New biostratigraphic constraints show rapid emplacement of the Central Atlantic Magmatic Province (CAMP) during the end-Triassic mass extinction interval

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ABSTRACT

Different lines of evidence suggest that the main trigger mechanism for the end-Triassic mass extinction was the release of volcanic and thermogenic gases during the emplacement of the Central Atlantic Magmatic Province (CAMP). However, the short duration of the biotic and environmental crisis and the magmatic activity hinders precise control on the relative timing between these events, especially when comparing the continental sedimentary record where there is no independent age control with the magmatic record. In order to disentangle the temporal relationships of the end-

Triassic events, we have analyzed the palynology of the sedimentary strata interlayered with CAMP lava flows from eleven sites throughout Morocco (Western and Central High Atlas, Middle Atlas, Western Meseta). The recovered sporomorphs help to constrain the age of CAMP volcanism, allowing the stratigraphic correlation of the basaltic volcanism with the extinction and geochemical records such as carbon-isotope and mercury shifts, recorded in marine sedimentary successions worldwide. Our new data show that CAMP erupted almost entirely during the end-Triassic mass extinction interval, just before the Triassic–Jurassic boundary (Tr-J). Hence, a very rapid emplacement of the CAMP very likely triggered the carbon cycle and ecological disruption at the Tr-J boundary.

Keywords: *Central Atlantic magmatic province, end-Triassic mass extinction, Triassic-Jurassic boundary.*

1. INTRODUCTION

The end of the Triassic, between about 201.7 and 201.3 Ma, (Schoene et al., 2010; Wotzlaw et al., 2014; Davies et al., 2017) was characterized by three global events: 1) the emplacement of the Central Atlantic magmatic province (CAMP) over 10 million square km in Europe, Africa, North and South America (Marzoli et al., 1999, 2004, 2011; Blackburn et al., 2013; Davies et al., 2017); 2) the end-Triassic mass extinction, one of the big five mass extinctions of the Phanerozoic (Raup and Sepkoski, 1982); 3) a severe perturbation of the carbon cycle as evidenced by three sharp negative carbon isotope excursions (CIEs) in organic matter and marine carbonate, which are recorded in several Tr–J stratigraphic sections (e.g. St Audries Bay, UK, Hesselbo et al. 2002; Mariental, Germany, Heunisch et al., 2010; Stenlille, Denmark, Lindström et al., 2012). At the GSSP Kuhjoch section, where the recorded excursions are only two, the first pronounced CIE has been correlated with the *initial* CIE of St Audries Bay (Ruhl et al., 2009), marking the last

occurrence (LO) of the Triassic ammonite *Choristoceras marshi*. An older CIE ("*Precursor* CIE"), preceding the "initial", was described at St Audries Bay by Ruhl and Kürschner (2011).
The youngest long-term CIE ("*Main* CIE" sensu Hesselbo et al., 2002) starts shortly before the first occurrence (FO) of the Jurassic ammonite species *Psiloceras planorbis*, marking the base of the Jurassic (Hettangian). Due to the lack, in the UK record, of the ammonite species *Psiloceras spelae,* chosen as biological marker for the base of the Jurassic (Hillebrandt et al., 2013), the correlation with the GSSP section was based on the pollen taxon *Cerebropollenites thiergartii,* recorded at Kuhjoch, approximately 3 m below the FO of the Jurassic ammonite (Kürschner et al., 2007; Bonis et al., 2010; Hillebrandt et al., 2013).
Recently, Lindström et al. (2017) re-named the three end-Triassic to early Jurassic CIEs, in order of time, as "*Marshi*", "*Spelae*", and "*Top Tilmanni*" on the base of biostratigraphic constraints. Lindström et al. (2017) used as palynological marker the peak in abundance of *Polypodiisporites polymicroforatus* considered more reliable than the FO of *C. thiergartii*, which seems not to be synchronous in different areas (Heunisch et al., 2010; Lindström, 2016; Lindström et al., 2017).
In several north-western European localities such as St. Audrie's Bay (UK), Stenlille and Rødby (Denmark), Mariental, Schandelah and Mingolsheim (Germany), Kuhjoch (Austria), the base of *P. polymicroforatus* abundance is preceded by a negative CIE (Lindström et al., 2017). This CIE, referred to as "*Marshi* CIE", has been tentatively correlated with the negative C_{org}-excursion at the top of the T-bed of the Kössen Formation at Kuhjoch (Lindström et al., 2017). The bed has been associated with the LO of *C. marshi,* which marks the onset of the extinction (Hillebrandt et al., 2013). The interpretation of Lindström et al. (2017) is in contrast with the traditional correlation showing that the first CIE at Kuhjoch corresponds to the sharp *Initial* CIE at St Audries Bay (Hesselbo et al., 2002, 2004; Ruhl et al., 2010; Hillebrandt et al., 2013), referred to as "*Main* CIE" (second in time order) in Lindström et al. (2017). Geochronological data (zircon U/Pb ages; Schoene et al., 2010, recalculated by Wotzlaw et al., 2014) and biostratigraphic correlations (Lindström et al., 2017) suggest an age of about 201.51 ± 0.15 Ma for the *Marshi* CIE, shortly

preceding the *Spelae* CIE dated at about 201.39 ± 0.14 and the Tr–J boundary at 201.36 ± 0.17 Ma. While the geochronologic and biostratigraphic data are now quite robust in defining the main end-Triassic events, it remains problematic to define the relative timing of the CAMP and the ETE, being both events clearly of very short duration, comparable to the errors of zircon U/Pb age data. Moreover, the correlation of CAMP magmatism (a continental event) with the ETE and the negative CIEs (mostly recorded and solidly age-constrained in marine sequences) is very problematic (e.g. Dal Corso et al., 2014; Lindström et al., 2017). While CAMP intrusions are now well dated (201.63 ± 0.03 to 200.92 ± 0.06 Ma; Blackburn et al., 2013; Davies et al., 2017), available geochronologic data for the volcanic rocks are much less precise. Recent studies show an increase in mercury concentrations within the interval between the beginning of the ETE and the Tr–J boundary, further supporting the hypothesis that CAMP emplaced in a very short time (Thibodeau et al., 2016; Percival et al., 2017). However, the exact role of CAMP volcanism in triggering the CIEs and the ETE remains questionable. The end-Triassic negative CIEs suggest a massive input into the atmosphere of large quantities of ^{13}C-depleted CO_2 (Hesselbo et al., 2002; Ruhl et al., 2011; Dal Corso et al., 2014). Given the synchrony, the emplacement of CAMP is the most likely trigger of the negative CIEs (Marzoli et al., 2004; Guex et al., 2004; Bonis et al., 2010; Whiteside et al., 2010; Ruhl et al., 2011), via repeated magmatically triggered releases of highly depleted thermogenic CO_2 and CH_4 and/or clathrate methane (Dickens et al., 1995; Svensen et al., 2004; Davies et al., 2017). The emission of volcanogenic gases such as CO_2 or SO_2 (Callegaro et al., 2014) could be invoked as the initial trigger of the ETE. Notably, increase of atmospheric $p\mathrm{CO_2}$ recorded by fossil leaf stomata and soil carbonates has been predicted to cause global warming and ocean acidification during the time of peak CAMP magmatic activity (McElwain et al., 1999; Bonis et al., 2010; Schaller et al., 2011; Martindale et al., 2012). The continental volcano-sedimentary sequences of North America and Morocco record a negative CIE in the bulk organic matter and Late Triassic sporomorph assemblages below the first known CAMP basalt (Whiteside et al., 2010; Deenen et al., 2010, 2011; Dal Corso et al., 2014). It remains controversial, to which of Rhaetian

CIEs this continental CIE can be correlated. Based on an extensive review of the published literature and new data from Denmark and Germany, by combining biostratigraphic, geochemical and geochronological constraints, Lindström et al. (2017) argued that most of CAMP basalts were emplaced in correspondence to the *Marshi* CIE and before the *Spelae* CIE. Hence, nearly the entire sequence of CAMP basalts in Morocco could have been erupted before and/or during the ETE interval. To test this hypothesis, we studied the palynological association of the sedimentary strata interlayered within the volcanic sequences in the Argana valley (Western High Atlas), the Central High Atlas, the Middle Atlas, and the Western Meseta, from the base of the CAMP basaltic flows to the top of the lava pile, with the aim to biostratigraphically constrain the age of the volcano-sedimentary sequence of Morocco and thus the duration of CAMP volcanism.

2. GEOLOGICAL SETTING

CAMP lava flow sequences crop out in several areas of central and northern Morocco, i.e. in the Central High Atlas (CHA), the Western High Atlas (Argana valley), the Middle Atlas, the Eastern and the Western Meseta (Fig. 1). These volcanic sequences reach a maximum thickness of nearly 300 m in the southern CHA, while in the northern CHA, the Argana valley and the Middle Atlas, the maximum preserved thickness of basaltic flows reaches some 150 m. The lava flows have been subdivided into four main informal units based on geochemical, volcanological, and magnetostratigraphic data (Bertrand et al., 1982; Knight et al., 2004; Marzoli et al., 2004; El Hachimi et al., 2011). These units are named Lower, Intermediate, Upper and Recurrent Basalt. Lower and Intermediate Basalt are present in (almost) all lava flow sequences and constitute about 90% of the preserved volume of effusive CAMP rocks in Morocco (Fig. 2). The Lower Basalt is missing only in the northwestern Middle Atlas (as for example near the village of Agourai; Fig. 1), where the stratigraphically lowest basaltic lava flows have geochemical compositions pertaining to the Intermediate Basalt. The Upper Basalt is widespread in the CHA and occur sporadically in the Middle Atlas (e.g., at Midelt or at Tounfite section), while they are absent in the Argana Valley.

Recurrent Basalt are limited to the CHA and volumetrically negligible with respect to the rest of the lava piles (Marzoli et al., 2004). Over 20 high quality $^{40}Ar/^{39}Ar$ ages are available for the Moroccan CAMP (Knight et al., 2004; Nomade et al., 2007; Verati et al., 2007; Marzoli et al., 2011). These data indicate that the Lower to Upper Basalt were erupted at approximately 201.5 Ma, in a time-span shorter than the analytical uncertainties of the $^{40}Ar/^{39}Ar$ ages (roughly 0.5-1.5 Ma). One intrusive rock from the Argana basin (the Amelal sill) yielded a U/Pb zircon age of 201.56 ± 0.05 Ma and was assigned to the Intermediate Basalt (Blackburn et al., 2013). Only the Recurrent Basalt yielded significantly younger $^{40}Ar/^{39}Ar$ ages (approximately 199 Ma; Verati et al., 2007). Magnetostratigraphic data support a (very) short duration of eruption of Lower to Upper Basalt, since these were erupted as a total of five very short-lived volcanic pulses, each probably lasting just a few centuries (Knight et al., 2004).

The first CAMP basaltic lava flows were emplaced throughout Morocco on fine-grained silty deposits of probably lacustrine or lagoonal origin. Presence of load casts and a generally conformable layering of the sedimentary strata beneath the first lava flows indicates that lavas flowed over still soft sediments, arguing against a significant sedimentary gap before emplacement of the first CAMP lavas. These Lower Basalt flows emplaced subaerially (El Hachimi et al., 2011). Evidence for a progressive subsidence of the basins during emplacement of the basalts comes from widespread pillow lava structures observed at the base of the Intermediate lava formation (El Hachimi et al., 2011), and changes in detrital zircon source into the CHA and Argana basins (Marzoli et al., 2017). The thin columnar jointing of the Upper Basalt suggests that also these flows were emplaced under water. Sedimentary strata between the Intermediate and the Upper, and then on top of the Upper Basalt include carbonate layers, testifying for a further subsidence. This progressive ongoing subsidence argues against significant sedimentation gaps after emplacement of each flow package.

3. SAMPLED SECTIONS AND METHODS

For the palynological analysis we sampled intra- and infra-basaltic sediments from localities in the Argana valley (Western High Atlas; 2 sites), the Central High Atlas (CHA; 4 sites), the Middle Atlas (4 sites), and the Western Meseta (1 site) (Figs. 1; 2). All productive samples (except three, AN69, AN64 and AN520) were collected at the base of the CAMP lava piles, at stratigraphic distances of about 1 meter to about 5 cm below the first preserved Lower Basalt. Three sampling localities from the CHA provided productive samples at the base of the Lower Basalt flows, namely at Tiourjdal (southern CHA) and at Oued Lahr and Oued Amassine (Northern CHA). Samples from two of the studied localities (Tiourjdal and Oued Lahr) were already investigated by Marzoli et al. (2004), but were reprocessed and reanalyzed for our new study. In the northern CHA (Oued Lahr and Ikourker localities), also sedimentary layers located between the Upper and the Recurrent Basalt resulted productive (samples AN69, AN64). Middle Atlas sampling sites included two sections, one near the village of Teklit (Tounfite section, near the Oum-Rbia river sources), and one near Agourai. For this latter the productive sample is located at the base of the Intermediate Basalt. Two sections (Ahouli and Ajoundou N'fnouss) were sampled near Midelt, located at the intersection between the CHA and the Middle Atlas in central Morocco. Furthermore, we collected productive sediments at the base of the Maaziz sequence, in the Western Meseta (northwestern Morocco). The whole set of samples including also the non-productive ones are reported in the online supplementary Table 1 along with lithological description, stratigraphic position and geographic coordinates. The palynological preparations were made at the Sedimentary Organic Matter Laboratory of the Department of Physics and Geology, University of Perugia (Italy). Samples were crushed and then processed using a standard technique for palynological analysis (Green, 2001; Wood et al., 2002). Details on methods are reported in the online supplementary material.

4. RESULTS

The occurrences of the sporomorphs detected in the analyzed samples are given in Fig. 2 and the full species list and the results of the quantitative analysis in the online supplementary Table 2, Table 3 and Fig. S1. The main palynological markers are illustrated in Fig.3. In the Argana basin, all the samples from the strata below the Lower Basalt were productive and yielded a palynological assemblage, which includes abundant *Classopollis* group (*Classopollis meyerianus, Classopollis murphyae, Classopollis torosus*) and common *Patinasporites densus* in association with rare to common *Calamospora mesozoica, Ricciisporites tuberculatus*, *Todisporites* sp., *Triadispora* sp. and *Tsugaepollenites pseudomassulae.*

In the CHA basin (southern Tiourjdal section and northern Oued Lahr, Oued Amassine, and Ikourker sections), the palynological assemblage detected in all strata at the base of the Lower Basalt is similar to that of the Argana basin. In the southern CHA section of Tiourjdal (samples AN50, AN52 and AN150), the association is dominated by *Classopollis* group of which common *C. meyerianus*, common to abundant *C. murphyae* and common *C. torosus.* Variable percentages of *P. densus* (from rare to abundant), rare *C. mesozoica, Perinopollenites elatoides, Parvisaccites triassicus, Vitreisporites pallidus* and bisaccate pollen (e.g. *Alisporites* sp., *Triadispora* sp.) also occur. The assemblage recorded in the northern CHA sections of Oued Lahr (samples AN59, AN60) and Oued Amassine (AN1 sample) yielded rare to abundant *Classopollis* spp. (with higher percentages of *C. meyerianus*) and common *P. densus*, in association with common *C. mesozoica*, rare *R. tuberculatus, T. pseudomassulae, Alisporites* sp. and *Triadispora* sp.. In the Middle Atlas (Tounfite, sample AN533) and Midelt sections (Ahouli, sample AN214 and AN221), the sedimentary beds at the base of the Lower Basalt yielded a microfloral assemblage containing abundant *C. meyerianus* and rare to common *C. torosus* in association with common *P. densus*, and rare *Enzonalasporites vigens, Ovalipollis ovalis, Ovalipollis pseudoalatus, Vallasporites ignacii* and *Vesicaspora fuscus*. The base of the Maaziz sequence (Western Meseta, sample AN 600) below the Lower Basalt yielded a palynological association comparable with that of the Tiourjdal section (CHA) marked by the abundance of *C. meyerianus* in association with frequent *P. densus* and rare

C. torosus and bisaccate pollen such as *Alisporites similis* and *Alisporites* sp.. ~~Productive samples are available~~ Also the sedimentary layers at the base of the Intermediate and above the Upper Basalt flows in the sections of the CHA and Middle Atlas basins result to be palynologically productive. The sedimentary interval at the base of the Agourai basaltic flows (Middle Atlas basin, sample AN520) yielded an assemblage with abundant *C. meyerianus* and rare *C. torosus* in association with common *P. densus*. Notably, here the lowest flows pertain to the Intermediate Basalt, which are conformably emplaced on top of the analyzed siltstone layer. At the Oued Lahr and Ikourker sections (northern CHA) the palynological assemblage of the samples AN69, AN203 and AN64 from the sedimentary strata between the Upper and the Recurrent Basalt is still characterized by the dominance of the *Classopollis* group (abundant *C. meyerianus* and *C. murphyae* and common *C. torosus*) and rare to common *P. densus*, in association with rare long range species such as *Alisporites* sp. and *C. mesozoica*.

5. DISCUSSION

5.1 Biostratigraphic constraints on CAMP volcanism

The palynoassemblages characterizing the sedimentary layers below the first flow in the CHA and Argana basins, below the Intermediate flows in the Middle Atlas (at the Agourai section), and above the Upper Basalt flows in the CHA can be overall ascribed to the Rhaetian. The dominance of *Classopollis* spp. and the presence of taxa typical of Late Triassic assemblages, such as common *Patinasporites densus* and rare *Enzonalasporites vigens*, *Tsugaepollenites pseudomassulae* and *Vallasporites ignacii* confirm this hypothesis.

The Last Occurrence Datum (LOD) of *P. densus*, was commonly recorded and well documented in marine sedimentary successions, before the end of the Rhaetian (Cirilli, 2010; Kürschner and Herngreen, 2010). In continental settings (e.g. Chinle Formation, Colorado Plateau), *P. densus* was recorded in Norian – early Rhaetian sedimentary strata (Litwin et al., 1991; Irmis et al., 2015) together with *Enzonalasporites* and *Vallasporites*) (Lindström et al., 2016). In some Moroccan samples (Ahouli and Midelt section), rare specimens of *E. vigens* and *V. ignacii* are recorded in co-occurrence with *P. densus,* in association with the dominant *Classopollis* group therefore suggesting an age slightly older than latest Rhaetian (Cirilli et al., 2010; Lindström et al., 2016). The Late Triassic age is further confirmed by the absence of Jurassic palynological diagnostic markers such as *Cerebropollenites thiergartii* and/or the acme of *Polypodiisporites polymicroforatus* (Hillebrandt et al., 2013; Lindström et al. 2017).

The Moroccan palynological associations dominated by the *Classopollis* group in association with *P. densus*, coming from the sedimentary layers intercalated with the Intermediate and Upper Basalt, are very similar to those recorded in the continental sedimentary successions of Fundy (Nova Scotia, Fowell and Traverse, 1995; Cirilli et al., 2009) and Newark basins (eastern North America (Whiteside et al., 2010 and references cited therein). Both in the Fundy basin and in the Newark basin, the highest record of *P. densus* occurs below the oldest CAMP lava flow, whilst, in Morocco, it does not disappear before the first CAMP basalt. It is still recorded at the base of the Intermediate lava flows, as well as above the Upper Basalt of Morocco, permitting to date as Late Triassic the entire sedimentary sequence. The presence of *E. vigens* and *V. ignacii* in the sedimentary intercalations at the base of Lower Basalt in the Ahouli and Midelt section let to consider a slightly earlier onset of CAMP volcanism in Morocco than in the Newark basin, USA. This has already been suggested by Marzoli et al. (2004) based on geochemical, magnetostratigraphic, and biostratigraphic data and seems consistent also with recent geochronological data (Blackburn et al., 2013). Therefore, the palynological data from the entire CAMP sedimentary sequence in Morocco could suggest a diachronous emplacement of lava flows. The age attribution of the Moroccan CAMP flows to the latest Triassic has further implications for the correlation of the CAMP activity to end-Triassic CIEs and mass extinction. Deenen et al. (2010) and Dal Corso et al. (2014) found a negative CIE below the Lower Basalt of the Argana valley and of the CHA (Fig. 4). Dal Corso et al. (2014) suggested that this negative CIE was likely caused by eruption of early CAMP lava flows that have been rapidly eroded after their emplacement (see also Schaller et al., 2011), as witnessed by the chemical and mineralogical composition of the infra-basaltic sediments. Additionally, early-emplaced CAMP intrusions could have triggered the release of depleted thermogenic CO_2 or CH_4, thus causing the carbon-cycle disruption CIE (Davies et al., 2017). Magnetostratigraphic and chemostratigraphic data have been used to correlate the negative CIE below the Lower Basalt unit in Morocco with the "*initial*" CIE recorded at St. Audries Bay and GSSP (Kuhjoch) sections (Kürschner et al., 2007; Bonis et al., 2010; Deenen et al., 2010; Hillebrandt et al., 2013; Dal Corso et al., 2014). Considering the correlation proposed by Lindström et al., (2017), the infra-basaltic negative CIE in Morocco could be alternatively correlated to the *Marshi* CIE (Fig. 4). The correlation between the Moroccan assemblages and those found in the key marine sections for the Tr-J boundary (e.g. Kuhjoch, Hillebrandt et al., 2013; St. Audries Bay, Bonis et al., 2010) results to be difficult because of the several dissimilarities among the assemblages and the lack of ammonite stratigraphy in the Moroccan successions, which are deposited in continental to coastal environments. Nevertheless, at least the sedimentary levels below the Lower Basalts, containing common *P. densus* in association with *E. vigens* and *V. ignacii*, and the last co-occurrences of *O. ovalis*, *T. pseudomassulae,* and *R. tuberculatus* could be correlated with the the *Rhaetipollis – Limbosporites* (RL) palynozone of the GSSP for the Tr–J boundary at Kuhjoch (Fig. 4), and to the Rhaetian assemblage SAB1 defined for the marine Tr–J boundary section at St. Audries Bay in the UK (Bonis et al., 2010) (Fig. 4). The absence of other, more specific palynozone markers in our samples hampers a higher resolution and a more detailed correlation between the European sections and the sedimentary layers intercalated with the Intermediate and Upper Basalt. However, the palynological assemblages justify the age attribution of the entire sedimentary sequence in Morocco to the Rhaetian and therefore below the higher portion of the TH and SAB 4 zones, including the Tr-J boundary, from Kuhjoch and St. Audries Bay, respectively.

Combining the carbon isotopic data (Deenen et al., 2010; Dal Corso et al., 2014) and the new palynological data, the emplacement of (almost) the entire volcanic pile of CAMP in Morocco occurred within the ETE interval (Fig. 4). The onset of CAMP volcanism in Morocco, shortly preceded by a negative CIE may be either correlated to the precursor (*Marshi* sensu Lindström et al., 2017) or to the initial (*Spelae sensu* Lindström et al., 2017) CIE at St. Audries Bay. In either case, our data constrain the short duration of CAMP volcanism in Morocco, which occurred entirely within the ETE interval. Within this interval, high mercury concentrations have been recorded in several sedimentary successions, including St. Audries Bay and Kuhjoch (Fig. 4) and have been interpreted as the signal of large-scale emissions of volcanic gasses from CAMP (Thibodeau et al., 2016; Percival et al., 2017). Our study confirms this hypothesis.

5.2 Implications for the duration of CAMP volcanism

The Moroccan palynological assemblages, integrated with the carbon isotope data, constrains nearly the entire sequence of CAMP basalts in Morocco within the Rhaetian and thus during the ETE interval. Deenen et al. (2010) estimated that the CAMP volcanism can be linked to the onset of two pulses of flood basalts. The first pulse (Moroccan event) can be linked to the initial CIE. The second pulse (just 20 Kyrs apart from the first one) pre-dates the Tr–J boundary by about 80 Kyrs, resulting in a very brief duration of the CAMP volcanism of less than 100 Kyrs. Based on the U/Pb ages obtained from the Rhaetian–Hettangian sequences of the Pucara basin in Peru, the ETE interval had an estimated duration of about 150 Kyrs (from 201.51±0.15 Ma to 201.36±0.17 Ma; Schoene et al., 2010; Wotzlaw et al., 2014). Using carbon isotope data from marine carbonates from Peru and assuming a constant sedimentation rate, Yager et al. (2017) estimated a slightly longer duration of this interval (0.28±0.09 Ma). This implies that 95% of CAMP volcanism in Morocco was erupted in less than 150 Kyrs (or less than 280 Kyrs, following Yager et al., 2017). This is consistent with the U/Pb age obtained by Blackburn et al. (2013) for the Amelal sill (201.56±0.05 Ma). More recently, the correlations of Lindström et al. (2017) highlighted that both the lower and intermediate CAMP basalts are synchronous to or pre-date the *Marshi* CIE and the extinction interval. Very rapid emplacement of CAMP basaltic flows is also consistent with previous magnetostratigraphic studies of the Tiourjdal volcanic pile (Knight et al., 2004) that showed that basaltic eruptions occurred as a series of five pulses, each of which lasted less than a secular variation cycle (about 450 years by analogy with the duration of these cycles in the Holocene; Schnepp et al., 2003). Summarizing, our new findings and the previous geochronologic and magnetostratigraphic data indicate that the emplacement of the CAMP was a very rapid event, which occurred during the ETE interval.

6. CONCLUSIONS

New palynological data from the volcano-sedimentary sequences of the Central High Atlas, Middle Atlas and Argana basins in Morocco constrain the age of CAMP volcanism in Morocco to the latest Triassic (Rhaetian). The occurrence of palynological assemblages characterized by the *Classopollis* group in association with the index Triassic species *Patinasporites densus* from the sedimentary strata below the Lower and Intermediate Basalt to those above the Upper Basalt allows assigning almost the entire CAMP volcanism (Lower, Intermediate, and Upper flows) to the Rhaetian. The occurrence in some Moroccan samples (Ahouli and Midelt sections) collected below the Lower Basalt of rare specimens of *Enzonalasporites vigens* and *Vallasporites ignacii* suggests an age slightly older than latest Rhaetian and in turn an earlier emplacement of the CAMP in Morocco than in the North America (Newark and Fundy basins). The palynological data let to tentatively correlate the sedimentary strata below the Lower Basalt to the older Rhaetian palynozones defined in the Kuhjoch sections (*Rhaetipollis – Limbosporites* (RL), and in the St. Audries Bay (SAB1). Although the lack of palynological markers prevent a detailed correlation, the palynological assemblages from the sedimentary beds intercalated with the Intermediate and the Upper Basalt indicate a Rhaetian age and constrain the CAMP basalt eruption below the higher portion of the TH and SAB 3 zones from Kuhjoch and St. Audries Bay respectively.

Beyond the still debated possible correlations that can be adopted to correlate marine Tr–J section (e.g., the GSSP at Kuhjoch and St. Audries Bay), the associations recovered in the sedimentary strata, both below and above the Moroccan CAMP basalt flows, are Rhaetian, thus excluding an early Jurassic age for the volcanic pile. By combining the carbon isotopic data and U-Pb ages with the new palynological data, we show that the emplacement of almost all CAMP basalts in Morocco occurred during the end-Triassic extinction interval and was very fast (probably less than 150 Kyrs). Hence, our results precisely link the ETE to the CAMP volcanism. This shows that very rapid release of large amounts of volcanic gases (mainly CO_2 and SO_2) into the latest Triassic atmosphere – land – ocean system caused widespread disruption of the ecosystems.

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FIGURE CAPTIONS

Fig.1: Location and geological setting of the study area. Schematic geology of the investigated areas in the Argana Basin (Alemzi and Agouersuine sections), in Central High Atlas (southern Tiourjdal section and northern Oued Lahr, Amassine and Ikourker sections), Middle Atlas (Ahouli and Midelt, Tounfite and Agourai sections,) and Western Meseta region (Maaziz section).

Fig.2: Distributions of the recorded sporomorphs within the studied sections in Morocco. Below Lower Basalt - Argana Basin, Alemzi and Agouersuine sections (samples AN101, AN131); central High Atlas Basin: 1) South, Tiourjdal section (AN50, AN52, AN150); 2) North, Oued Lahr (AN59, AN60) and Amassine (AN1) sections; Middle Atlas Basin, Midelt and Ahouli sections (AN214, AN221) and Tounfite section (AN 533); Western Meseta region, Maaziz section (AN600). Below

Intermediate Basalt: Middle Atlas Basin, Agourai section (AN520). Above Upper Basalt: northern central High Atlas Basin, Oued Lahr (AN69, AN203) and Ikourker (AN 64) sections.

Fig. 3: Sporomorphs from the studied sites in Morocco. A-E) Below Lower Basalt, southern central High Atlas – Tiourjdal section; F) Below Lower Basalt, northern central High Atlas – Oued Lahr section; G-H) Below Lower Basalt, Middle Atlas basin -Midelt and Ahouli sections; I) Below Lower Basalt, Middle Atlas Basin – Tounfite section; J-K) Below Intermediate Basalt, Middle Atlas basin – Agourai section; L) Above Upper Basalt, Central High Atlas Basin – Oued Lahr section. A) *Patinasporites densus*, sample AN50, England Finder coordinates (E.F.c.) Q40(3); B) *Classopollis meyerianus*, AN50 E.F.c. C36(3); C) *Classopollis murphyae*, AN50 E.F.c. C29(1); D) *Classopollis murphyae*, AN50 E.F.c. L30(1); E) *Vitreisporites pallidus*, AN52 E.F.c. O49(1); F) *Classopollis torosus*, AN59 E.F.c. J44(2); G) *Patinasporites densus*, AN214 E.F.c. E40(2); H) *Ovalipollis* sp., AN214 E.F.c. E36(2); I) *Ovalipollis pseudoalatus*, AN533 E.F.c. D41(3); J) *Patinasporites densus*, AN520 E.F.c. K31(3); K) *Tsugaepollenites pseudomassulae*, AN520 E.F.c. H53(1); L) *Patinasporites densus*, AN64, E.F.c. T19(3). Scale Bar 10 μm.

Fig. 4: An attempt to correlate the Tiourjdal section (CHA, Morocco) with the GSSP section for the Tr-J boundary (Khujoch, Austria) (Hillebrandt et al., 2013) and with St. Audrie's Bay (UK) section (Bonis et al., 2010), based on palynological associations, ammonites, $\delta^{13}C$-isotopes, geochronological data (Blackburn et al., 2013) and Hg/TOC (Percival et al., 2017). Geochemical data of Morocco section are from Dal Corso et al., 2014). The negative carbon isotope shift at the base of the Lower Basalt can be referred to the *initial* CIE, according to the traditional correlation by (Hesselbo et al., 2002, 2004; Ruhl et al., 2010; Hillebrandt et al., 2013) (red dotted line labelled as 1), and to the *Marshi* CIE, according to Lindström et al. (2017) (red dotted line labelled as 2). Beyond the possible correlations that can be adopted, the new palynological data discussed in this

study indicate a Rhaetian age for the most part of the sedimentary strata intercalated with the CAMP basalts, thus excluding an Early Jurassic age for the volcanic pile.

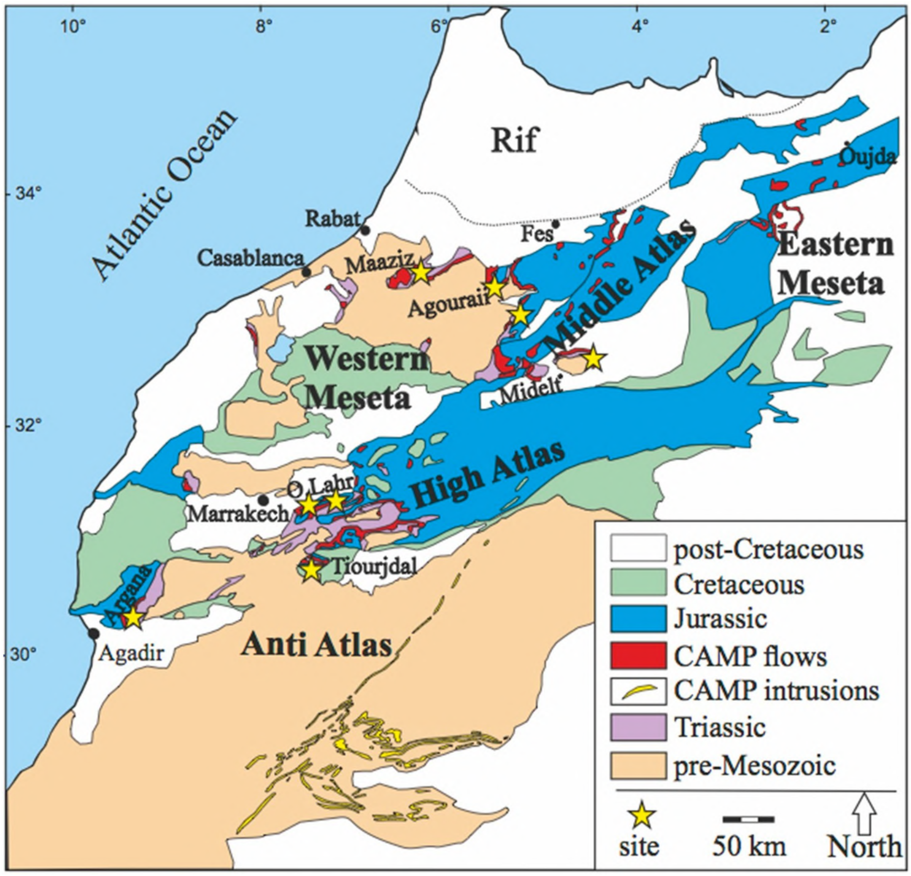
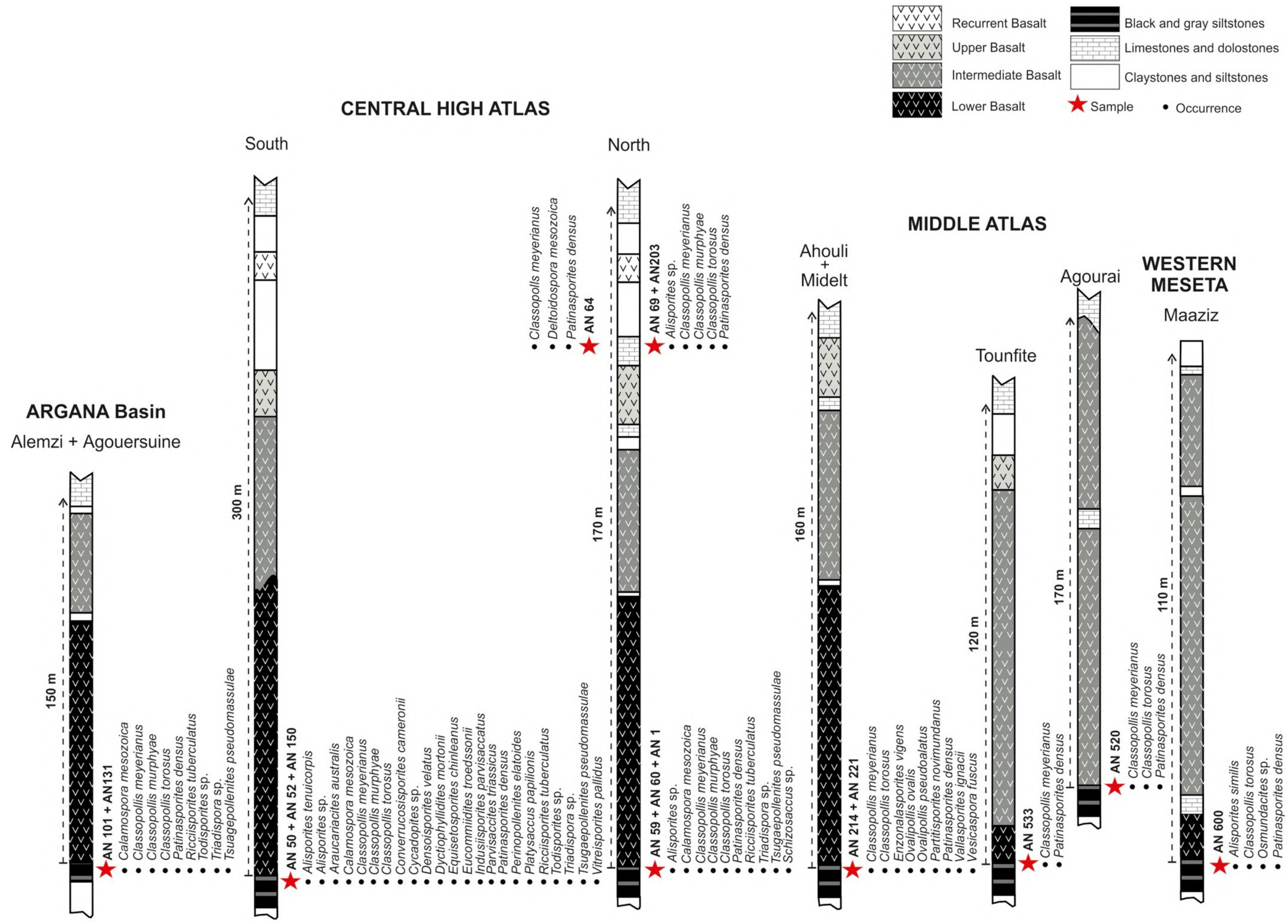

10°
8°
6°
4°
2°
34°
32°
30°
Atlantic Ocean
Rif
Rabat
Casablanca
Fes
Oujda
Maaziz
Agourai
Middle Atlas
Eastern
Meseta
Western
Meseta
Midelt
High Atlas
O. Lahr
Marrakech
Tiourjdal
Argana
Agadir
Anti Atlas
post-Cretaceous
Cretaceous
Jurassic
CAMP flows
CAMP intrusions
Triassic
pre-Mesozoic
site
50 km
North

Fig 1



CENTRAL HIGH ATLAS
MIDDLE ATLAS
WESTERN MESETA
ARGANA Basin
Alemzi + Agouersuine
South
North
Ahouli + Midelt
Tounfite
Agourai
Maaziz
Recurrent Basalt
Upper Basalt
Intermediate Basalt
Lower Basalt
Black and gray siltstones
Limestones and dolostones
Claystones and siltstones
Sample
Occurrence
150 m
300 m
170 m
160 m
120 m
170 m
110 m
AN 101 + AN131
AN 50 + AN 52 + AN 150
AN 64
AN 69 + AN203
AN 59 + AN 60 + AN 1
AN 214 + AN 221
AN 533
AN 520
AN 600

Fig. 2.

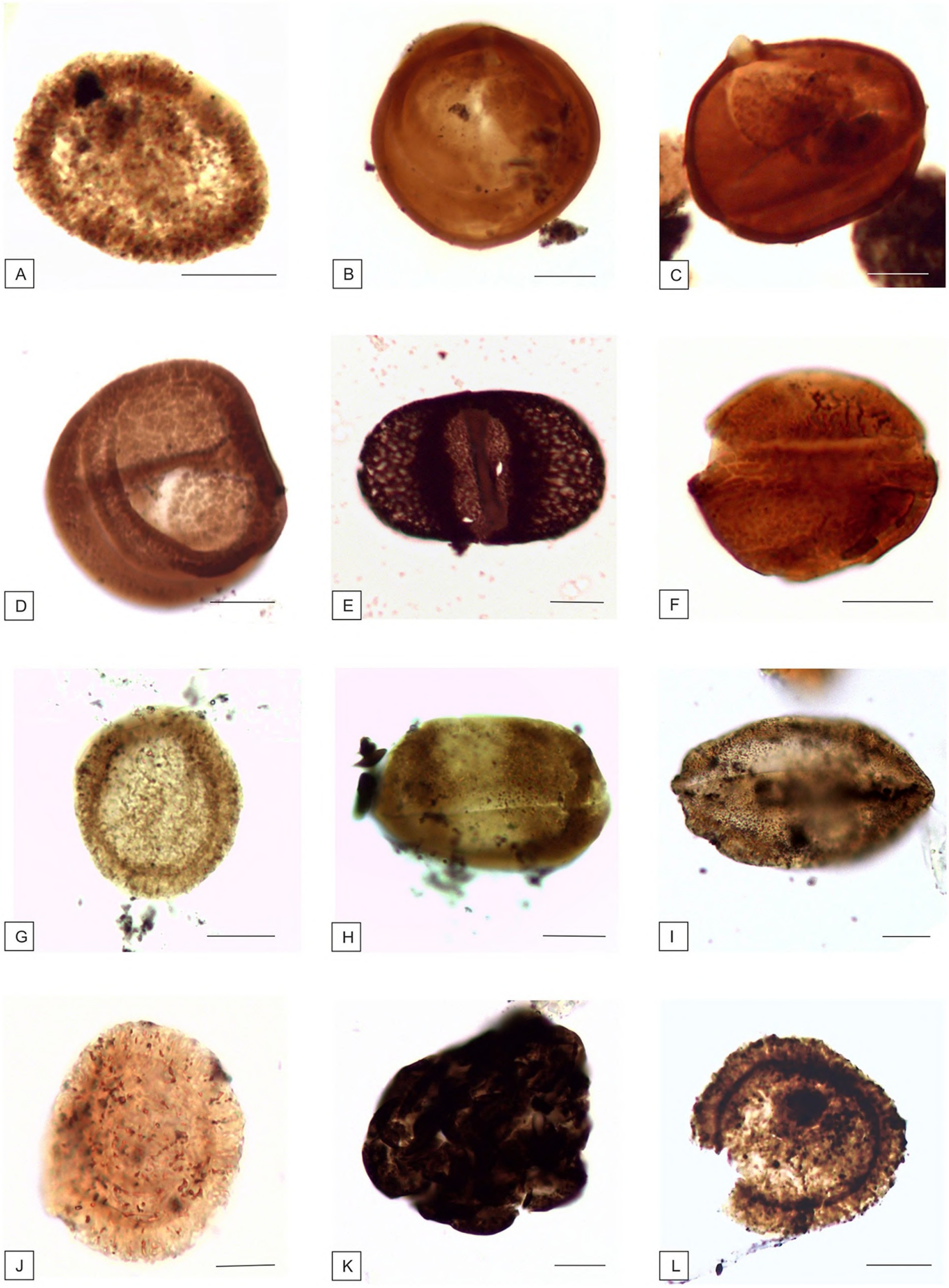


Fig. 3.

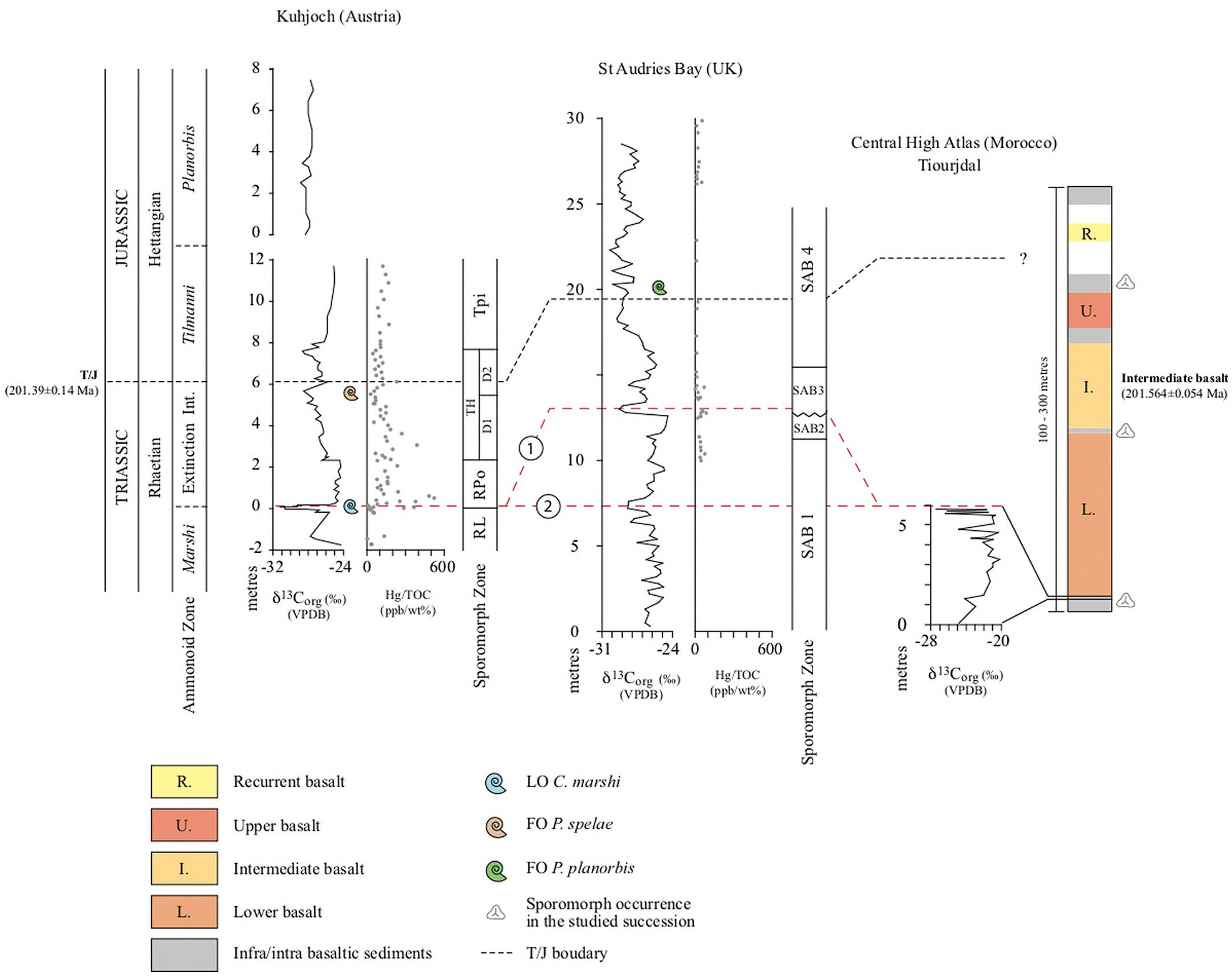

Kuhjoch (Austria)
St Audries Bay (UK)
Central High Atlas (Morocco)
Tiourjdal
JURASSIC
TRIASSIC
Hettangian
Rhaetian
Planorbis
Tilmanni
Extinction Int.
Marshi
Ammonoid Zone
T/J
(201.39±0.14 Ma)
metres
δ13Corg (‰)
(VPDB)
Hg/TOC
(ppb/wt%)
Sporomorph Zone
Tpi
TH
D2
D1
RPo
RL
SAB 4
SAB3
SAB2
SAB 1
100 - 300 metres
R.
U.
I.
L.
Intermediate basalt
(201.564±0.054 Ma)
Recurrent basalt
Upper basalt
Intermediate basalt
Lower basalt
Infra/intra basaltic sediments
LO C. marshi
FO P. spelae
FO P. planorbis
Sporomorph occurrence
in the studied succession
T/J boudary

Fig. 4.