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Mass-production of Cambro–Ordovician quartz-rich sandstone as a consequence of chemical weathering of Pan-African terranes: Environmental implications

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Abstract

A vast sheet of mature quartz sand blanketed north Africa and Arabia from the Atlantic coast to the Persian Gulf in Cambro–Ordovician times. U–Pb geochronology of a representative section of Cambrian sandstone in southern Israel shows that these sediments are dominated by 550–650 Ma detrital zircons derived from Neoproterozoic Pan-African basement. The short time lag between magmatic consolidation of a Pan-African source and deposition of its erosional products indicates that, despite their significant mineralogical maturity, the voluminous quartz-rich sandstones on the northern margin of Gondwana are essentially first-cycle sediments.

Mass production of these voluminous first-cycle quartz-rich sandstones resulted from widespread chemical weathering of the Pan-African continental basement. We suggest that conditions favoring silicate weathering, particularly a warm and humid climate, low relief and low sedimentation rates prevailed over large tracts of Gondwana in the aftermath of the Pan-African orogeny. An unusually corrosive Cambro–Ordovician atmosphere and humid climate enhanced chemical weathering on the vegetation-free landscape. We infer that late Neoproterozoic–Cambro–Ordovician atmospheric pCO_2 rose as a consequence of widespread late Neoproterozoic volcanism, followed by an uptake of CO_2 by chemical weathering to produce the Cambro–Ordovician sandstone as a negative feedback.

Keywords: Cambro–Ordovician; sandstone; Gondwana; chemical weathering

1. Introduction

A vast sheet of Cambro–Ordovician sandstone with an estimated volume of 15 million km^3 was deposited on the northern margin of Gondwana following the Neoproterozoic Pan-African–Brasiliaño orogeny that built the supercontinent [1,2]. The Pan-African orogeny was followed by continental-scale uplift, erosion, the formation of intramountain basins and rifting and the development of an extensive peneplain that can be traced from Morocco to Oman [3]. The peneplain de-

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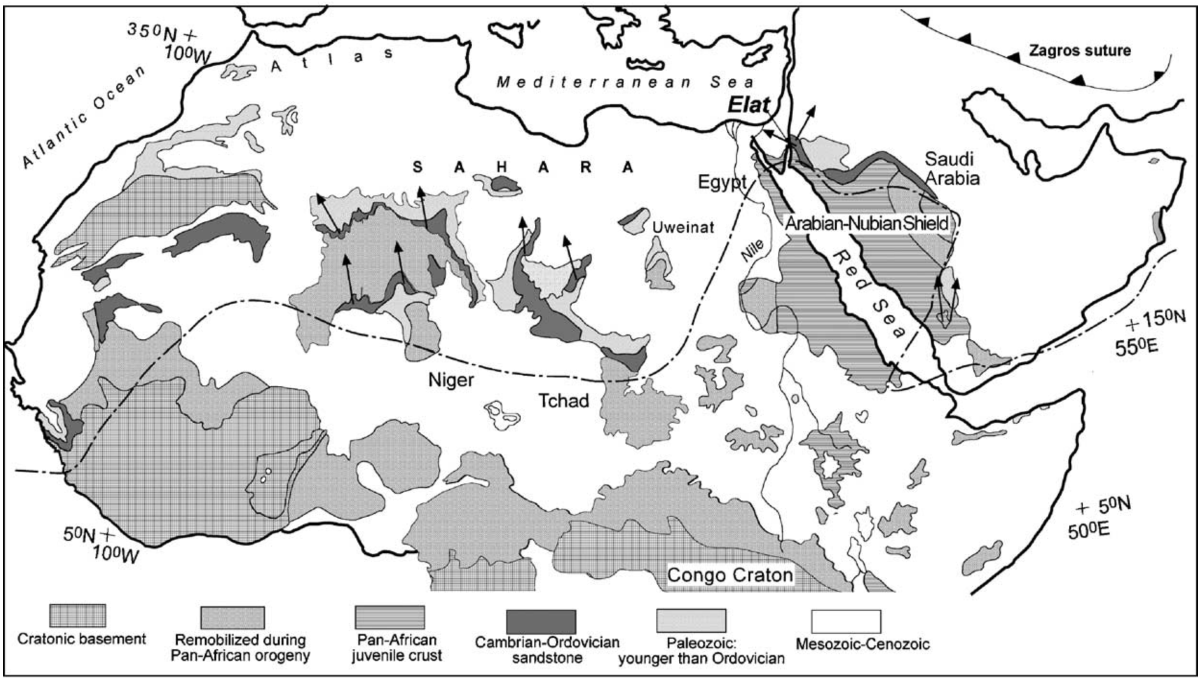

Fig. 1. Simplified geological map of North Africa and Arabia showing distribution of Precambrian basement rocks and Paleozoic sediments (after [4,5]). Dashed line marks the southern limit of Early Paleozoic sandstone. Black arrows mark direction of sedimentary transport (compiled from [7–10]).

veloped on exhumed Precambrian basement as well as on late Neoproterozoic rift basins. It denotes the beveling of relief developed by late Neoproterozoic collision, and the onset of the Cambro–Ordovician platform-type siliciclastic sedimentation [Fig. 1; 2,4,5]. Burke et al. [2] suggested that accommodation space for deposition the Cambro–Ordovician (520–440 Ma) sandstone resulted from thermal subsidence in the aftermath of late Neoproterozoic (post-orogenic) rifting, and estimated that these quartz-rich sandstones are the most widespread detrital sequence ever deposited on continental crust. Integration of field evidence indicate that sedimentation was consistent with transport via a continent-wide braided stream system with a general south-to-

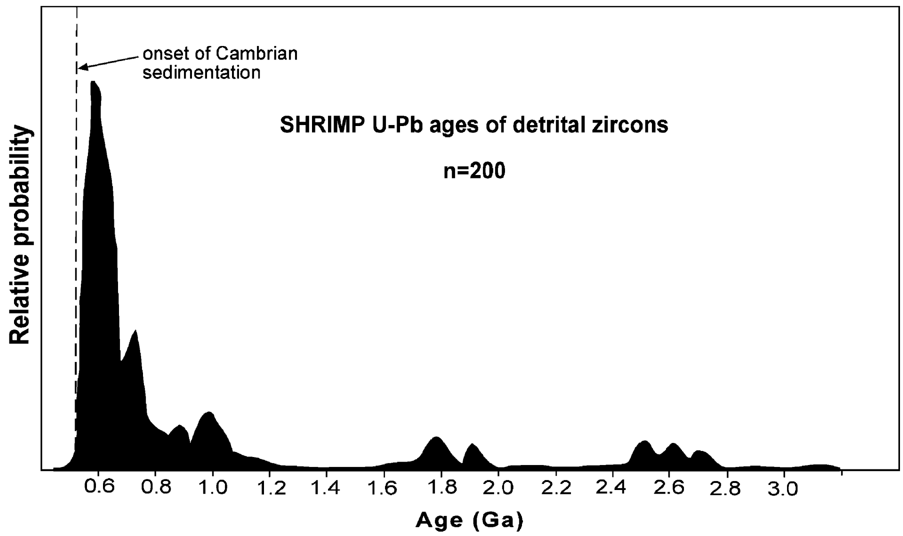

Fig. 2. Histogram showing age distribution of detrital zircons from Cambrian siliciclastic section of southern Israel. Total number of zircons = 200 (from [3]). Ages are calculated as weighted mean age, including concordant and discordant ages.

north paleocurrent direction throughout North Africa and Arabia (Fig. 1).

Intensive erosional denudation of Gondwana and production of voluminous Cambro–Ordovician sandstones coincided with important global changes such as oscillations in ocean chemistry [11], a significant rise of atmospheric pCO_2 [12] and the Cambrian biotic explosion [13]. Here, we assess the role of chemical weathering in the Cambro-Ordovician sandstone formation and demonstrate that the petrogenesis of these sandstones is an important indicator of Neoproterozoic–early Paleozoic global environment.

2. The Cambro–Ordovician quartz-rich sandstone

Cambro–Ordovician sandstones are exposed in North Africa and Arabia over an area averaging 1500 km in width and 6000 km in length, extending from Morocco in the west to the Persian Gulf in the east (Fig. 1). From south to north, depositional facies in the sandstone change progressively from fluvial to shallow marine [7]. They usually thin southward, where progressively younger units rest on top of the peneplained Precambrian basement ([6], and references therein). West of the Nile, exposures of Cambro–Ordovician sandstone reach south as far as northern Chad, whereas east of the Nile exposures extend to Yemen and Ethiopia (Fig. 1).

In the Algerian Sahara, late Cambrian to Tremadocian (Early Ordovician) fluvial sandstone ("Tassili interne") overlies the peneplained Pan-African basement of the Hoggar massif [7,14]. The basement beneath the Cambrian siliciclastics is deeply weathered, and the lower part of the Cambrian Ajjer formation consists of coarse-grained homogeneous quartz sandstone containing pebbly horizons [7,14]. Strikingly uniform paleocurrent directions measured around the Hoggar, including its southern border, indicate transport of sand from south to north over a very gentle slope [7].

To the east, fluviatile and shallow-marine sandstones were deposited over the northern edge of the Arabian–Nubian shield beginning at ~520–510 Ma [5]. Cambrian sandstones are exposed in southern Israel and in southern Jordan (Fig. 1). In southern Israel, the Cambrian section is 300 m thick, changing gradually upward from arkose to subarkose to mature quartz arenite [15,16]. Fluvial deposits are common at the base of the section, but shallow marine sandstones dominate the remainder. The heavy mineral suite in the Cambrian section of southern Israel and Jordan [17,18] is characterized by zircon–tourmaline–rutile and plagioclase is practically absent, indicating sediment maturity. Long-distance transport has been suggested [17,6] but some Cambrian units, especially at their base, are texturally immature and probably locally derived.

Farther to the east in Saudi Arabia, the Siq Formation [19] lies atop Neoproterozoic basement. Its basal few meters are gritty arkosic sandstone and conglomerate containing pebbles from the underlying crystalline rocks, but the remainder of the unit is fine- to medium-grained quartz sandstone. The planar-cross bedded Saq sandstone of Lower Ordovician age resembles the Ram-Umm Sham sandstone of NW Arabia and southwest Jordan in that it is a mature arenite, usually lacking arkose [19]. The remote southeast edge of the shield is covered by the Cambro–Ordovician Wajid sandstone, more than 900 m of mature quartz-sandstone [10]. In the southern exposures of this unit, the sandstone was deposited in a fluvial (probably braided stream) environment, whereas a littoral and sublittoral environment prevailed to the north. In all areas, the Wajid sandstone is remarkably mature in composition, with quartz exceeding 98% [10]. Paleocurrent directions indicate northerly transport [10], implying that rather than being the source for the Wajid sandstone, the presently exposed Arabian–Nubian shield was a Cambro–Ordovician depocenter.

As a whole, the Cambro–Ordovician sequences are dominated by mineralogically and often texturally mature sandstone. The base of the section, up to a few tens of meters above the Precambrian basement, typically contains arkose and pebbles but subarkose (quartz >75%) and quartz-arenites dominate the rest of the section. This compositional maturity may have been enhanced by long distance transport. But chemical weathering must also have been significant (and perhaps dominant) because in the southernmost exposures that record short transport, such as the Wajid of southern Saudi Arabia, the siliciclastic blanket is comparably quartz-rich (e.g. [10]).

3. Quartz sandstone petrogenesis — insights from detrital zircon geochronology

U-Pb SHRIMP detrital zircon ages (Fig. 2) from several Cambrian sandstone units in the Elat area of southern Israel were reported by Avigad et al. [3] and by Kolodner et al. [20]. The Elat section is a representative part of the Cambro–Ordovician sandstone of north Gondwana. Most of the detrital zircons yielded concordant Neoproterozoic ages between 0.55 and 0.65 Ga, indicating that the Cambrian sandstones are principally Pan-African erosional detritus [3,20]. A crucial point to our argument is that the U–Pb ages demonstrate that the time lag between the consolidation of the Pan-African granitoid source and deposition of the sandstone derived from it was short, on the order of a few tens of million years or less. Thus, despite their mineralogical maturity, the Cambro–Ordovician sandstone of north Gondwana were principally derived directly from Neoproterozoic basement rocks that were themselves emplaced shortly before deposition. Williams et al. [21] reported U–Pb detrital zircon ages from Cambrian and Ordovician rocks in Algeria showing they are also dominated by late Neoproterozoic detrital zircons. Thus, the U–Pb data provide unequivocal evidence that the mature quartz-rich sandstones of northern Gondwana are essentially first-cycle sediments. Any significant recycling of older cratonic sediments is ruled out but the possibility that some Ediacaran arkose and conglomerates accumulated during the collapse of the Pan-African orogenic edifice [6,22] or Neoproterozoic diamictites [3] have been reworked into the Cambro–Ordovician section cannot be excluded. However, the detrital material in Infracambrian basins is immature: it retains the entire basement mineralogy from which it was derived (including the labile components) and has been little transported. Recycling of late Neoproterozoic basin fill, if it indeed has taken place, had a negligible effect on maturity. Selley [8] proposed that the lower part of the Cambrian section has been recycled into the overlying Cambro–Ordovician but further petrographic examinations of the Cambrian to Early Orodovician section in Jordan did not support this [18]. Indications for recycling are mainly confined to the overlying supermature Mesozoic quartz-arenites [18]. Dott [23] concluded that it was possible to form quartz arenites in a single sedimentation cycle, but that this was not common. The Cambro–Ordovician siliciclastics of North Africa and Arabia may thus be unique not only because of their great volume but also because they represent a convincing example of quartz-rich sandstone that formed in a single cycle of sedimentation.

4. The role of chemical weathering in formation of quartz arenites

The origin of quartz arenites, particularly if they can be produced in a single sedimentary cycle, has long been debated ([23], and references therein). Suttner et al. [24] argued that first-cycle quartz arenites cannot be produced under normal weathering, transportation and deposition conditions, and that a special combination of factors operating over a long time is required. Wind transport and abrasion is thought to play an important role in winnowing and rounding quartz grains, but the key issue is the removal of all but quartz and refractory accessory grains [23]. Transport distance plays a role in maturing sandstone texturally, but it is not the dominant factor in mineralogical maturation, which requires the decomposition and leaching of all major rock-forming minerals except quartz. Decomposition and leaching require prevalent chemical weathering at the source, during transportation and possibly during deposition [25]. Humid climate is a prerequisite for in situ weathering at the source, and low relief is required to allow the development of deep weathering profiles. Mass production of quartz arenites therefore requires a specific set of paleogeographic and paleoclimatic conditions. Suttner et al. [24] doubted if such conditions occurred frequently in the geological past, and concluded that the bulk of ancient quartz arenite must be of multicyclic origin.

As described above, U–Pb detrital zircon geochronology provides unequivocal evidence that the mature quartz-sandstone of northern Gondwana are first-cycle sediments, and geological data indicate that these sandstone were produced in Cambro–Ordovician time. Modern production of first-cycle quartz arenites has been documented only at 8° north in the Orinoco River drainage basin [26] in an area dominated by a humid-tropic climate and low relief. We suggest that the Cambro–Ordovician quartz-rich sandstone can be taken to indicate that Orinoco-like climate and relief conditions prevailed over northern Gondwana in the Cambrian through the (pre-glacial) Ordovician.

5. Field evidence for chemical weathering in late Neoproterozoic–Cambrian times

Our interpretation of the voluminous arenites of northern Africa and Arabia as first-cycle sediments requires the involvement of intensive chemical weathering, but few field descriptions of late Neoproterozoic–Cambro–Ordovician chemical weathering phenomena are known in Gondwana. A detailed description of late Neoproterozoic–Cambrian weathering was reported by Beuf et al. [7], who reported the widespread occurrence of weathering profiles developed on Neoproterozoic granitoids of the Hoggar Massif in the Algerian Sahara, where the contact between the Neoproterozoic basement peneplain and Cambro–Ordovician sandstone is well exposed. Kaolinite is an abundant alteration product in the basement rocks and in the overlying sandstone, and ferruginous crusts were also described. Beuf et al. [7] also recognized the presence of weathered granite clasts in the overlying sandstone supporting the interpretation that weathering predated deposition of the Cambrian sand.

Laterite was extensively developed in northwest Sudan (Jebel Tawiga–Jebel Tageru area) where a weathered crust consisting of both kaolinitic saprolite and overlying bauxitic laterite developed on strongly deformed Neoprotetozoic metabasalts and metapelites. The weathering profile is up to 25 m thick and is overlain by shallow marine Skolithos-bearing sandstones [27,28] of late Ordovician to early Silurian age, setting a lower age limit for the alteration process.

In southern Israel, the peneplain contact between Cambrian subarkose and the underlying Neoproterozoic basement is exposed. Our field investigations reveal a weathering profile a few meters thick occurring at the contact where it was formed on late Neoproterozoic granites of the Arabian–Nubian shield (Fig. 3). In the N. Sheoret area, a 5-m thick horizon at the top of a basement granite has been completely weathered, leaving original igneous quartz grains embedded in an otherwise completely altered clay matrix. Pegmatitic quartz veins are unique remnants of the original igneous complex. At the base of the weathered profile, the dominant clay mineral is ordered illite-smectite, which is the burial diagenetic product of an original smectite. Near the top of the weathering profile, kaolinite is widespread (Fig. 4), suggesting the original presence of a much thicker laterite that was later removed during peneplanization.

These data, together with reports of paleosols and saprolites in southern Jordan [8] and the Wajid area of south Saudi Arabia [29], suggest that at the beginning of the Paleozoic, chemical weathering of basement rocks was widespread in northern Gondwana. The presence of kaolinite in the weathering profiles indicates severe leaching of the original basement granite source terranes, analogous to modern humid-tropical climates. We suggest that erosion of these deeply weathered basement granitoids yielded the mature, quartz-rich sandstone of North Africa and Arabia in a single weathering-transport cycle (see also [2]).

Arkose and similarly less mature sandstones are also found within the Cambro–Ordovician section. In view of the overall maturity of the rest of the sedimentary sequence, we suggest that arkose was derived from local basement highs and rejuvenated relief, where downcutting penetrated below the weathered veneer. Abundant arkose at the base of Cambrian sections such as the Amudei–Shelomo formation of southern Israel were probably deposited before basement peneplain formation was complete. These basal sequences therefore received detritus from a mixture of variably weathered source areas.

Alongside quartz sandstones that were trapped on land, weathering of Neoproterozoic basement rocks must have produced a voluminous clay fraction that was transported offshore. These fine clastics are thus

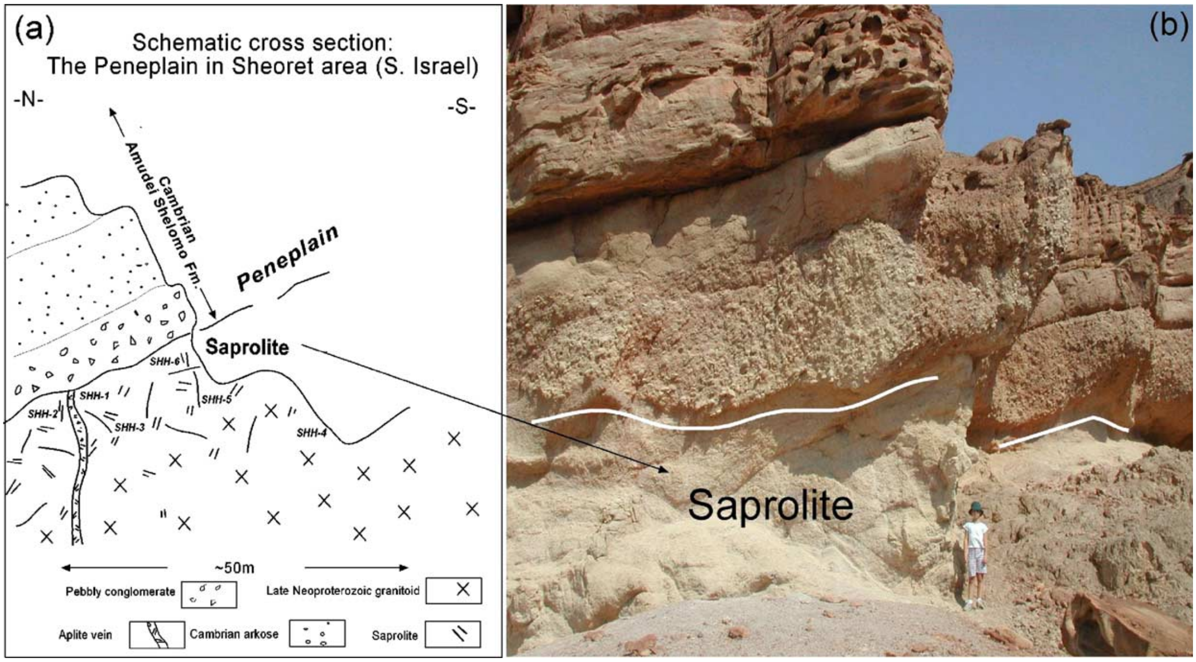

Fig. 3. (a) Schematic geological section in the Sheoret area (S. Israel: Coord. 2962637N; 3493180E). (b) A saprolite (clear horizon), essentially composed of illite-smectite and kaolinite, defines the top of the Neoproterozoic basement in the Sheoret area (southern Israel).

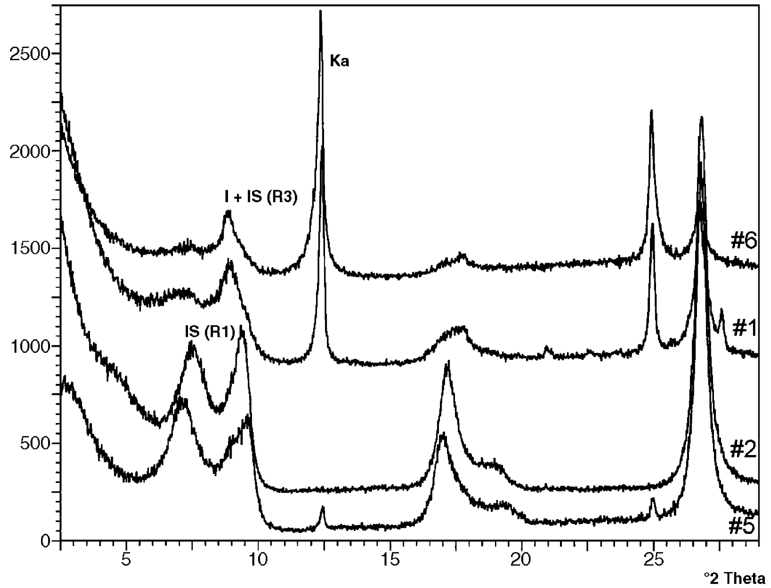

Fig. 4. Difractograms of the oriented glycolated <2 μm fraction of selected samples from the weathering profile of the Sheoret area. Sample #6 is the most weathered granite preserved at the top of the currently exposed profile. This sample is dominated by kaolinite (Ka). Sample #1 is located 0.5 m below the peneplain. It is also dominated by kaolinite. Samples #2 and #5 are less weathered granites located close to the bottom of the weathered section at a distance of about 5 m below the peneplain. Both samples are dominated by ordered IS of R1 type. All four samples contain subordinate IS of R3 type. This indicates that the original clay in the lower part was smectite, whereas up the profile kaolinite was the main weathering product. Illitization of smectite occurred at maximum burial during late diagenetic stages.

expected to occur in continental fragments detached from north Gondwana. Indeed, one of the most spectacular examples is the huge Cambro–Ordovician deep-sea fan siliciclastic (clay mud and greywacke) of the lower part of the Meguma fan [31]. It was deposited off what is now the coast of Morocco, and now outcrops over most of the Canadian province of Nova Scotia [31].

6. Evidence from Sr isotopes

The Sr isotopic composition of seawater, as recorded by Neoproterozoic–Cambrian carbonates, supports our interpretation that intensive chemical weathering took place on the continents at the time that the quartz-rich sandstones were produced.

At about 600 Ma, the oceanic $^{87}Sr/^{87}Sr$ began to rise (Fig. 5), reaching 0.7080 by 580 Ma and 0.7091 by 570 Ma [11,30]. Although Neoproterozoic seawater Sr evolution is by no means well known, this change may represent the largest sustained increase in $^{87}Sr/^{87}Sr$ in the past 800 Ma. The rate and magnitude of the $^{87}Sr/^{87}Sr$ increase between 600 and 570 Ma approach those found in late Cenozoic time, variations attributed to chemical weathering of the Himalayas.

The positive $^{87}Sr/^{87}Sr$ excursion at the end of the Neoproterozoic through the Cambrian has been linked to continental denudation in the aftermath of the Pan-African orogeny [32], but the nature of the eroded terranes and the location of the ensuing sedimentary bodies have not been identified in detail. We suggest that the weathered and decomposed feldspathic fraction of exposed Neoproterozoic basement throughout north Gondwana is a likely candidate. Fig. 5 shows that formation and deposition of the Cambrian siliciclastic rocks coincides with the period of elevated $^{87}Sr/^{87}Sr$ in the ocean, consistent with these rocks being derived from chemically weathered continental basement. Moreover, the Ordovician $^{87}Sr/^{87}Sr$ decline (Fig. 5) is consistent with the then-weathered Precambrian basement being progressively covered and removed from the oceanic $^{87}Sr/^{87}Sr$ system by the developing siliciclastic blanket.

7. Paleoenvironmental implications

We attribute the mature, first-cycle nature of the North African Cambro–Ordovician siliciclastic sections to intensive chemical weathering in a warm-humid climate that prevailed over north Gondwana from the end of the Neoproterozoic to the (pre glacial) Ordovician.

Other studies emphasized the presence of evaporites [33,34] and ventifacts [7] in the Cambrian of north Gondwana indicating residence under warm-arid weather so that environmental conditions may have

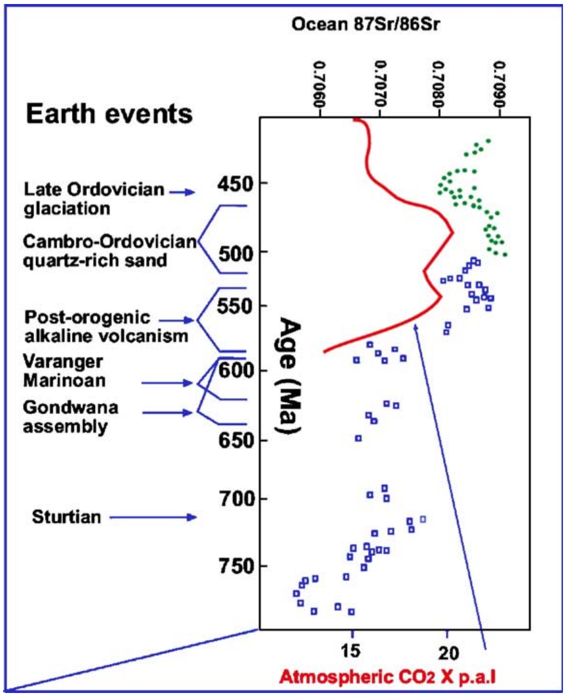

Fig. 5. Diagram showing late Neoproterozoic to Ordovician geological events, including deposition of the Cambro–Ordovician quartz-rich sandstone, versus the history of ocean $^{87}Sr/^{86}Sr$ (green dots from [44]; and open squares from [11]) and the history of atmospheric pCO_2 (red line; after [12]). Deposition of the Cambrian sandstone coalesced with elevated ocean $^{87}Sr/^{86}Sr$ ratio, which is a proxy for continental chemical weathering. Note also that atmospheric pCO_2 rose to over 20 p.a.l. during post-orogenic alkaline volcanism of North Africa and Arabia, and remained elevated during Cambro–Ordovician time. This figure demonstrates the close interaction between continental weathering, formation of quartz-rich sandstone, ocean chemistry and atmospheric pCO_2 during the late Neoproterozoic to the Cambro–Ordovician.

fluctuated considerably. Somewhat in conflict with the above field evidence and with the presence of tropical carbonates in Morocco, Cambrian paleogeographic reconstructions tend to place North Africa at rather high latitudes — this area was under an extensive ice sheet by the Late Ordovician. The reconstructions suggests that at around 545 Ma [35] and 514 Ma [36], the Arabian–Nubian shield was located at 25–30° S and Algerian Sahara lay in even higher latitudes at 40–50° S. If correct, this would imply that intensive chemical weathering produced quartz-rich sandstone across the entire north Gondwana margin, regardless of paleolatitude.

Moreover, the Table Mountain Group which unconformably overlies the Neoproterozoic basement in South Africa (on the other side of Gondwana), comprises a thick, supermature quartz-arenite sequence of Ordovician age. Rust [37] noted that "the volume of the clean quartz sand included in the Table Mountain Group is staggering." U–Pb SHRIMP dating [38] demonstrated that the quartz-arenites are dominated by Neoproterozoic to Cambrian (700–520 Ma) detrital zircons. This suggests that the quartz-arenites in the Table Mountain Group are also first-cycle sediments and that chemical weathering must have played an important role in their formation. Recent geochemical investigations of the fine clastics in the Table Mountain Group indicate their formation indeed involved intensive chemical weathering [39].

Thus, whereas modern production of first cycle quartz-arenites is confined mainly to the nearly equatorial Orinoco basin, the production of quartz-rich sand in Cambro–Ordovician time took place on a continental scale across a range of paleolatitudes, requiring a warm, global greenhouse climate. A postglacial Neoproterozoic to Cambrian shift to a warmer climate is supported by C isotope analyses of Cambrian carbonates suggesting that atmospheric pCO_2 rose to over 20 times p.a.l. (Fig. 5; e.g. [12]; and see also [40]).

Elevated greenhouse gas content of the atmosphere could occur by a number of scenarios [41]. Bentor [42] and references therein] suggested that the 580–540 Ma post-orogenic alkaline igneous activity that terminated the Pan-African orogeny in the Arabian–Nubian shield and in other parts of North Africa [43] may have been one of the largest igneous province in Earth's history. It is possible that degassing associated with this late Neoproterozoic CO_2-rich alkaline volcanism produced the unusual increase in atmospheric pCO_2 (e.g. [12]). Elevated atmospheric CO_2 led to extensive deep weathering of continental basement (via acid rain) and formation of voluminous Cambro–Ordovician quartz-rich sandstones as a negative pCO_2 feedback. The elevated atmospheric pCO_2 and the concomitantly more corrosive atmosphere, may also serve to resolve the question of the how intense chemical weathering could have occurred in the absence of land plants (e.g. [23]).

We conclude that the production and deposition of the expansive, first-cycle quartz-rich sand sheet blanketing the northern margin of Gondwana, together with the development of a lateritic paleo-weathered profile (saprolite) in the basement rocks, was a consequence of intense chemical weathering. Detrital zircon ages indicate that these sands were derived from the weathering of late Neoproterozoic arc-related igneous rocks that were emplaced only shortly before deposition of the sandstone sheet commenced. Further, this weathering occurred across a range of paleolatitudes, implying a warm, humid climate over much of the early Paleozoic Earth. As such, these deposits are a line of independent geological evidence in support of models inferring sharply elevated pCO_2, as well as an explanation for the dramatic rise in oceanic $^{87}Sr/^{87}Sr$ during this time.

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