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1 **The impact of the end-Ordovician glaciation on sediment routing systems: A case**  
2 **study from the Meseta (northern Morocco)**

3

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24 **ABSTRACT**

25 Assessment of sediment redistribution by end-Ordovician ice sheets is crucial for the  
26 reconstruction of Lower Paleozoic source-to-sink patterns. Focussing on the ice-distal,  
27 deepwater Tazekka depocenter (Moroccan Meseta), we thus performed a provenance  
28 study that combined whole-rock geochemistry, petrography and insights from high-  
29 resolution detrital zircon ages. The results show that the glacial sediments are  
30 compositionally —mineralogically and geochemically— more mature than preglacial  
31 strata. This observation points to a preferential cannibalization of the “great Lower  
32 Paleozoic quartz-rich sandstone sheet”, with a limited input of first-cycle, far-travelled  
33 clastic sediments. Differentiation of glacial units is not straightforward, yet the glaciation  
34 acme is typified by a highly mature sedimentary source and an age spectrum lacking  
35 Mesoproterozoic zircon grains, both features strongly indicating derivation from the  
36 Cambrian–Lower Ordovician cover of the Tuareg Shield. More regional sources are  
37 expressed during the earlier glaciation stages, during which lowstand remobilisations  
38 unrelated to subglacial erosion are also suspected. Subordinate but notable late Tonian  
39 (~ 0.8 Ga) and latest Stenian to early Tonian (~1 Ga) zircon populations are also  
40 evidenced in Morocco, which may have implications for future paleogeographic  
41 reconstructions.

42

43

44 **Keywords**

45

46 sediment cannibalization, glacial erosion, zircon geochronology, source-to-sink,  
47 Hirnantian, peri-Gondwana

48

## 49 **1. Introduction**

50 The end-Ordovician glaciation culminated in the growth of a large ice sheet over  
51 Gondwana (Le Heron and Craig, 2008; Ghienne et al., 2014; Pohl et al. 2016). From West  
52 Africa to Arabia, ice-sheet divides and flow orientations were not necessarily  
53 superimposed on preglacial fluvial drainage systems (e.g., Meinhold et al., 2013); the  
54 latter serving as guidelines for peri-Gondwana paleotectonic reconstruction based on  
55 detrital zircon geochronology (e.g., Pastor-Galán et al., 2013; Shaw et al., 2014). In  
56 particular, the assessment of Mesoproterozoic zircon grains in NW Africa is of interest  
57 (Avigad et al., 2012; Pratt et al., 2015). As such ages are generally regarded in the north  
58 African context as marking a source originating in the Sahara metacraton (NE Africa;  
59 Henderson et al., 2015; Chelle-Michou et al., 2017), multi-stage sediment recycling  
60 events (see discussion in Andersen et al., 2016) and potential mixing linked to the end-  
61 Ordovician glaciation may have severely altered the true significance of zircon  
62 provenance. Alternatively, glacially fed routing systems can introduce, or enhance, the  
63 contribution of far-travelled sediment sources that were absent or subordinate in  
64 preglacial watersheds (Doornbos et al., 2009; Hofmann et al. 2015; Gürsu et al., 2018).  
65 For instance, the massive arrival of >2.3 Ga zircon grains that has been detected in the  
66 Upper Ordovician strata of the ice-proximal reaches of the glaciated platform in the  
67 southern Hoggar (Linnemann et al., 2011) might be a consequence of the reorganization  
68 of sediment dispersal trends owing to glaciation. Actually, the degree to which the end-  
69 Ordovician glaciation impinged on the Paleozoic dispersal systems of the Gondwana  
70 remains unknown (Avigad et al., 2012, 2017).

71 At the scale of NW Africa, ice flows departing from an oversimplified centrifugal  
72 scheme, which in addition does not fully conform to the preglacial fluvial transport  
73 directions (Fig. 1), should be supported by changes in sediment provenance preserved

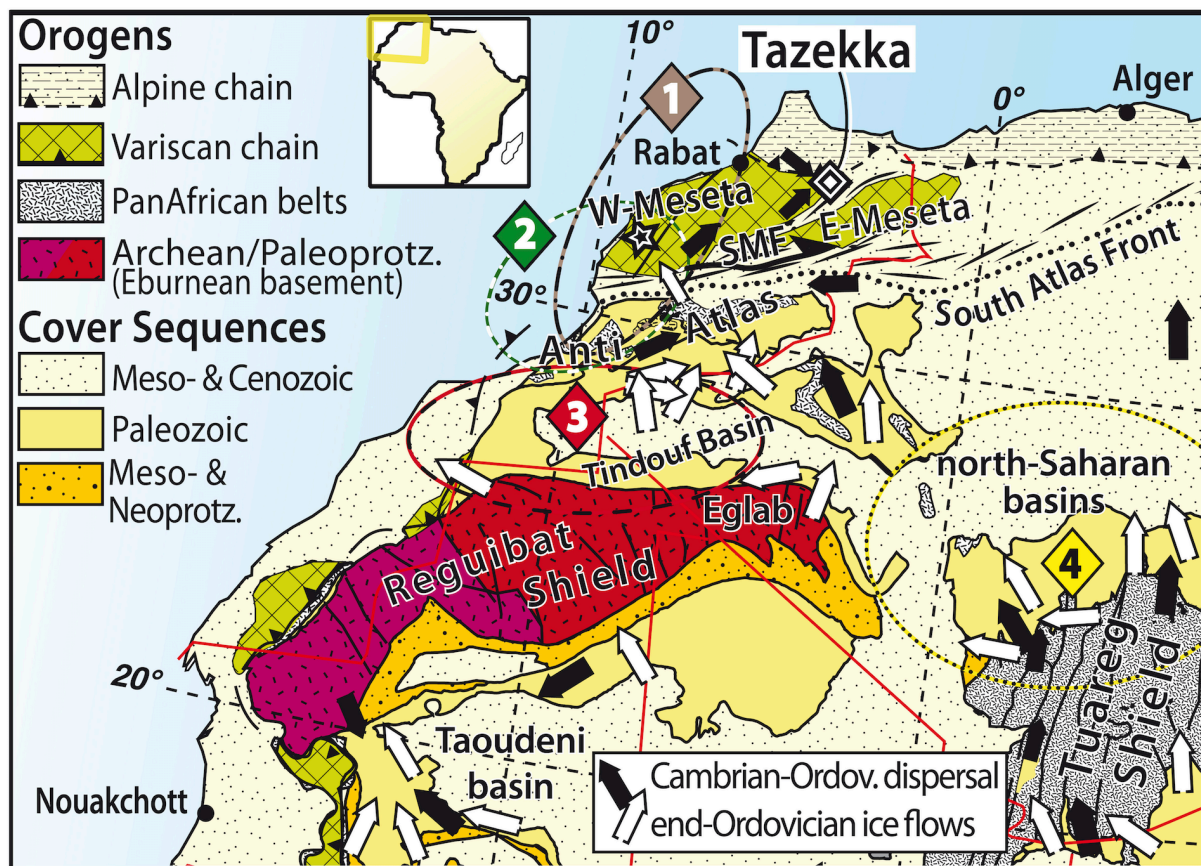
74 in the glacial stratigraphic record. We have performed a systematic and detailed  
75 provenance study focusing on the glaciogenic sediments of the Tazekka Massif (northern  
76 Morocco), a representative area of ice-distal platform segments in end-Ordovician  
77 reconstructions (Le Heron et al., 2007). As such, the Tazekka depositional system can be  
78 viewed as the final sink of the end-Ordovician, NW African glacial routing system. This  
79 new dataset aids in deciphering the impact of the glaciation on the continental-scale  
80 sediment dispersal, a resurgence of which may have occurred well after the glacial event  
81 through recycling (Pratt et al., 2015). Also, given that the end-Ordovician glaciation  
82 corresponds to a polyphase climatic event (Ghienne et al., 2007a, 2014), any clues from  
83 high-resolution provenance studies may help to delineate individual advance–retreat  
84 cycles of the end-Ordovician ice sheets, provided they relate to distinct sediment routing  
85 systems throughout the north-Gondwana platform. We tested if geochronological  
86 studies on glaciogenic sediments could constitute a valuable tool, which, beyond  
87 paleogeographical purposes, could help to better constrain stratigraphic correlations  
88 within the end-Ordovician glacial record, e.g. from relatively ice-distal area (Morocco,  
89 Europe) toward more internal domains of the north-Gondwana platform (from  
90 Mauritania to Chad); such correlations being a pre-requisite for robust paleoclimatic  
91 scenarios.

92

## 93 **2. Geological setting**

### 94 *2.1. Study area*

95 The Tazekka Massif is a part of the Moroccan Meseta (Fig. 1), the pre-Variscan  
96 configuration of which remains unclear, yet generally positioned NW of the Anti-Atlas  
97 between the Gondwana landmass and an undefined continental margin (Hoepffner et al.,  
98 2005; Michard et al., 2010; Chopin et al., 2014; Pérez-Cáceres et al., 2017). Above a



**Figure 1.** Geological setting (coordinates of the main section in the Tazekka inlier: c. 33,9588°N, 4,3802°W). The Paleozoic configuration was slightly different, owing to poorly constrained Variscan offsets (e.g., along the South Meseta Fault, SMF). The star positions the westernmost Meseta (samples NF01 & 15DL12; Fig. 6). Numbers in diamonds refer to zircon sources (see Figs. 2, 5 and 7). Ice flows orientations mainly from Ghienne et al. (2007), Deschamps et al., (2013), Dietrich et al., in press.

99 preglacial, essentially fine-grained succession (Tehar el Brehl Fm.), there is a thick  
100 glacial sandstone wedge forming the Tifarouine Fm., which was entirely deposited  
101 beyond the end-Ordovician ice fronts (Le Heron et al., 2007, 2008). In the framework of  
102 this study, supplementary sections were logged in and around the type area. Our revised  
103 stratigraphy allows us to outline five informal stratigraphic members (Fig. 2), the lateral  
104 extent of which is in excess of 20 km. Medium-grained sandstones and mudstone  
105 interbeds of Mbs 1 and 4 are interpreted as basin-floor turbiditic lobe complexes while  
106 amalgamated coarse-grained sandstone sheets of Mbs 3 and 5 represent oversupplied  
107 turbiditic systems reflecting two major glacial advances. Glacimarine influence  
108 characterizes Mb. 2 (channels, debris-flows, ice-rafted debris), as well as thin interbeds  
109 in Mbs 4 and 5. Silurian shales and cherts mark the post-glacial onset of outer shelf  
110 conditions. Limited paleocurrent data in turbiditic deposits highlight relatively uniform  
111 flows through time from the NW, the W or the SW, yet the original orientations —  
112 potentially altered by Variscan thrust tectonics (Hoepffner et al., 2005) — are  
113 admittedly unknown.

114

## 115 *2.2. Paleoglacial setting*

116 From the nearby ice-proximal Anti-Atlas record (Fig. 1), it has been shown that Late  
117 Katian and lower Hirnantian lowstand wedges characterize the early glaciation phases,  
118 during which glaciers did not reach Morocco (Loi et al. 2010; Ghienne et al., 2014). In  
119 contrast, several advance–retreat cycles of the ice sheets are recognized during the late  
120 Hirnantian glaciation maximum associated with ice flows from the SE–SSE or from the  
121 WNW–WSW (Ghienne et al., 2007a, Le Heron, 2007; Le Heron et al., 2007; Ghienne et al.,  
122 2014; Ravier et al., 2015; Dietrich et al., in press). However, temporal correlation of this  
123 sequence of events with the Tazekka record is still unresolved.

124 In Morocco, the glaciers of the end-Ordovician glacial maximum essentially  
125 flowed over Upper Ordovician sediments. However, further toward the SW, S or SE, they  
126 eroded Lower Ordovician to Cambrian strata (Ghienne et al., 2007 a, b). As shown by  
127 rare exotic pebbles —mainly granites, less mafic or metamorphic lithologies— in  
128 glacimarine deposits, the basement has directly sourced the glacial sediments, at  
129 least locally (Fig. 1; Eglab area, Rognon et al., 1972).

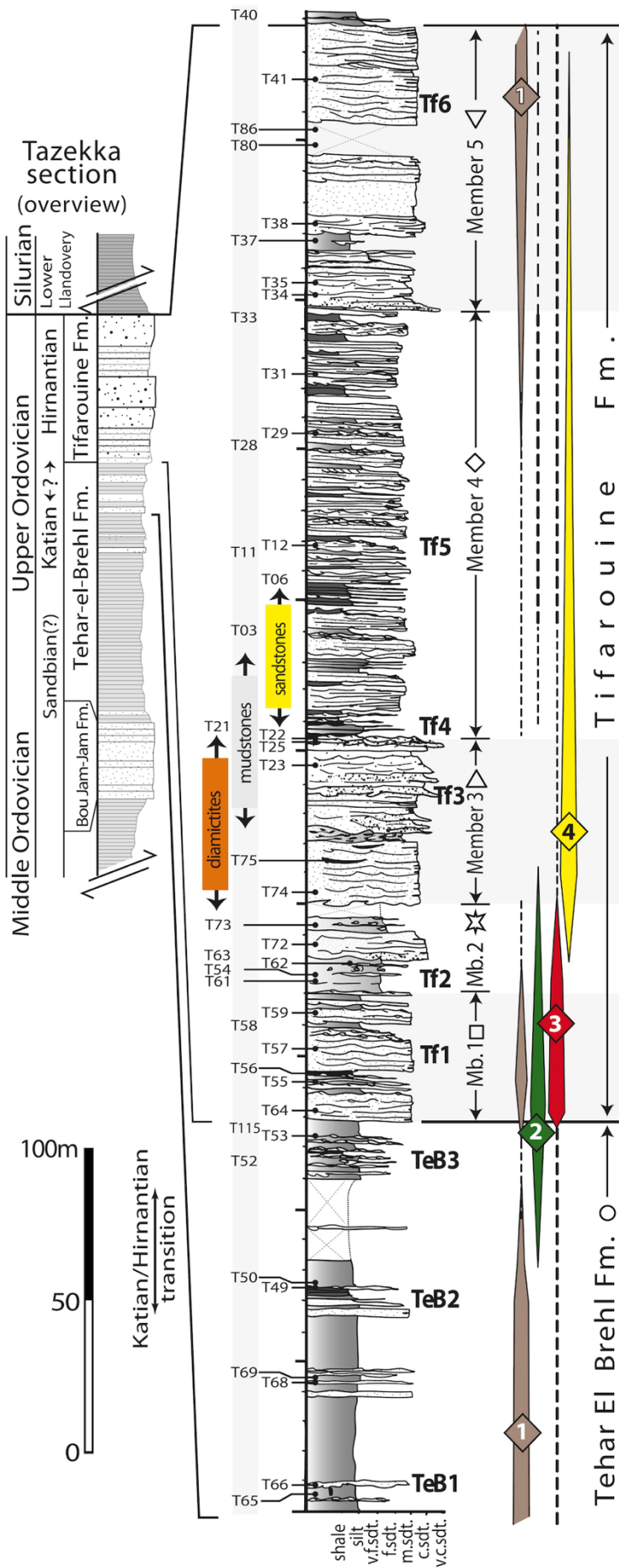
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### 131 **3. Methods**

#### 132 *3.1. Geochemical and petrographic analysis*

133 Whole-rock geochemical (XRF and LA-ICP-MS) and automated petrographic (QEMSCAN)  
134 analysis were performed on seven samples from the Tehar-el-Brehl Fm. and on 36  
135 samples distributed through the five members of the Tifarouine Fm. (19 sandstones, five  
136 diamictites and 12 mudstones; Fig. 2). Major element compositions were determined by  
137 X-ray fluorescence (XRF) with a *PANalytical Philips PW2400* spectrometer at the  
138 University of Lausanne. The trace-element concentrations of whole rocks were  
139 measured on glass beads by laser ablation inductively-coupled-plasma mass  
140 spectrometry (LA-ICP-MS) with an *Agilent 7700* laser ablation system at the University  
141 of Lausanne. Data were reduced with *LAMTRACE* software (Longerich et al. 1996;  
142 Jackson 2008). Automated mineral characterization was performed using an *FEI*  
143 *QEMSCAN® Quanta 650F* facility installed at the Department of Earth Sciences,  
144 University of Geneva equipped with two *Bruker QUANTAX* light-element energy  
145 dispersive X-ray spectrometers at high vacuum, accelerating voltage of 25 kV, and probe  
146 current of 10 nA on the carbon-coated polished thin sections. Data processing was  
147 performed using the *FEI iDiscover* software package. The effect of weathering,  
148 diagenetic, hydraulic sorting, and source rock composition over the compositional





**Figure 2.** Synthetic section of the Tazekka succession, built from the compilation of five sedimentological logs. On the left, position of samples on which geochemical and petrographic analyses have been performed (Figs. 3 & 4). Samples used for U-Pb geochronology of detrital zircon populations are positioned on the right (TeB 1-3 and Tf 1-6 ; probability plots of Fig. 5). On the right: the inferred scenario for source development (see text for details). Symbols (star, triangle...) associated to stratigraphic units are linked to codes used in figures 3 and 4.

149 results of the investigated samples were investigated following the procedures  
150 described in McLennan et al. (1993, 2003), Fralick (2003) and Nesbitt (2003).

151

### 152 *3.2. U–Th–Pb Geochronology*

153 Three samples from the Tehar el Brehl Fm. (TeB 1-3) and six samples from the  
154 Tifarouine Fm. (Tf 1-6) were processed. Detrital zircon grains were separated from  
155 several kilograms of samples by sorting, magnetic separation and conventional heavy  
156 liquid separation. The final zircon fraction was purified by handpicking in ethanol using  
157 a binocular microscope. Zircon samples were mounted in epoxy resin, polished and  
158 imaged by cathodoluminescence to reveal the internal structures of zircon grains by  
159 employing a *Tescan MIRA 3GMU* electron microprobe (Oxford Instruments), housed at  
160 the Czech Geological Survey.

161 The U–Th–Pb dating was performed using an *Analyte Excite* 193 nm excimer laser  
162 ablation system (Teledyne CETAC, Omaha, Nebraska, USA), equipped with a two-volume  
163 HelEx ablation cell, in tandem with an *Agilent 7900x* ICPMS (Agilent Technologies Inc.,  
164 Santa Clara, USA), housed at the Czech Geological Survey. Samples were ablated in He  
165 atmosphere ( $0.8 \text{ l min}^{-1}$ ) at a pulse repetition rate of 5 Hz using a spot size of 25  $\mu\text{m}$  and  
166 laser fluence of  $7.59 \text{ J cm}^{-2}$ . Each measurement consisted of 20 s of blank acquisition  
167 followed by 40 s sample signal acquisition. The masses 202, 204, 206, 207, 208, 232 and  
168 238 were collected using the SEM detector, with one point per mass peak and the  
169 respective dwell times of 10, 10, 15, 30, 20, 10 and 15 ms per mass (total sweep time of  
170 0.134 s). Instrumental drift was monitored by repeat measurements of 91500 reference  
171 zircon (Wiedenbeck et al. 1995) after every 20 unknowns. Data deconvolution using the  
172 *Iolite* software followed the method described by Paton et al. (2010), including an 'on

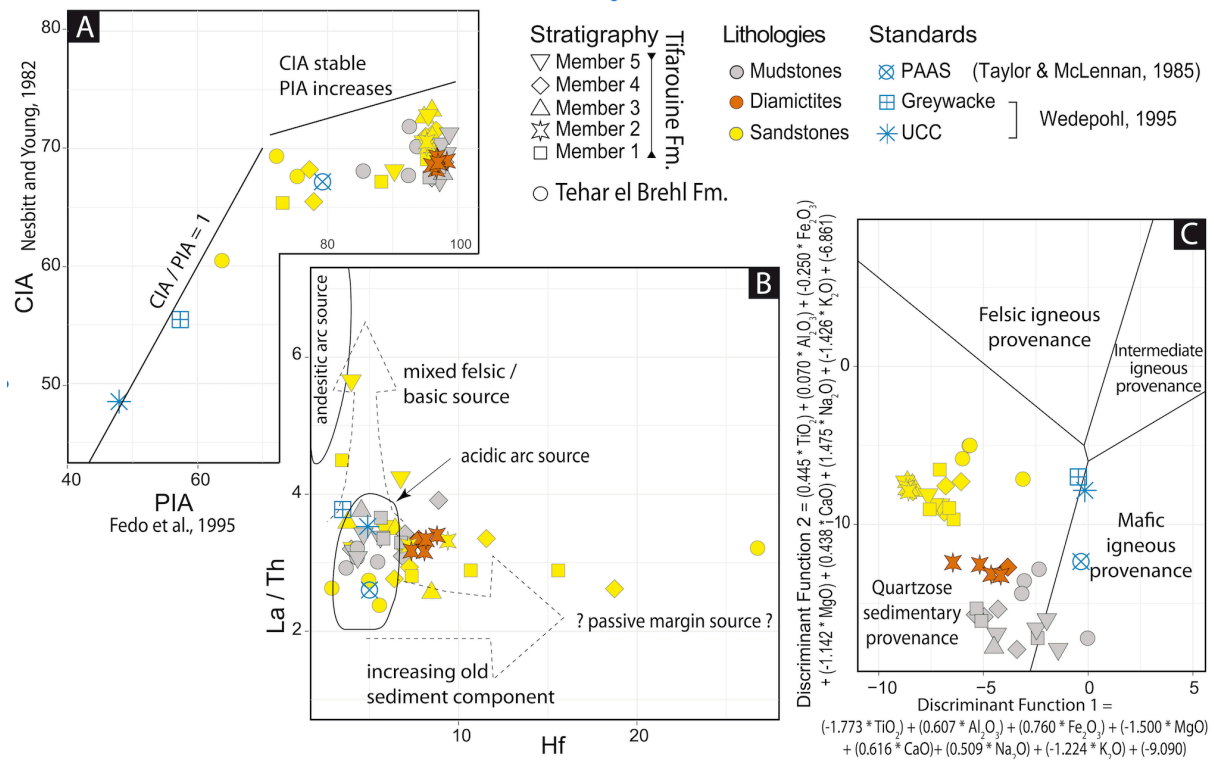
173 peak' gas blank subtraction followed by correction for laser-induced elemental  
174 fractionation (LIEF) by comparison with the behavior of the 91500 reference zircon  
175 (Wiedenbeck et al. 1995). The weighted mean concordia age of  $1062.8 \pm 2.5$  Ma ( $n =$   
176  $420, 2\sigma$ ) was obtained for 91500 reference zircon. In addition zircon reference samples  
177 GJ-1 ( $\sim 609$  Ma; Jackson et al. 2004) and Plešovice (337 Ma; Sláma et al. 2008) were  
178 analysed periodically during this study and yielded the concordia ages of  $607.9 \pm 2.8$  Ma  
179 ( $n = 170, 2\sigma$ ) and  $338.2 \pm 2.3$  Ma ( $n = 320, 2\sigma$ ), respectively. We have used decay  
180 constants incorporated in the Isoplot software (Ludwig, 2012), which are from Jaffey et  
181 al. (1971). No common Pb correction has been applied to the data due to the high level  
182 of isobaric Hg interferences derived from the carrier gases. We did not apply the  
183  $^{207}\text{Pb}/^{206}\text{Pb}$  criteria for older zircon grains, but the information is included in the data  
184 table (Supplementary Material). Instead, the Concordia function of Isoplot software was  
185 used for detrital zircon probability plots, which calculates the concordia age based on  
186 the  $^{206}\text{Pb}/^{238}\text{U}$  and  $^{207}\text{Pb}/^{235}\text{U}$  ratios and their errors and which yields a more precise  
187 mean age than that commonly obtained using either ratio alone.

188

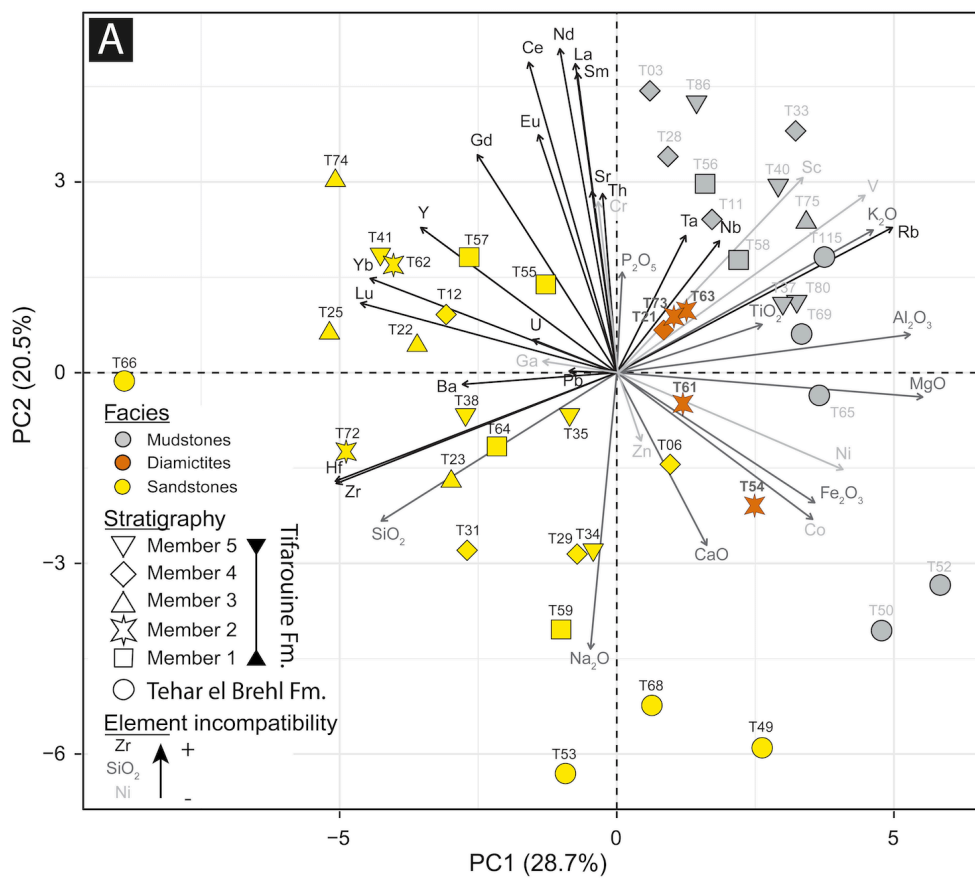
## 189 **4. Results**

### 190 *4.1. Insights from petrography and geochemistry*

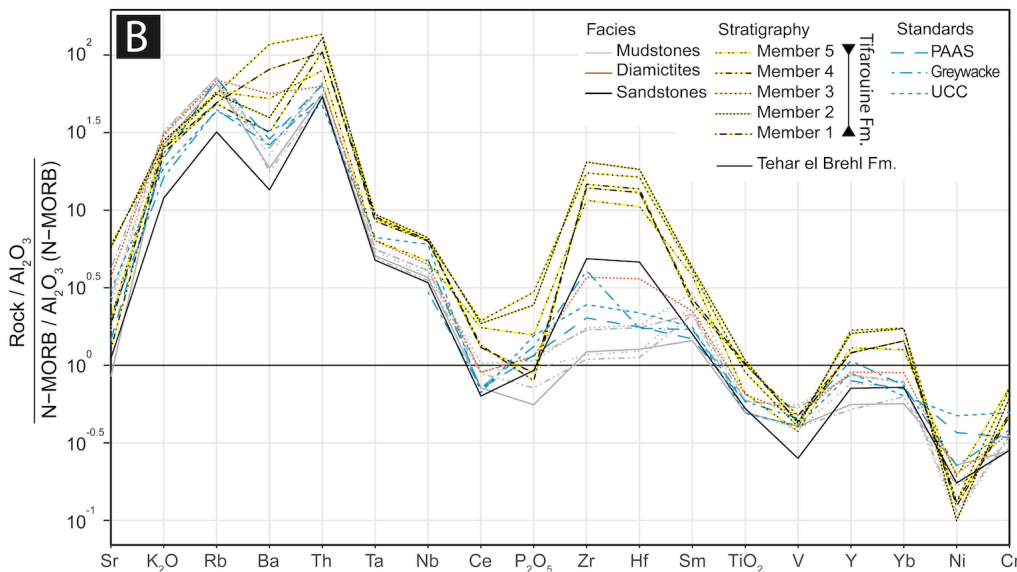
191 Sandstones share a medium-high compositional maturity while mudstones are  
192 relatively enriched in K-rich clay minerals. Glacigenic sandstones are dominated by  
193 quartz ( $>70$  modal %, but generally  $> 80\%$ ) and depleted in feldspars; high values of the  
194 Chemical Index of Alteration (Nesbitt and Young, 1982) from 65 to 75 and, especially, of  
195 the Plagioclase Index of Alteration ( $> 65$  but more usually  $> 90$ ; Fedo et al. 1995), prove  
196 intense weathering in the source area (Fig. 3A). Preglacial sandstones are characterized  
197 by higher proportions of detrital sodic feldspars (up to 17 modal %) suggesting less



**Figure 3.** Geochemical results. A: Bivariate diagram between Chemical (CIA, Nesbitt & Young, 1982) and Plagioclase (PIA, Fedo et al., 1995) Indexes of Alteration. B: Provenance characterization diagram (Floyd & Leveridge, 1987). C: Discrimination diagram for sedimentary provenance based on major elements (Roser & Korsch, 1988).



**Figure 4. A:** Principal component analysis of prevalently immobile elements. The two major components describe roughly half of the total variance of the geochemical composition of the investigated deposits.  $\text{Na}_2\text{O}$  and  $\text{CaO}$  (largely present in feldspars) and compatible elements correlate positively with the deposits of Tehar-el-Brehl Fm. Incompatible elements correlate with those of the Tifarouine Fm. Mudstones and sandstones are



separated along a direction perpendicular to the one that delimits the stratigraphic formations, indicating that grain size does not influence any unit differentiation based on geochemistry. **B:** Spider diagrams of selected element concentrations of preglacial and glacial deposits normalized to  $\text{Al}_2\text{O}_3$  and N-MORB. High concentrations of incompatible elements, and LILE (Rb, Cs, Sr, Ba) in particular, compared to the compatible elements suggest that the initial source rock composition of the investigated deposits was acidic.

198 weathered preglacial sources. Notable recycling processes of sedimentary deposits are  
199 suggested by the higher-than-average content in sandstones of heavy minerals enriched  
200 in Zr–Hf, especially glaciogenic sandstones, compared to the greywacke and UCC standard  
201 values (Fig. 4B). The greater maturity of the glaciogenic sediments, for which a higher  
202 degree of chemical alteration is unlikely (Bahlburg and Dobrzinski 2011), highlights a  
203 re-organization in sediment provenance at the glaciation onset. A discriminant diagram  
204 based on major elements (Roser and Korsch, 1988) confirms that a sedimentary source  
205 was prevalent (Fig 3C). The compositional difference between the Tehar-el-Brehl and  
206 Tifarouine Fms. must be principally related to distinct composition of the sedimentary  
207 sources. This is in line with a principal component analysis of major and trace elements  
208 concentrations (Fig. 4A) showing preferential enrichment of incompatible elements in  
209 glaciogenic deposits, which suggests that the source rocks of the glaciogenic sediments  
210 were originally derived from more evolved magmatic rocks.

211         Glaciogenic sediments mutually differ very slightly, with the exception of higher  
212 concentrations of elements such as Hf in individual sandstone samples of Mbs 1 & 4 (Fig.  
213 3B). Interestingly, abundance shifts are not reflected by a higher maturity of those  
214 samples and are recorded in both sandstones and mudstones. This indicates a  
215 preferential reworking of strata that were already enriched in heavy minerals (zircon,  
216 monazite), for instance coastal placers, which are recurrently observed in Ordovician  
217 nearshore deposits (e.g., Pistis et al., 2016). Diamictites are plotted in between  
218 sandstones and mudstones (Figs. 3C and 4A), indicating grain-size mixing rather than a  
219 specific sourcing. Sandstones in Mbs 2 and 3 are associated with the most  
220 mineralogically and geochemically mature source composition. This is particularly  
221 apparent in Figs. 3A, 3C and 4B where these sandstones have, for instance, and on  
222 average, (i) higher indices of alteration, (ii) parameters indicative of a sedimentary

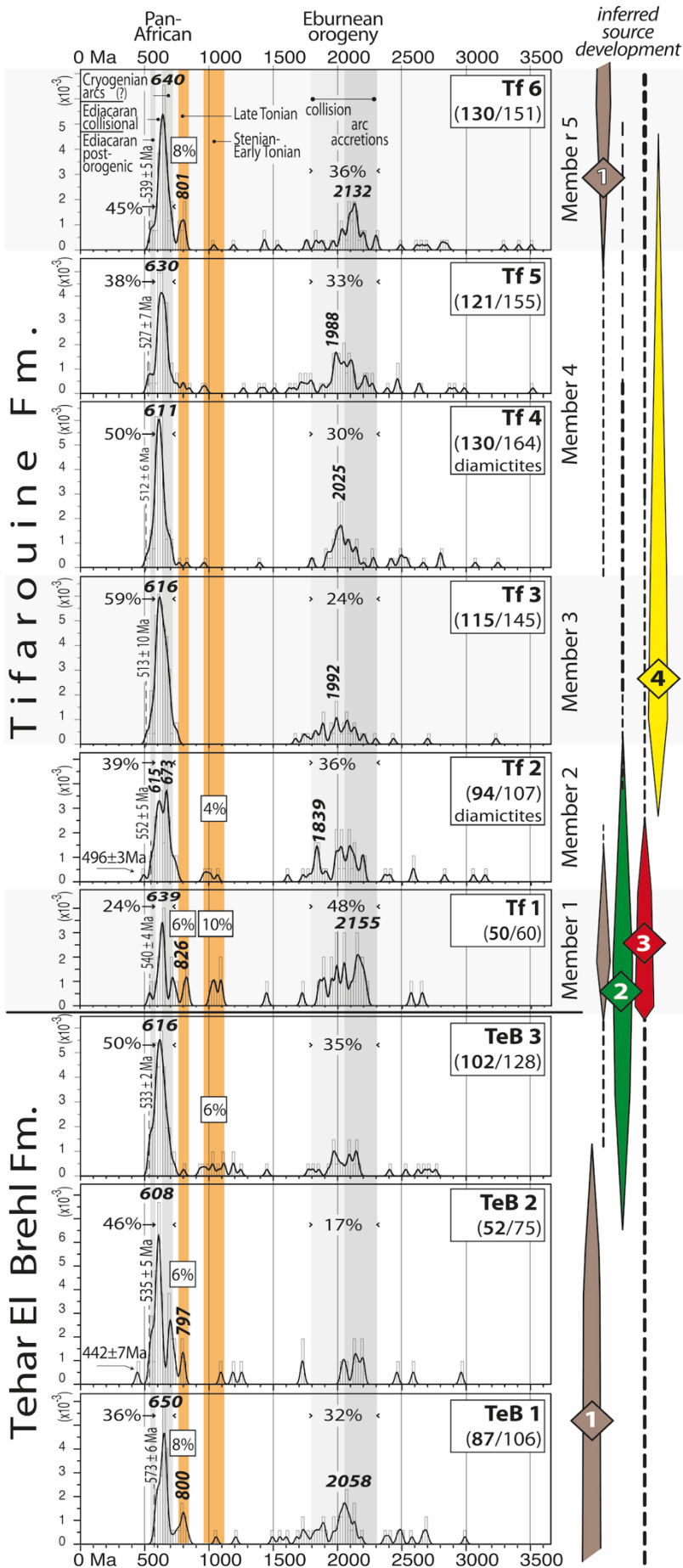
223 source largely dominated by a quartzose provenance, and (iii) higher concentrations of  
224  $P_2O_5$ , Hf, Zr, Yb. This does not solely reflect the coarse-grained nature of the deposits as  
225 samples of the similarly coarse-grained Mb. 5 behave distinctively. The more mafic  
226 composition of the latter marks the resumption of a preglacial signal, which was never  
227 totally cut off during the glaciation as shown by some specific samples in Mbs 1 & 4, the  
228 composition of which echoes the one of the preglacial deposits.

229

#### 230 *4.2. Insights from U–Th–Pb datings*

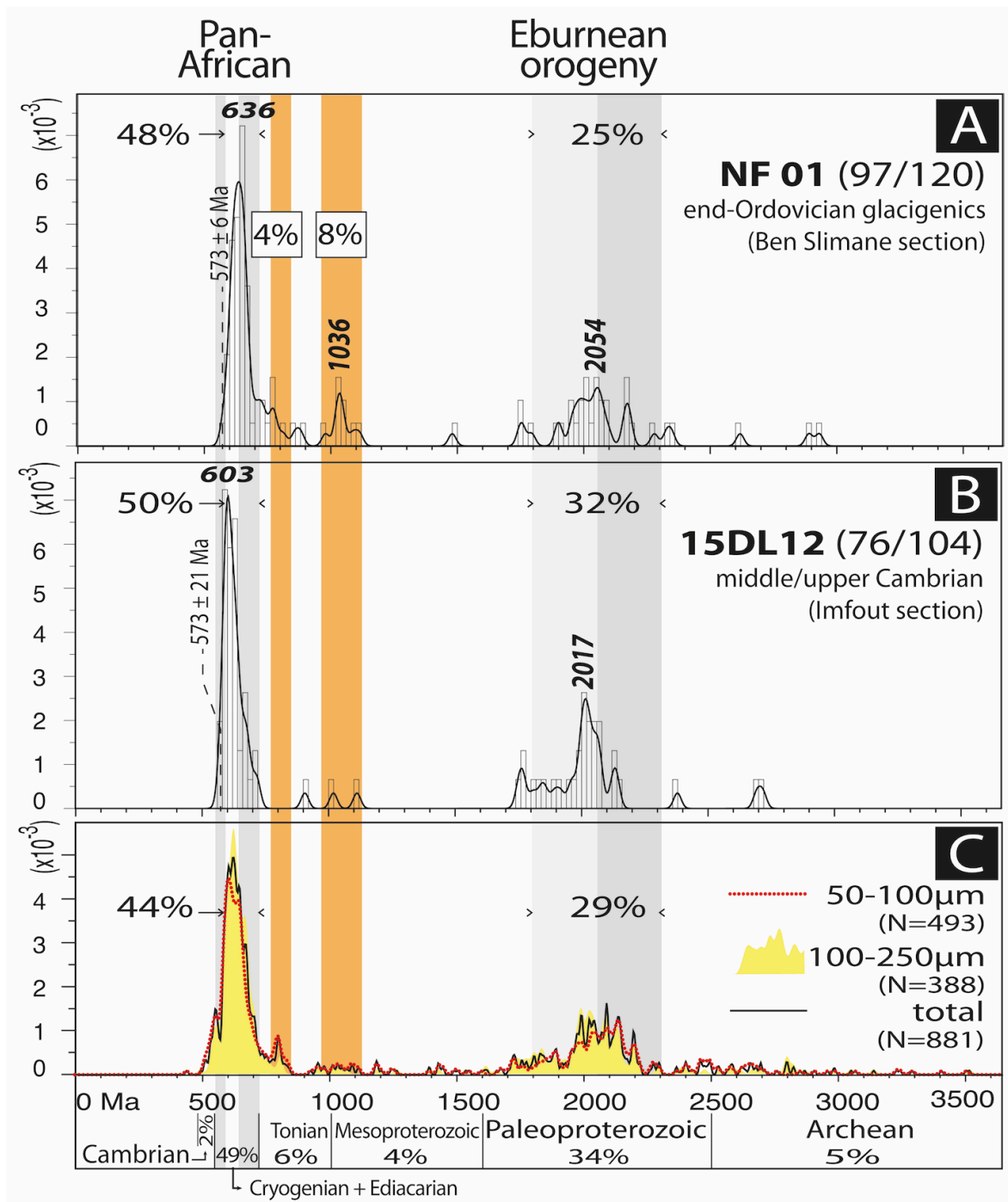
231 The U–Th–Pb LA-ICPMS measurements were performed on 881 detrital zircon grains  
232 from the nine samples of the Tazekka section. Probability plots in Fig. 5 only include  
233 ages with a concordance between 95 and 105%. One additional probability plot from the  
234 glacial sediments of the westernmost Meseta (NF01) is also given (Fig. 6B), to  
235 compare with the ages from a middle–upper Cambrian sandstone of the same area  
236 (15DL12; Letsch et al., 2018; Fig. 6B). The compilation of the 881 ages of the Tazekka  
237 section (Fig. 6C) shows a very similar age distributions for the 50–100 $\mu$ m and 100–250  
238  $\mu$ m grain-size ranges, which indicates that hydraulic processes did not significantly  
239 impact our zircon record.

240 It is apparent from Figs. 5 and 6C that Cryogenian–Ediacaran (Pan-African, 580–  
241 720 Ma; Ennih and Liégeois, 2001; Gasquet et al., 2008) and Paleoproterozoic  
242 (Eburnean, 1790–2300 Ma, Abati et al., 2012) ages dominate the record. The two  
243 populations, and the lull in between, which corresponds to the West African magmatic  
244 gap of Linnemann et al. (2011), are regarded as a signature of the western segment of  
245 the north Gondwana platform. Except sample Tf 3 showing the greatest ratio of Pan-  
246 African to Eburnean zircon grains (59 vs. 24%), which is comparable to most of previous  
247 published works (Linnemann et al., 2011; Avigad et al., 2012; Gärtner et al., 2017), the



**Figure 5.** Binned frequency (bin size: 20 Ma) and probability density distribution plots of concordant zircon ages from the end-Ordovician Tazekka record. Late Tonian and late Stenian–early Tonian populations (orange bands) are particularly well defined in TeB 2 and Tf 1, in spite of a limited number of measured ages. Minimum zircon ages are specified on the left of each plot as well as proportion (%) of distinctive populations. Note that the scenario for source development also integrates petrographic and geochemical insights (section 4.1. and Fig. 2).





**Figure 6.** A & B: Binned frequency (bin size: 20 Ma) and probability density distribution plots of concordant zircon ages from samples of the westernmost Meseta ('Coastal Block', located by the black star in Fig. 1), either (A) glacigenic deposits of the Ben Slimane section (this study) or (B) middle-upper Cambrian strata, El Hank Fm., Imfout section (modified from Letsch et al., 2018). C: age compilation of the 881 zircon ages of the Tazekka section plotted in Fig. 5. Orange bands refer to the late Tonian and late Stenian-early Tonian population discussed in the text. Grey bands in Pan-African ages, see Fig. 5.

248 other glaciogenic samples have a notable proportion of Eburnean zircon grains and  
249 sample Tf 1 yields significantly more Eburnean (48%) than Pan-African (24%) zircon  
250 grains.

251 Several Archean and Cambrian zircon grains were also detected, the latter being  
252 absent from the westernmost Meseta (Fig. 6). Post-orogenic Late Ediacaran zircon  
253 grains form a restricted population (<8%), which peaks at 554Ma (Fig. 6C), yet it is most  
254 often identifiable in the form of a shoulder rather than an actual peak in individual plots  
255 (Fig. 5). Most interesting are two subordinate but distinctive populations: a late Tonian  
256 population, ranging from 840 to 760 Ma, and a late Stenian–early Tonian population  
257 showing a broader age cluster, ca. 960–1120 Ma (~1 Ga; Fig. 5). The latter, best observed  
258 in sample Tf 1, is also well defined in NF01. These two age populations, though their  
259 presence/absence characterizes and differentiates some samples in this study (Fig. 5),  
260 appear poorly detectable in the age compilation (Fig. 6C).

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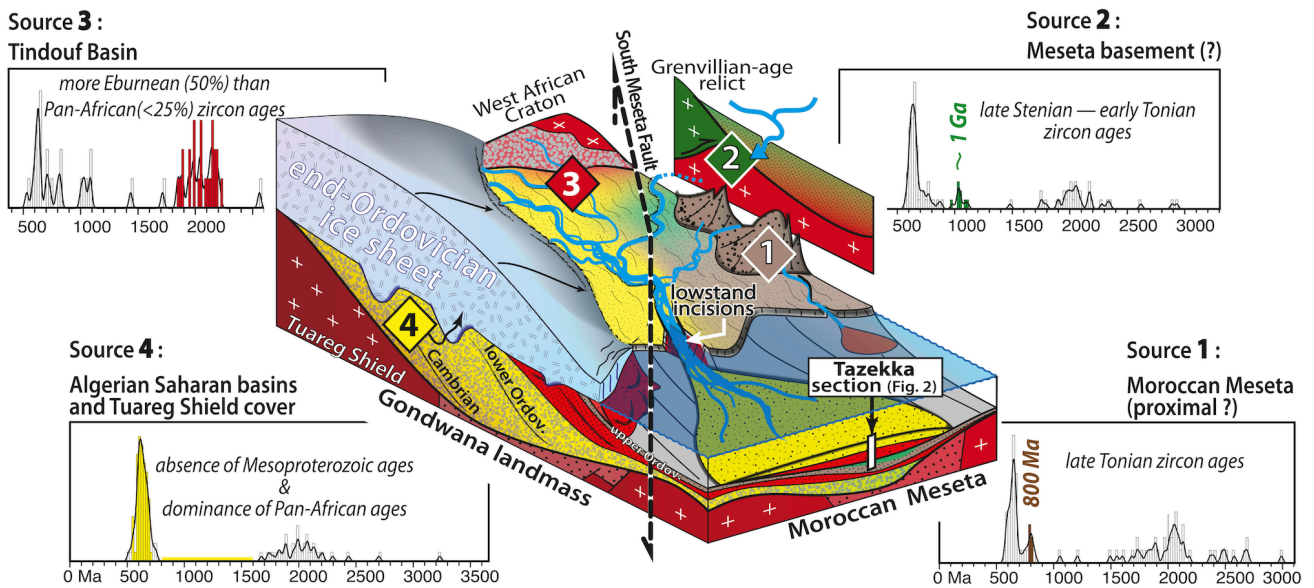
## 262 **5. Discussion**

### 263 *5.1. Deciphering sediment sources.*

264 The fact that the westernmost Meseta zircon record is similar to that of the deeper-  
265 water Tazekka succession is in line with the northeastward ( $\pm 45^\circ$ ) orientation of shelf  
266 progradation across the Meseta during the Ordovician (Razin et al., 2002). However,  
267 latest Ediacaran–early Cambrian zircon grains throughout the Tifarouine Fm., absent  
268 from NF01 and 15DL12, suggest that the Tazekka watershed was not restricted to the  
269 Meseta. This is corroborated by the great thickness of the glaciogenic succession (>350  
270 m), largely exceeding that of other coeval peri-Gondwanan records that are generally no  
271 more than a few tens of metres in thickness (Chatalov, 2017 and references therein).  
272 The Tazekka was connected to the West African dispersal system and its relatively

273 isolated current location at the NE tip of Western Meseta (Michard et al., 2010) cannot  
274 be fully representative of the Lower Paleozoic configuration.

275         The overall Tazekka record combining sedimentology, geochemistry and insights  
276 from zircon populations is best understood in terms of the interplay of four sources that  
277 can be inferred for the Ordovician in and around Morocco (Figs. 2 and 5). Preglacial  
278 Source 1 has a less mature composition and includes the late Tonian zircon population  
279 (TeB 1 and TeB 2). Sample TeB 3 shows the cut-off of Source 1 or, more probably, its  
280 dilution by Source 2, which is marked by the ~1 Ga zircon population. Associated with  
281 the onset of sandstone deposition in the uppermost preglacial sediments, Source 2 also  
282 characterizes the glaciogenic deposits of the westernmost Meseta (Fig. 6). Source 3 is  
283 inferred from the Tf 1 and Tf 2 record, typified by a great proportion of Eburnean zircon  
284 grains. In Mb 1, at the base of the Tifarouine Fm., the late Tonian (i.e. 840–760 Ma) and  
285 ~1 Ga populations are well defined, suggesting that sources 1 and 2 were still active,  
286 either directly, or indirectly through the reworking of older strata. Source 4 (Tf 3) shows  
287 the most mature composition (Mb. 3 in Figs 3 and 4), the greatest Pan-African zircon  
288 grains, the younger Cambrian zircon population, a striking West African magmatic gap  
289 — no more Mesoproterozoic zircon grains in discordant ages — and no Tonian zircon  
290 grains. The overlying glaciomarine interbed (Tf 4) mainly shares similar features. Due to  
291 its association with the coarsest unit (Mb. 3), Source 4 is regarded as linked to the  
292 maximum advance of the end-Ordovician glaciers in NW Africa. It may have been  
293 activated slightly earlier in the succession, considering that the compositional signature  
294 of the sandstone filling in the channels of the glaciomarine depositional system (Mb. 2)  
295 is similar to that of Mb. 3 (see above; Figs. 3C & 4B). In the upper part of the Tifarouine  
296 Fm., samples Tf 5 and Tf 6 show the re-appearance of Mesoproterozoic zircon grains and  
297 the progressive re-increase of the Eburnean zircon population. Further, a recurrence of



**Figure 7.** Conceptual model for glaciation-impacted sediment dispersal trends as understood from the Tazekka record. Patterns and colours as in Fig. 1. Numbers in diamonds relate to provenances discussed in the text (see also Fig. 2), the proposed location of which is given in Fig. 1. Probability plots selected from Figs. 5 and 6 illustrate the zircon age records tied to individual sources that together mixed and fed the Tazekka depocenter. Source 4 originates from glacial erosion of the Cambrian-Ordovician sedimentary cover (Algerian basins, Tuareg Shield cover), while other sources, of more local origin, may have involved a significant contribution of lowstand cannibalisations (fluvial incisions, shelf-margin canyons) and restricted truly glaciogenic inputs.

298 the late Tonian population is recognized in Tf 6 (Fig. 5). It reflects the progressive  
299 upwards dilution of Source 4 understood as a recovery stage after the glaciation  
300 maximum. This is in line with slightly more mafic compositions noted in Mb. 5 samples,  
301 a reminiscence of a signal observed in preglacial samples of the Tehar el Brehl Fm. (Fig.  
302 3C). The last glacial advance, marked by renewed coarse-grained sedimentation in Mb.  
303 5, remobilized a material dominated by Source 1. As sediment sources are suspected to  
304 continuously mix through time, none of the probability plots (Figs 5 and 6) is so far fully  
305 representative of one particular provenance. Four of them, which can be regarded as  
306 typifying each of the four proposed provenances, are however used in Figure 7 to  
307 approximate, or at least illustrate, the zircon age records tied to individual sources that  
308 together fed the Tazekka depocenter.

309

## 310 *5.2. Sediment sources and glaciation development*

311 The scenario of sediment source development through the Tazekka stratigraphic  
312 record, representing only a ca. 5 Myr time span, is understood in the framework of the  
313 end-Ordovician glaciation. In addition, the regional-scale source diversity arisen from  
314 the complex Lower Paleozoic evolution around the Meseta domain during peri-  
315 Gondwana rifting events should be considered. Source 1 in preglacial sediments shows a  
316 contribution of first-cycle clastic sediments, potentially in relation with a single Upper  
317 Ordovician zircon recovered in TeB 2. We suspect a genetic link with a coeval thermal  
318 event (Clauer et al., 1995) and the local denudation of Ediacaran basement rocks (Tahiri  
319 et al., 2010) (Fig. 7), both possibly related to the magmatic (e.g., Caroff et al., 2009)  
320 and/or extensional events (e.g., Martinez-Catalan et al., 1992) affecting the north-  
321 Gondwana domain at the end of the Ordovician. The late Tonian population, which is  
322 absent from sample 15DL12 from Cambrian strata of Coastal Meseta (Letsch et al., 2018;

323 Fig. 6), reflects the erosion of rocks exposed only after the Cambrian, which are possibly  
324 in relation with uplifts tied to the opening of Rheic ocean (Ouanaimi et al., 2016; Gärtner  
325 et al., 2017). The paucity of Cambrian zircon grains indicates that (i) Cambrian rift  
326 basins (Pouclet et al., 2008; Michard et al., 2010; Letsch et al., 2018) were buried at that  
327 time, and (ii) the Eburnean basement of the Meseta cannot be considered as a source for  
328 Paleoproterozoic zircon ages (e.g., El Houicha et al., 2018).

329 Source 2, activated prior to the onset of massive sandstone deposition in the  
330 Tazekka, and relatively well-defined in the westernmost Meseta (Fig. 6A), suggests that  
331 the ~1 Ga zircon population reflects the activation of a nearby source. Indeed, ~1 Ga  
332 zircon grains do not represent contribution of a more southern remote source, which  
333 would have had a wider age spectrum regarding Mesoproterozoic ages (De Waele et al.,  
334 2015; Gärtner et al., 2017). Combined with other ~1 Ga ages documented in the  
335 Moroccan context (a charnockite outcrop off Morocco, Michard et al., 2010; recycled  
336 zircon in Ediacarian granites, Tahiri et al., 2010; recycled zircon in Trias volcanics,  
337 Marzoli et al., 2017), Source 2 highlights the existence a currently undefined relict of  
338 Grenvillian-aged crust. The latter has sourced, most likely from the west, directly  
339 (erosion of Mesoproterozoic rocks) or indirectly (erosion of late Neoproterozoic  
340 magmatic rocks having recycled Mesoproterozoic zircon), the end-Ordovician Moroccan  
341 glacial dispersal system (Fig. 7), independently from other well-known sources related  
342 to the largely more eastern Saharan metacraton (e.g., Meinhold et al., 2013; Henderson  
343 et al., 2015). This ca. 1 Ga zircon population may derived from an exotic terrane issuing  
344 from an Avalonian crust and later accreted, during the Pan-African and/or Cadomian  
345 developments, to the West African Craton (Abbo et al., 2015; Marzoli et al., 2017;  
346 Gärtner et al., 2017). The ca. 1 Ga zircon population, predating the massive arrival of

347 glaciogenic sediments, is not introduced in the Moroccan context by the end-Ordovician  
348 glaciation (see discussion in Pratt et al., 2015).

349 Source 3 is tied to the onset of mature glaciation-related deposits (Mb. 1), yet it  
350 was continuously providing sediments as shown by the great proportion of Eburnean  
351 zircon grains in the overall Tazekka record (Fig. 6C). In Mb. 1 of the glaciogenic Tifarouine  
352 Fm., both the high Hf content that reflects the reworking of coastal placers, and the lack  
353 of evidence for any glacial depositional processes, suggest the local remobilisation of an  
354 older shelf succession; the later yielding a prevalent Eburnean population. The Source 3  
355 signal is absent, or at least subordinate, in the westernmost Meseta (Fig. 6). It points to a  
356 southern derivation of material tied to the recycling of Cambrian–Ordovician strata of  
357 the Tindouf Basin, which themselves have been initially sourced predominantly from an  
358 Eburnean basement (Reguibat Shield; Fabre and Kazi-Tani, 2005; Fig. 1). Whether or not  
359 the Sources 2 and 3 have involved glacial erosions remains unclear. Additional work is  
360 needed to decipher if this sequence is related to watershed reorganisations, including  
361 meltwater captures and then glaciogenic sediments, or to strictly localized lowstand  
362 cannibalizations (e.g., incised valley or shelf-margin canyon; Fig. 7).

363 Showing none of the local signals, glacial maximum strata (Mb. 3 of the Tifarouine  
364 Fm.) were principally fed from outside the Meseta and are tied to a fourth provenance.  
365 Source 4 provides evidence for a major remobilization of the Cambrian–Ordovician  
366 strata from the northern Saharan Basins or of the ancient cover of the Tuareg Shield  
367 (Fabre and Kazi-Tani, 2005), the age spectrum of which (Linnemann et al., 2011) is very  
368 similar to sample Tf 3. Source 4 is thus viewed as the signature of the NW-oriented ice  
369 flows recognized in the Anti-Atlas (Fig. 1), and originating from the surroundings of the  
370 current Tuareg Shield, where glacial downcuttings essentially eroded the Cambrian-  
371 Ordovician cover, and more rarely the Pan-African rocks of the Trans-Saharan Belt (Fig.

372 7; Fekirine and Abdallah, 1998; Ghienne et al., 2007b; Deschamps et al., 2013). The flux  
373 of >2.3 Ga zircon grains detected upstreamward (Linnemann et al., 2011), which is  
374 unrecognized in the Tazekka sequence, is suspected to correspond to a local and  
375 transient input, rapidly redistributed by postglacial transgressive systems (cf. HOG6 and  
376 HOG7 probability plots of Linnemann et al., 2011). Coarse-grained sediments of Mb. 5,  
377 compositionally slightly less mature and showing a renewed contribution of Source 1,  
378 suggest that the last glacial advance reworked a great proportion of local material, most  
379 likely including earlier end-Ordovician glacigenics, with a fading contribution of Source  
380 4. Mb. 5 is tentatively linked with glaciers that, in the Anti-Atlas, flowed from the W  
381 (Dietrich et al., in press).

382

## 383 **6. Conclusions**

384 The Tazekka glacigenic deposits essentially derived from the cannibalization of the  
385 “great Lower Paleozoic quartz-rich sandstone sheet”, itself initially having recycled the  
386 Pan-African molasse and flysch basins (Avigad et al., 2017), rather than recording a  
387 pulse of fresh, far-travelled, first-cycle clastic sediments issuing from basement rocks.  
388 This finding is in line with conclusions of Chatalov (2017) and Gärtner et al. (2017), also  
389 dealing with the north Gondwana area but is in contrast with common views about the  
390 limited maturity of syn-glaciation deposits (Nesbitt and Young, 1982; Yan et al., 2010;  
391 Bahlburg and Dobrzinski, 2011; Huang et al. 2014). More interestingly, end-Ordovician  
392 glacigenic deposits in South Africa show a significantly lower CIA than that of the  
393 underlying preglacial succession (Young et al., 2004), which is in contrast to the north-  
394 Gondwanan examples from this study, even regarding the diamictite samples (Fig. 3A).  
395 It might suggest two distinct modes of glacial erosion, involving eroding highlands in the



396 first case, essentially recycling the preglacial shelf sediments in the second case, with  
397 potential contributions from remote highlands absent or greatly diluted.

398         Glacial erosion of the Cambrian–Ordovician strata, especially during the glacial  
399 maximum, boosted the transfer of compositionally —i.e., mineralogically and  
400 geochemically— mature material toward the continental margin, temporarily masking  
401 regional signals expressed only before the glaciation or in its earlier stages (late Tonian  
402 and late Stenian–early Tonian zircon ages, respectively). The glacial maximum was  
403 responsible for a notable provenance change of a broader significance which may be  
404 traceable outside Morocco, rather than just be a result of local adjustments. The first-  
405 order, continental-scale Lower Paleozoic dispersal trends nevertheless pertained  
406 through the glaciation. They were buffered by the voluminous, north-African Lower  
407 Paleozoic sandstones that furnished the main contribution to the glacial material,  
408 which consequently show more mature compositions than those prevailing in Morocco  
409 prior to the end-Ordovician glaciation.

410

411

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