007*a*). This dolomite 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–dolomicrite unit. The basal portions of the formation consist of several hundred metres of predominantly massive beige dolomite (Fig. 44.3, Chew *et al.* 2007*a*). 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 dolomicrites (e.g. Cobbing 1981; Chew *et al.* 2007*a*). The Chiquerío and San Juan formations are overlain unconformably by unmetamorphosed Mesozoic and Cenozoic sediments (Caldas 1978).

Chemostratigraphy

Chew *et al.* (2007*a*) 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 chemostratigraphic 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 δ^{13}C values between 0‰ and +2‰ (VPDB) (Fig. 44.3). Finely laminated pink dolostone and dark dolomicrite overlie the carbonate diamictite. This dolostone unit yields consistent negative δ^{13}C values of −2‰ (Fig. 44.3, Chew *et al.* 2007*a*).

The overlying San Juan Fm. exhibits a recovery in δ^{13}C 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 δ^{13}C values from −5‰ to −8‰ (five data points, Fig. 44.3, Chew *et al.* 2007*a*). Above this unit, there is a return to deposition of massive dolomite and the δ^{13}C 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‰) δ^{13}C excursion have been identified (Chew *et al.* 2007*a*).

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 biostratigraphic 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 Chiquerío 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.* (2007*a*) from the Chiquerío and San Juan formations are consistent with derivation from the Proto-Andean margin (Chew *et al.* 2007*b*). 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.* 2007*a*). 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.* 2007*a*) 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 (Tohver *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 $22 + 6/-5^\circ$ for the Amazonian block just after deposition of the Puga diamictites. Although direct ages for the Puga Fm. are not yet available, ^{87}Sr/^{86}Sr ratios and δ^{13}C 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

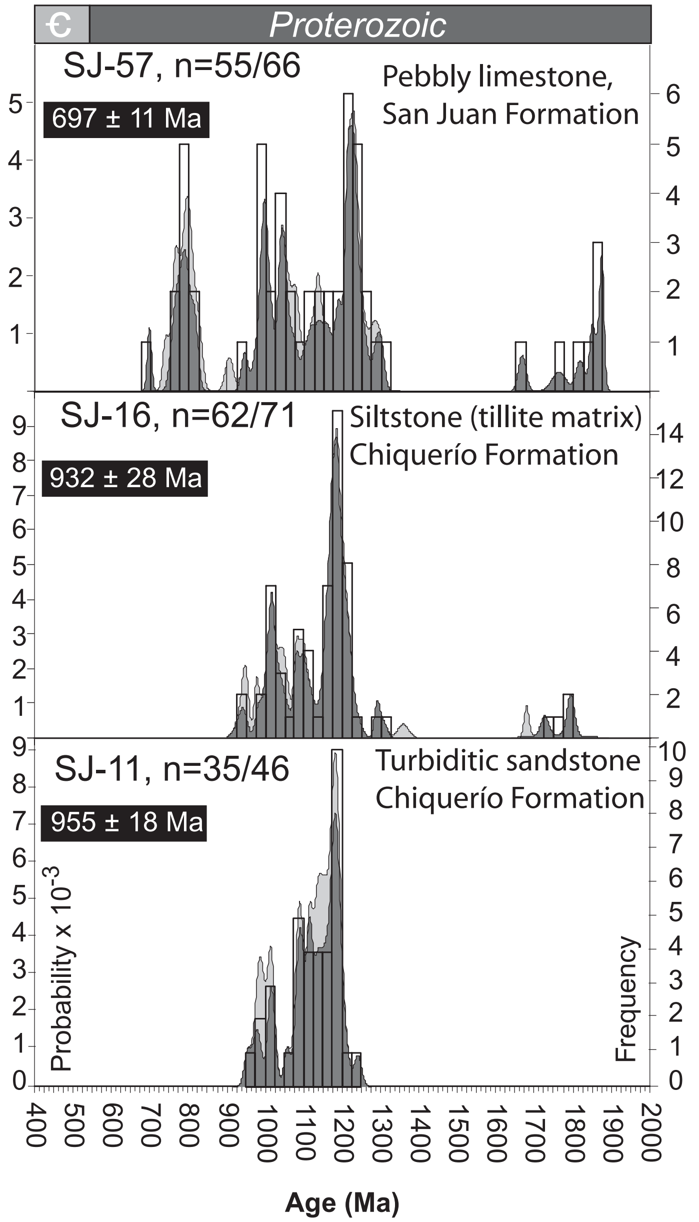

Fig. 44.4. Zircon probability density distribution diagrams from the Chiquerío Fm. (SJ-11, SJ-16) and the San Juan Fm. (SJ-57) (Chew *et al.* 2007*a*). Light grey curves represent all ages from each sample, and the dark curves represent ages that are >90% concordant. The youngest detrital zircon age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

Loewy *et al.* (2004) also dated three clasts from the Chiquerío Fm. 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.* (2007*a*) 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 Fm. 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.* 2007*a*, Fig. 44.4). SJ-16 is a sample of diamictite matrix from the Chiquerío Fm. 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.* 2007*a*, Fig. 44.4). The detrital zircon data from these Chiquerío Fm. 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 Fm., 1412 m above the Chiquerío Fm.–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.* 2007*a*, Fig. 44.4). A *c.* 700 Ma grain provides a maximum age constraint for the deposition of this portion of the San Juan Fm.

Discussion

The depositional environment of the Chiquerío Fm. 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 lamination in graded turbiditic sandstone beds, thus suggesting a glacially influenced marine environment (Caldas 1978; Cobbing 1981; Loewy *et al.* 2004; Chew *et al.* 2007*a*). 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.* 2007*a*). The San Juan Fm. consists predominantly of massive beige dolomite with little internal structure. The possible Precambrian stromatolites described by Injoque & Romero (1986) would suggest a shallow marine or intertidal environment for portions of the San Juan Fm.

The laminated dolostone facies at the top of the Chiquerío Fm. and its associated large negative δ^{13}C excursion are characteristic of cap dolostone associated with Late Neoproterozoic glacials (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.* (2007*a*) considered the Chiquerío Fm. and the pronounced negative C-isotope excursion in the San Juan Fm. 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 Fm. 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 Chiquerio Fm. (Chew *et al.* 2007*a*) is inferred. In either case, a Late Neoproterozoic (<700 Ma) age is supported by the youngest detrital zircon population in the San Juan Fm. The Proto-Andean margin of Amazonia is characterized by abundant zircon detritus between 1300–900 Ma and 650–550 Ma (Chew 2007*b*). The absence of Late Neoproterozoic (700 Ma and younger) zircon in the Chiquerío Fm. 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.

Further global correlation of the Chiquerío 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 'Sturtian' glacial episode (see Hoffman & Li 2009 for a review), the lack of absolute age constraints for the Chiquerío 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.

This study was funded by the Swiss National Science Foundation under a grant held by U. Schaltegger. We are extremely grateful to Urs Schaltegger at the University of Geneva, the Geological Survey of Peru (INGEMMET) and C. Moreno of S. Marcos University in Lima for scientific advice and logistical support during the field seasons in Peru. The careful and insightful reviews of V. A. Ramos, E. Le Guerroué and editor E. Arnaud are gratefully acknowledged. This work represents a contribution of the IUGS- and UNESCO-funded IGCP (International Geoscience Programme) project #512.

References

Caldas, J. 1978. *Geología de los Cuadrángulos de San Juan, Acarí y Yauca, Hojas: 31-m, 31-n, 32-n*. Instituto de Geología y Minería, Lima.

Caldas, J. 1979. Evidencias de una glaciación Precambriana en la costa sur del Perú. *Segundo Congreso Geológico Chileno* **J**, Arica, 29–37.

Chew, D. M., Kirkland, C. L., Schaltegger, U. & Goodhue, R. 2007*a*. Neoproterozoic glaciation in the Proto-Andes: tectonic implications and global correlation. *Geology*, **35**, 1095–1099.

Chew, D. M., Schaltegger, U., Košler, J., Whitehouse, M. J., Gutjahr, M., Spikings, R. A. & Miškovic, A. 2007*b*. U–Pb geochronologic evidence for the evolution of the Gondwanan margin of the north-central Andes. *Geological Society of America Bulletin*, **119**, 697–711.

Cobbing, E. J. 1981. Tillites at the base of the possible Early Palaeozoic Marcona Formation, southwest coastal Peru. *In*: Hambrey, M. J. & Harland, W. B. (eds) *Earth's Pre-Pleistocene Glacial Record*. Cambridge University Press, Cambridge, 899–901.

Cobbing, E. J. & Pitcher, W. S. 1972. Plate tectonics and the Peruvian Andes. *Nature*, **246**, 51–53.

Condon, D., Zhu, M. Y., Bowring, S., Wang, W., Yang, A. H. & Jin, Y. G. 2005. U–Pb ages from the Meoproterozoic Doushantuo Formation, China. *Science*, **308**, 95–98.

de Alvarenga, C. J. S., Santos, R. V. & Dantas, E. L. 2004. C–O–Sr isotopic stratigraphy of cap carbonates overlying Marinoan-age glacial diamictites in the Paraguay Belt, Brazil. *Precambrian Research*, **131**, 1–21.

Halverson, G. P., Hoffman, P. F., Schrag, D. P., Maloof, A. C. & Rice, A. H. N. 2005. Toward a Neoproterozoic composite carbon-isotope record. *Geological Society of America Bulletin*, **117**, 1181–1207.

Hambrey, M. J. & Harland, W. B. 1981. *Earth's Pre-Pleistocene Glacial Record*. Cambridge University Press, London & New York.

Hawkes, N., Clark, A. H. & Moody, T. C. 2002. Marcona and Pampa de Pongo: Giant Mesozoic Fe-(Cu, Au) deposits in the Peruvian Coastal Belt. *In*: Porter, T. M. (ed.) *Hydrothermal Iron Oxide Copper–Gold & Related Deposits: A Global Perspective*. PGC Publishing, Adelaide, Australia, **2**, 115–130.

Hoffman, P. F. & Schrag, D. P. 2002. The snowball Earth hypothesis: testing the limits of global change. *Terra Nova*, **14**, 129–155.

Hoffman, P. F. & Li, Z.-X. 2009. A palaeogeographic context for Neoproterozoic glaciation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **277**, 158–172.

Hoffmann, K. H., Condon, D. J., Bowring, S. A. & Crowley, J. L. 2004. U–Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: constraints on Marinoan glaciation. *Geology*, **32**, 817–820.

Injoque, J. & Romero, L. 1986. Estromatolitos (?) en la formación San Juan, San Juan de Marcona. Evidencia de estructuras fósiles precámbricas en el Perú. *De re metallic.De la minería y los metales: Revista del Instituto Geológico Metalúrgico*, **11**, 4–5.

Kennedy, M. J., Runnegar, B., Prave, A. R., Hoffmann, K. H. & Arthur, M. A. 1998. Two or four Neoproterozoic glaciations? *Geology*, **26**, 1059–1063.

Le Guerroué, E., Allen, P. A., Cozzi, A., Etienne, J. L. & Fanning, C. M. 2006. 50 Myr recovery from the largest negative δ^{13}C excursion in the Ediacaran ocean. *Terra Nova*, **18**, 147–153.

Loewy, S. L., Connelly, J. N., Dalziel, I. W. D. & Gower, C. F. 2003. Eastern Laurentia in Rodinia: constraints from whole-rock Pb and U/Pb geochronology. *Tectonophysics*, **375**, 169–197.

Loewy, S. L., Connelly, J. N. & Dalziel, I. W. D. 2004. An orphaned basement block: The Arequipa–Antofalla basement of the central Andean margin of South America. *Geological Society of America Bulletin*, **116**, 171–187.

MARCONA MINING COMPANY. 1968. Geologic Map of the Marcona iron deposits.

Omarini, R. H., Sureda, R. J., Götze, H. J., Seilacher, A. & Pflüger, F. 1999. Puncoviscana folded belt in northwestern Argentina: testimony of Late Proterozoic Rodinia fragmentation and pre-Gondwana collisional episodes. *International Journal of Earth Sciences*, **88**, 76–97.

Ramos, V. A. 2008. The basement of the Central Andes: the Arequipa and related terranes. *Annual Review of Earth and Planetary Sciences*, **36**, 289–324.

Shackleton, R. M., Ries, A. C., Coward, M. P. & Cobbold, P. R. 1979. Structure, metamorphism and geochronology of the Arequipa Massif of coastal Peru. *Journal of the Geological Society*, **136**, 195–214.

Shields, G. A. 2005. Neoproterozoic cap carbonates: a critical appraisal of existing models and the plumeworld hypothesis. *Terra Nova*, **17**, 299–310.

Tohver, E., D'Agrella-Filho, M. S. & Trindade, R. I. F. 2006. Paleomagnetic record of Africa and South America for the 1200–500 Ma interval, and evaluation of Rodinia and Gondwana assemblies. *Precambrian Research*, **147**, 193–222.

Trindade, R. I. F., Font, E., D'Agrella-Filho, M. S., Nogueira, A. C. R. & Riccomini, C. 2003. Low-latitude and multiple geomagnetic reversals in the Neoproterozoic Puga cap carbonate, Amazon craton. *Terra Nova*, **15**, 441–446.

Wilson, P. A. 1975. *Potassium–argon age studies in Peru with particular reference to the chronology of emplacement of the coastal batholith.* PhD thesis, University of Liverpool.