Université des Sciences et Technologies de Lille 1
UFR des Sciences de la Terre
UMR 8198 “Evolution, Ecologie, Paléontologie”
Ecole Doctorale 104 – Sciences de la Matière, du Rayonnement et de l’Environnement

Doctorat de l’Université de Lille 1
Géosciences, Ecologie, Paléontologie, Océanographie
Lorena TESSITORE

LE POTENTIEL DE LA BIOSTRATIGRAPHIE DES CHITINOZOAIRES DANS LE DECRYPTAGE DE LA GLACIATION FINI- ORDOVICIENNE SUR LES MARGES GONDWANIENNES

Thèse dirigée par Thomas Servais et encadrée par Thijs Vandenbroucke
Soutenue publiquement le 13 Décembre 2016

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THE POTENTIAL OF THE BIOSTRATIGRAPHY OF CHITINOZOANS FOR DECIPHERING THE END-ORDOVICIAN GLACIATION ON THE GONDWANAN MARGINS

PhD thesis directed by Thomas Servais and supervised by Thijs Vandenbroucke
Public defense on the 13th of December 2016

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This publication is not deemed nor intended to be valid for publication for the naming of new taxa as stipulated in the article 8.2 of the International Code of Zoological Nomenclature, 4th edition, 2000, eds. W.D. Ride *et al.*

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ACKNOWLEDGMENTS/REMERCIEMENTS

I will start to thank the jury who kindly accepted to read the manuscript and come and judge my PhD defense, I am very thankful!

Ensuite, je continue en français pour remercier plein des gens fantastiques qui m'ont fait passer 3 ans superbes à Lille! Tout d'abord je remercie Jean-François pour la création d'un super projet scientifique et j'espère avoir apporté ma petite partie sur la compréhension d'une super période glaciaire. Je remercie aussi Thijs qui m'a permi de faire partie de ce projet et qui m'a donné la possibilité de découvrir et de travailler sur des microfossiles fanscinants dont j'ignorais l'éxistence avant d'arriver à Lille. Merci aussi à Thomas pour avoir rendu tout ça possible au niveau administratif et pour son implication dans le rush finale.
Je ne peux pas oublier toute l'équipe du SN5 ! C'est grâce à vous que je me suis sentie comme chez moi, même à plus de 1000Km du vrai chez moi. Je tiens à remercier ma super collègue et amie de bureau Chloé, qui m'a supportée pour bien 2 ans, merci pour tout ! Ensuite je remercie aussi (ordre random) Sandra, Fabio, Cesar, Noémie, Anastasia, Ninon, Maxime, Matthieu, Martin, Brenda, Melesio, Alexi, Laurence, Philippe, Régine, Jessie, Andy, Claude, Sébastien, Elizabeth et tous les gens du SN5. Merci aussi à tous les non-géologues que j'ai connu à Lille et qui m'ont suivi jusqu'à la fin.

Je tiens à remercier du fond du cœur mon chéri qui m'a supportée dès notre première rencontre et qui m'a poussée à surpasser mes limites pour finir dans la meilleure des façons.

Obbligo è di finire in italiano per ringraziare la mia famiglia ! Grazie per avermi sempre spinta e motivata a fare ciò in cui credevo e amo, la geologia, e grazie per aver reso tutto ciò possibile a livello finanziario (cosa che non è stata proprio impresa facile). Un enorme grazie mami, papi e bruder!! E un grazie va anche a tutti i miei amici ticinesi!

Grazie a tutti !!
Merci à tous !!

ABSTRACT

The Upper Ordovician (Katian-Hirnantian, ~10 Myrs) is mainly known for its major glaciation at the Hirnantian Stage, but also for the first 'Big Five' mass extinction events on Earth history. Understanding Earth system dynamics during glaciations is crucial to approach three of the main challenges facing the society in the 21st century: climate change and its environmental impacts, energy, and water resource management.

The aim of this work is focused on the analyses of a powerful biostratigraphic tool, the chitinozoans, in an ice-distal, relatively deep depositional domain (Tazekka Massif, North Morocco), an ice-proximal area that has few stratigraphic gaps (Central Anti-Atlas, South Morocco), and in a low palaeolatitude region that presents a well defined fauna against the chronostratigraphy (South China). The objectif is to correlate all these regions during the end Ordovician glaciation. Indirect proxies for glaciation, such as carbon isotopes and related changes in microfossil assemblages, are also studied here and they can be calibrated against the direct ice-sheet signal. The goals are to (1) recognize the faunal changes on a spatial and temporal scale in the Central Anti-Atlas basin; (2) understand the palaeonvironmental changes thanks to the chitinozoan assemblages; (3) identify the Katian-Hirnantian boundary; (4) understand the meaning of the geochemical proxies ($\delta^{13}C_{org}$) in the Tazekka Massif; and (5) confirm the global nature and impact of the glaciation.

Key words.
Chitinozoans, Biostratigraphy, Hirnantian Glaciation, Carbon Isotopes, Upper Ordovician, Morocco, China.

RESUME

L'Ordovicien Supérieur (Katien-Hirnantien, ~10 Ma) est principalement connu pour son importante glaciation à l'Hirnantien, mais aussi pour enregistrer la première des cinq grandes extinctions de masse connues sur Terre. Comprendre le Système Terre et ses dynamiques pendant les glaciations est un facteur crucial pour aborder trois des plus grands défis auxquels la société du 21ème siècle fait face: le changement climatique et ses effets environnementaux, l'énergie, et la gestion des ressources en eau.

Le but de ce travail se concentre sur l'analyse d'un puissant outil biostratigraphique, les chitinozoaires, dans un domaine glaciaire distal et de dépôt relativement profond (le Massif du Tazekka, Nord du Maroc), dans une région glaciaire proximale qui présente quelques lacunes stratigraphiques (l'Anti-Atlas Central, Sud du Maroc), et dans une région à basses paléolatitudes comme le Sud de la Chine. L'objectif principal est de corréler ces régions pendant la glaciation fini-Ordovicienne. Les objectifs de la thèse sont de (1) reconnaître les changements fauniques à l'échelle spatiale et temporelle dans le bassin de l'Anti-Atlas Central; (2) comprendre les changements paléoenvironnementaux grâce aux assemblages des chitinozoaires; (3) identifier la limite Katien-Hirnantien; (4) comprendre la signification des proxies géochimiques ($\delta^{13}C_{org}$) dans le Massif du Tazekka; et (5) confirmer l'impact et la nature globale de la glaciation Hirnantienne.

Mots clés.

Chitinozoaires, Biostratigraphie, glaciation Hirnantienne, Isotopes de carbone, Ordovicien supérieur, Maroc, Chine.

TABLES OF CONTENTS

RESUME ETENDU EN FRANCAIS

Chapter I: Introduction

Le projet SeqStrat-Ice

Ce projet financé par l'Agence Nationale de la Recherche (ANR) cherche à développer des concepts de stratigraphie séquentielle applicables à l'enregistrement sédimentaire glaciogénique, seule archive directe des glaciations anciennes. La compréhension de cette archive est d'une importance fondamentale pour les modélisations des changements climatiques du passé (et la prédiction de celles du futur) et pour l'étude des signaux biogéochimiques à travers l'histoire de la Terre. En effet, la compréhension des systèmes dynamiques de la Terre pendant les périodes de glaciations est d'une importance cruciale pour faire face aux problèmes que rencontre la société moderne, comme le changement climatique et son impact sur les environnements, le problème des ressources d'énergie (renouvables ou pas), ou encore la gestion des ressources en eau.

Le projet SeqStrat-Ice s'articule autour de trois piliers. Le premier concerne la modélisation numérique des systèmes de dépôts liés à une glaciation: le pari est de relier un outil de modélisation stratigraphique à un modèle de calotte glaciaire qui guide les avancées/retraits des fronts glaciaires. Le deuxième pilier est caractérisé par une étude approfondie de l'enregistrement glaciaire de la fin de l'Ordovicien, un des exemples les mieux connus d'un enregistrement glaciogénique pré-Quaternaire. C'est dans le cadre de cette thématique qu'a été identifié la nécessité d'une meilleure caractérisation biostratigraphique des archives glaciaires de la fin de l'Ordovicien, objet de la présente thèse de doctorat. Enfin, le troisième pilier se focalise sur l'intégration des résultats dans un cadre conceptuel unifié et évolutif. Le but final du projet sera la conception d'un modèle original et universel de stratigraphie séquentielle pour les successions glaciogéniques du passé.

Les objectifs

Le projet de cette thèse se concentre principalement sur l'enregistrement glaciaire de la fin de l'Ordovicien. La thèse s'insère dans une étude intégrée des successions sédimentaires pré-, syn-, et post-glaciaires, à une échelle de plateforme et à travers un intervalle de temps d'environ 10 Ma (Katien-Hirnantien). L'intégration de données à partir de la littérature et les nouvelles données récoltées au cours de cette étude sera le squelette du modèle conceptuel pour la stratigraphie séquentielle glaciaire sur des plateformes continentales peu profondes.

L’Anti-Atlas Central et la Meseta (respectivement Sud et Nord du Maroc) servent de laboratoire naturel principal avec des aires étendues (150 km x 600 km) de séquences de dépôts glaciaires (Second Bani Group dans l’Anti-Atlas Central et la Formation de Tifarouine dans le Massif du Tazekka, Hirnantien) et de plateformes pré-glaciaires (Ktaoua Group supérieur, cf. Loi et al. (2010) pour l’Anti-Atlas Central et la Formation de Tehar el Brehl pour le Massif du Tazekka, Katien). Les localités offrent le spectre total des faciès de dépôt, des turbidites distales aux environnements subglaciaires. En utilisant un dense et large réseau de données (en incluant aussi les données précédentes de la littérature), on pourra décrire l’architecture de dépôt à l’échelle du bassin, en corrélant les sections sédimentaires (logs), les niveaux repères et les surfaces spécifiques. Etant donné que les sections glaciaires proximales montrent des lacunes stratigraphiques dues à différents facteurs tels que l’érosion glaciaire, il faudra faire une étude approfondie pour assurer les corrélations à travers le bassin. Pour ce faire, la thèse se focalise sur l’analyse des chitinozoaires du Maroc pour enfin permettre des corrélations entre une zone proximale (Anti-Atlas Central) et une zone plus distale (le Massif du Tazekka) au cours de la fin de l’Ordovicien. Une zone supplémentaire a été ajoutée, le Sud de la Chine, pour permettre une étude à plus grande échelle, étant donné sa position à plus basse paléolatitute, et son statut de (para)stratotype de l’Hirnantien.

L’ Ordovicien

Le Système Ordovicien, qui couvre environ 42 Ma (entre 485.4 ± 1.9 Ma et 443.8 ± 1.5 Ma) du Paléozoïque inférieur, est divisé en 3 séries (Inférieur, Moyen, et Supérieur) et 7 étages (Trémadocien, Floien, Dapingien, Darriwilien, Sandbien, Katien et Hirnantien). Webby et al. (2004a) ont proposé une série non-officielle de “time-slices” (“intervalle de temps”) pour l’Ordovicien de façon à faciliter une corrélation inter-régionale à haute résolution. L’Ordovicien est caractérisé par la “Grande Biodiversification Ordovicienne” (“The Great Biodiversification Event”, GOBE) qui est caractérisée par une augmentation importante de la biodiversité de la plupart des groupes d’organismes marins au cours de l’Ordovicien (Webby et al., 2004b). Cette radiation est différente de l’ “Explosion Cambrienne” car elle concerne une émergence d’écosystèmes plus complexes et une augmentation plus forte de diversité, surtout dans les rangs taxonomiques plus bas (p. ex. : Harper, 2006 ; Sepkoski, 1995).

Les causes biologiques (intrinsèques) et géologiques (extrinsèques) de cette radiation ordovicienne restent toutefois controversées (Servais et al., 2009). Une explication parmi d’autres est celle de Servais et al. (2008) qui ont proposé qu’une augmentation de la production primaire dans les océans pouvant en être le déclencheur principal. L'excursion de $\delta^{13}C_{carb}$ du Cambrien supérieur (Paibien) (SPICE) serait ainsi liée à une oxygénation des océans et un augmentation importante du phytoplancton qui aurait alimenté ainsi la radiation ordovicienne (Servais et al., 2008 ; Saltzman et al., 2011). Une multitude d'autres causes de la biodiversification ordovicienne ont été proposées : niveaux marins particulièrement élevés, encore des plateformes littorales très étendues, la présence d'un super-panache ou un refroidissement important du climat (p.ex. Servais et al., 2009).

Palynomorphes du Paléozoïque

Le terme "palynomorphe" n'a pas de définition universelle, il est appliqué à tout objet organique étudié dans le domaine de la palynologie. Selon une interprétation pragmatique et commune, un palynomorphe est tout simplement un microorganisme qui résiste à un traitement palynologique, ce qui est notamment le cas pour des objets avec une paroi organique résistante aux acides forts. La paléopalynologie, sous-discipline de la palynologie, est l'étude des palynomorphes fossiles. Elle est donc également une sous-branche de la (micro)paléontologie. Les palynomorphes du Paléozoïque inférieur les plus communs sont les acritarches, les spores de plantes terrestres ou aquatiques ou encore les chitinozoaires. Il y a aussi plusieurs groupes moins fréquents, dont les plus connus sont les scolécodontes (Hints et al., 2004; Hints et Eriksson, 2007; Szaniawski, 1996). Une fois les échantillons palynologiques préparés, on peut y retrouver à côté des chitinozoaires, des acritarches, et des scolécodontes, également d'autres parties d'organismes marins, comme des fragments de graptolites (Cooper et al., 2001) ou encore des cuticules d'euryptérides (scorpions de mer; Braddy et al., 2004; Lamsdell et al., 2015) et autres groupes.

Les chitinozoaires (fossiles étudiés en détail dans ce travail) sont des microfossiles à paroi organique en forme de cône ou de vase, avec une ouverture à l'une des extrémités (Fig. 1.8; Eisenack, 1931). Malheureusement, leur affinité phylogénétique reste inconnue à présent. Au jour d'aujourd'hui, selon la théorie la plus acceptée sur leur origine biologique, les chitinozoaires seraient des oeufs d'un animal marin inconnu (Paris et Nõlvak, 1999), qui faisait partie du zooplankton épipélagique (Vandenbroucke et al., 2010).

Les micro- et macrofaunes de l'Ordovicien Supérieur au Maroc

Chapter II : The record of the end-Ordovician glacial and faunal events in the Central Anti-Atlas (southern Morocco) : the chitinozoan case

Il s'agit d'un chapitre de thèse destiné à devenir une publication dans le journal *Review of Palaeobotany and Palynology* avec la collaboration de participants au projet SeqStrat-Ice.
Dans cette partie, la distribution des chitinozoaires à la fin de l'Ordovicien a été investiguée dans l'Anti-Atlas Central, Sud du Maroc. Cette localité est située dans une zone marginoglaciaire caractérisée par des environnements sous-glaciaires à marins restreints pendant le maximum glaciaire de la fin de l'Ordovicien. Les environnements 'normaux' de plate-forme caractérisent cependant ce domaine la plus grande part de l'Hirnantien précédant le maximum glaciaire.

L'Anti-Atlas a été une zone d'étude additionnelle à la zone d'étude principale (le Massif du Tazekka, chapitre 3) du projet SeqStrat-Ice. Il inclut la section type fini-ordovicienne (Bou Ingarf, Bourahrouh et al., 2004; Loi et al., 2010). C'est pour cette raison que l'Anti-Atlas est présenté en premier. Le but est ici d'étudier la distribution des microfaunes de chitinozoaires, ses niches écologiques et ses significations, etc., à une échelle de bassin et plus précisement à travers, et de part et d'autre de la limite Katien-Hirnantien. Quelques relations stratigraphiques entre les régions sud, central, nord, et est de l'Anti-Atlas seront de plus éclaircies. En particulier l'âge de remplissage des incisions présentes dans la partie nord-est, bien que dans certains cas des problèmes de remaniement limitent les interprétations.

Chapter III: The chitinozoan record in the Tazekka Massif, northern Morocco: a benchmark for the end-Ordovician glaciation?

Il s'agit d'un chapitre de thèse présenté sous la forme d'un manuscrit qui sera soumis pour publication dans le journal *Gondwana Research* avec la collaboration de participants au projet SeqStrat-Ice et de collaborateurs externes.

La fin de l'Ordovicien est un intervalle de temps très bien connu enregistrant une glaciation majeure, des *turnovers* fauniques et des excursions isotopiques. Certaines lacunes sont présentes au niveau mondial et pour combler ces lacunes entre basses et hautes paléolatitudes, nous avons décidé de revisiter les affleurements du Massif du Tazekka, au nord du Maroc. Le Massif du Tazekka est proche de la marge continentale gondwanienne et il expose une succession très épaisse (plus que 600 m) de l'Ordovicien Supérieur. Ce cadre relativement proximal (vers le pôle Sud), mais assez distal par rapport aux fronts glaciaires, a l'avantage d'inclure des indicateurs directs de l'activité de la calotte glaciaire de l'Ordovicien. En outre, les plus de 450 m de dépôts épais et virtuellement continus à travers la limite Katien-Hirnantien et à travers l'Hirnantien font du Tazekka un des meilleurs endroits où étudier la fin de l'Ordovicien. Dans cette étude on a spécifiquement exploré le potentiel de la biostratigraphie des chitinozoaires dans le déchiffrage du développement de la glaciation. De plus, on présente les résultats préliminaires de la courbe de $\delta^{13}C_{org}$ qui montre des variations qui semblent pouvoir être corrélées à l'échelle du domaine nord-gondwanien. Dans la zone d'étude, 5 assemblages de chitinozoaires ont été déterminés, correspondant respectivement à trois conditions environnementales différentes. Le premier assemblage correspond à des conditions pré-glaciaires ; du deuxième au quatrième assemblage les conditions sont glaciaires au sense large (syn-glaciation), et le dernier assemblage suggère une phase de récupération. Dans la succession du Tazekka ont été reconnues avec précision deux biozones à chitinozoaires: *nigerica* (dans la Fm. de Tehar el Brehl) et *elongata* (dans la Fm. de Tifarouine). L'abondance du genre *Sphaerochitina* dans le Massif du Tazekka et sa presque totale absence dans l'Anti-Atlas Central, suggèrent un environnement de vie correspondant à un domaine marin ouvert de type plate-forme externe.

Les chitinozoaires de l'Ordovicien Supérieur de Chine

Chapter IV: Chitinozoans from the Hirnantian GSSP in Wangjiawan, Yichang (South China)

Lorena Tessitore, Thijs R.A. Vandenbroucke, Junxuan Fan, Xu Chen, Thomas Servais & Jean-François Ghienne (manuscript *soumis au Review of Palaeobotany and Palynology*)

Trente-trois échantillons de la section de Wangjiawan Riverside dans la région de Yichang (Chine du Sud) ont été analysés palynologiquement, principalement pour les chitinozoaires.

La section se trouve dans une petite rivière directement adjacente (< 180 m) au stratotype de la base de l'Hirnantien (Global Boundary Stratotype Section and Point GSSP) dans la section appelée Wangjiawan North. Cet affleurement offre des roches beaucoup plus fraîches plus propices à la préservation de palynomorphes. Plus de 2000 spécimens de l'Ordovicien terminal au Silurien basal ont été récoltés, bien que leur préservation généralement mauvaise ne permette pas une analyse systématique précise ni une interprétation biostratigraphique détaillée. Néanmoins, cette étude illustre d'une manière exhaustive les premiers chitinozoaires du Kuanyinchiao Bed et de la Formation de Lungmachi dans la section de Wangjiawan Riverside. La présence des chitinozoaires est parfaitement calibrée sur la biozonation des graptolites et l'échelle temporelle internationale basée sur le GSSP de la base de l'Hirnantien dans la section de Wangjiawan North. Cette étude dévoile une faune de chitinozoaires particulièrement abondante et caractéristique dans le Kuanyinchiao Bed. Au contraire, les formations de Wufeng et Lungmachi dévoilent une faune très réduite et mal préservée. La présence de deux espèces clés de l'Hirnantien (*Tanuchitina elongata* et *Belonechitina llangrannogesis*) a permis une première corrélation entre les marges gondwaniennes pendant la période glaciaire de la fin de l'Ordovicien.

Perspectives

Le but de cette section est d'étudier l'enregistrement de la macro- et microfaune de l'Anti-Atlas Central, qui a été synthétisé par Destombes (2004) et nos propres donnés, pendant l'Ordovicien Supérieur afin de résoudre le problème d'identification d'une signature de la première phase d'extinction Hirnantienne. Notre base de données va nous permettre d'évaluer si le *turnover* de la macrofaune est relié à d'autres phases spécifiques des principaux cycles glaciaires. Pour ce faire, 7 zones ont été sélectionnées avec le but de voir les changements fini-ordoviciens de la macro- et microfaune pendant l'Hirnantien.

Les résultats préliminaires montrent qu'une diminution de l'abondance de la faune et de la biodiversité a été enregistrée, du Sud-Ouest vers Nord-Est, et à travers le temps, du premier cycle glaciaire vers le maximum glaciaire. Ce travail est encore en cours, donc ces résultats ne sont que préliminaires. Ils seront suivis par plus de données et interprétés par la suite, pour enfin aboutir sur une publication dans un journal scientifique.

CHAPTER I: INTRODUCTION

1. The PhD thesis in the framework of the SeqStrat-Ice ANR Project

This PhD thesis was proposed in the framework of the SeqStrat-Ice project (2013-2017) founded by the French ANR (Agence Nationale de la Recherche). The project aims at developing sequence stratigraphic concepts that will provide a robust framework for the investigation of the glaciogenic records through space and time. Understanding Earth systems dynamics during glaciations is crucial to approach three of the main challenges facing the society in the 21st century: climate change and its environmental impacts, energy, and water resource management. The SeqStrat-Ice is a project focused on the sequence stratigraphy of the glaciogenic sedimentary record, our only direct archive of ancient glaciations during the early Palaeozoic Era. Understanding this archive is of fundamental importance when modeling past (and predicting future) climate change and for the study of biogeochemical signals throughout Earth's history.

1.1 Research questions

The project is organized around three pillars. The first pillar is focused on the numerical modeling of glaciation-related depositional systems: the challenge is to connect a stratigraphic modeling tool to an ice-sheet model that drives the advancing/retreating ice fronts.

The second pillar is an in-depth study of the Late Ordovician glacial record, arguably the best-known example of a pre-Quaternary glaciogenic record. We postulate that the Ordovician glaciation is one of two end members in a conceptual glacial model: this end member comprises glaciations on shallow continental platforms. It contrasts with the other, well-known, Cenozoic-style end member where ice sheets extended over deep shelves. This hypothesis will be tested using old and new data from our natural laboratory in the Upper Ordovician strata in Morocco. A comparison with far-field signals will differentiate global events from local ones and will allow accurate time calibration, in turn permitting stratigraphic modeling. Finally, the third pillar consists on the integration of the results in an evolving unified conceptual skeleton. The total result will be a global sequence stratigraphic model for glaciogenic successions.

This project includes a research team from four academic partners: 3 french academic research groups (Institut de Physique du Globe de Strasbourg; Biogéosciences, Dijon; Evo-Eco-Paléo, Lille, and the IFP-Energies Nouvelles). Researchers from other universities (Bordeaux, Cergy Pontoise, Rennes, LSCE, international collaborators) also integrate the wide network in order to reach the objectives of the SeqStrat-Ice project.

1.2 Aim of this thesis

The PhD integrates the deep-time data collecting part of project, and focused on the end-Ordovician, glaciation-related stratigraphic record. It is part of the wider field-based study of the pre- glacial sedimentary successions and the overlying glaciogenic record, at platform scale and through a 10 Myr time interval (Katian to Hirnantian). Integrating data from the literature and new data will form the skeleton for the conceptual model for glacial sequence stratigraphy on shallow continental platforms. The Central Anti-Atlas and the Meseta (southern and northern Morocco, respectively) are our natural laboratory. Here are extensive exposures (150 km x 600 km) of the glacial depositional sequences in both regions (Second Bani Group, in the Central Anti-Atlas, and the Tifarouine Formation in the Tazekka Massif, Hirnantian) and of the pre-glacial platform (upper Ktaoua Group, with high-frequency cycles in the pre-glacial upper Ktaoua Fm. cf. Loi et al. (2010) in the Central Anti-Atlas, and the Tehar El Brehl Formation in the Tazekka Massif, of Katian age. In the Tazekka Massif the glaciation-related succession is in excess of 500 m, no glacial erosion surface has been identified, and outcrop conditions are excellent (Le Heron et al., 2007, 2008).

Morocco offers a unique opportunity to produce a geological model for the impact of a major glaciation on a low-angle continental platform. The record includes the total range of depositional facies, from the non-glacial outer shelf to subglacial environments. Using a dense network of datapoints, we will be able to define the depositional architecture at basin-scale, correlating sedimentary logs, marker beds, and specific surfaces.

Any sequence stratigraphic analysis and related stratigraphic modeling requires an accurate identification of the amplitude and tempo of the forcings. This helps to define the timing of the glacioeustatic cycles and the nature of the biogeochemical signal.

The PhD thesis is based on the glaciogenic record of an ice-distal, relatively deep, depositional domain (the Tazekka Massif), and an ice-proximal area that has few stratigraphic gaps (the Central Anti-Atlas). Comparing data from sites at low palaeolatitudes, such a near field but ice-distal record has the advantage that it includes direct indicators of the Ordovician ice-sheet activity. Indirect proxies for glaciation, such as carbon isotopes and related changes in microfossil assemblages are also studied here and they can be calibrated against the direct signal.

The PhD work is focused on the analyses of a powerful biostratigraphic tool, the chitinozoans, in the Upper Ordovician of Morocco in order to correlate the ice-distal area, such as the Tazekka Massif, with an ice-proximal area, such as the Central Anti-Atlas, during the end Ordovician glaciation. The study has been subdivided in the following research questions:

- Chitinozoan analysis (useful for high-resolution biostratigraphy) in the Central Anti-Atlas basin. What are the faunal changes on a spatial and temporal scale? Does the ouzregui marker bed properly indicate the Katian-Hirnantian boundary?
- Chitinozoan analysis on the ice-distal environment, the Tazekka Massif, will provide the first detailed chitinozoan data of this region. Where is the Katian-Hirnantian boundary located? What do the chitinozoan assemblages suggest about the palaeoenvironmental evolution?
- What do the geochemical proxies ($\delta\ ^{13}C_{org}$) of the Tazekka Massif indicate?
- Correlation with far-field settings should confirm the global nature and impact of the recorded events. Do chitinozoan data from low- (South China, Welsh Basin) and high- (Morocco) palaeolatitudes reflect this global glaciation?
- Does the construction of databases and multivariate statistical analyses (CONOP, R) improve the signal-recovery?
- Which indications are given by the macrofauna in the Central Anti-Atlas? Do they display an ecological niche migration? Do they fairly define the Katian-Hirnantian boundary?

1.3 Additional study – South China

An additional area has been added to this thesis as a complementary work relative to the SeqStrat-Ice Project. South China has been chosen because of its definition of the GSSP of the base of the Hirnantian. The chitinozoans from this region have been studied and the fixed chronostratigraphy helped to understand the relation between palynomorphs and time. It is possible to apply the results on a global scale and it may be possible to provide age assignments in places where other biostratigraphic data are missing (e.g. graptolites).

1.4 Realization

To reach these objectives, chitinozoan analyses are undertaken, the results of which are presented here as a series of research papers and manuscripts. In total, 464 samples have been collected, 326 (70%) of which were analyzed (amongst them 166 from the Central Anti-Atlas, 111 from the Tazekka Massif, 33 from South China, and 14 from West Sardinia). 215 (66%) samples of the 326 analyzed in the palynological laboratory yielded a total of 20,368 identified specimens (13,089 from the Central Anti-Atlas areas, 5,125 from the Tazekka region, 2,154 from China, but none from Sardinia). Moreover, geochemical analyses on 98 samples from the Tazekka Massif have been performed.

2. The Ordovician System

2.1 Geochronology and Palaeogeography

The Ordovician period (485.4 ± 1.9 Myrs to 443.8 ± 1.5 Myrs) is spanning 42 Myrs and it is in between the Cambrian and the Silurian Periods (Fig. 1.1). The Ordovician System is divided into 3 Series (Lower, Middle, and Upper) and 7 stages (Tremadocian, Floian, Dapingian, Darriwilian, Sandbian, Katian, and Hirnantian). Webby et al. (2004a) proposed a series of unofficial "time slices" for the Ordovician in order to determine high-resolution inter-regional correlation. Similarly, Bergström et al. (2009) defined 20 "stage slices" calibrated against the graptolite and conodont biostratigraphy. Indeed, the Ordovician stages are defined by the FADs of graptolites or conodonts (Bergström et al., 2008; Gradstein et al., 2012).

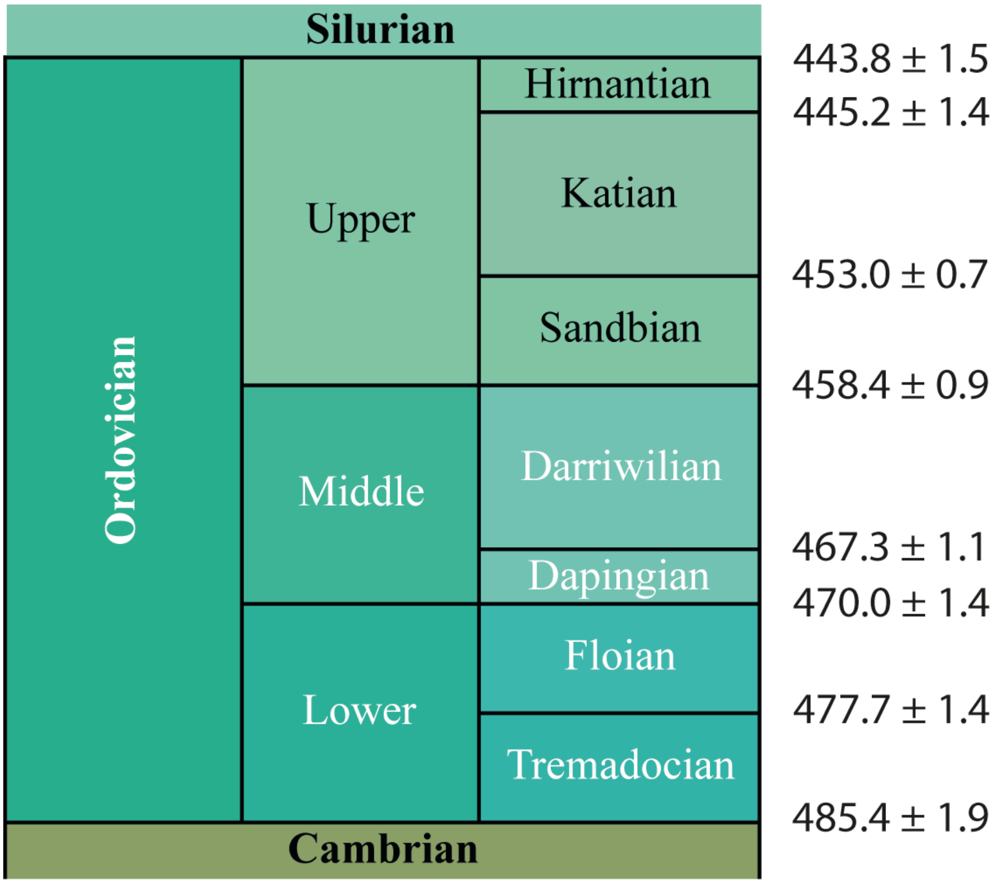

Fig. 1.1. Chronostratigraphy of the Ordovician, according to the International Chronostratigraphic Chart (state 2016; Cohen et al., 2013, updated).

The Ordovician System was a period of important tectonic plate dispersion. The land masses were mostly concentrated in the southern hemisphere with the exception of Laurentia and Siberia, which straddled the equator, while the vast Panthalassic Ocean occupied most of the northern hemisphere. According to Achab and Paris (2007), the occupation of new ecological niches, the temporary geographical isolation of faunas and the contrasting climatic belts of the Late Ordovician, largely contributed to the development of one of the highest Palaeozoic faunal diversities (Servais et al., 2008). Several authors (e.g. Scotese and McKerrow, 1990; Harper et al., 1996; Torsvik, 1998; Cocks, 2001; Stampfli et al., 2002; Cocks and Torsvik, 2002, 2005, 2007, 2011; Torsvik and Cokcs, 2009, 2011, 2013; Von Raumer et al., 2015; Blakey, 2016) created palaeogeographical reconstructions combining palaeomagnetic, palaeontological, stratigraphical, and tectonic data.

Gondwana, Laurentia, Baltica, and Siberia were the four major palaeocontinents occupying the Earth during the Ordovician (Fig. 1.2). Here below, their description and characteristics:

The Gondwana Palaeocontinent was the largest continent during the Lower Palaeozoic until the Carboniferous. It included the present day South America, Africa, Madagascar, Arabia, India, Antartica, and Australasia (Torsvik and Cocks, 2013). It extended across all southern-hemisphere palaeolatitudes, from the South Pole (placed in the current North Africa) to the equator (in Australasia), and remained at high palaeolatitudes through most of the Lower Palaeozoic. This large land mass was initially drifting southward, but it then moved progressively northward during the Ordovician (Paris and Robardet, 1990). Therefore, the 'northern' Gondwana regions changed from a polar position in the Early Ordovician to a little less high palaeolatitudinal location in the latest Ordovician (Scotese et al., 1999; Cocks and Torsvik, 2004; Evans, 2004).

The Baltica Palaeocontinent moved following a significant anticlockwise rotation of 120° during the Late Cambrian and Early Ordovician, changing from intermediate latitudes in the earliest Ordovician to lower latitudes in the Late Ordovician. Baltica included most of the present day Scandinavia, Eastern Europe, and the Russian platform.

The Laurentia Palaeocontinent overlapped the equator during the whole Ordovician period and it started to drift towards Baltica. Laurentia included current North America, Greenland and Scotland, and occupied a relatively stable palaeoequatorial position throughout the Ordovician.

Across the Iapetus Ocean, there were numerous peri-Gondwana and peri-Laurentia terranes including island complexes and microcontinents. For instance, Avalonia was located on the East of Laurentia during the Late Cambrian-earliest Ordovician times (Prigmore et al., 1997), but it drifted more rapidly than Baltica and anchored with it by the Late Ordovician (Harper, 1996; Cocks and Fortey, 2009). The merged continents from the impact between Avalonia and Baltica collided then with Laurentia during the middle Silurian, which created the Caledonian Orogeny.

The Ordovician Period was a very tectonically and magmatic active period with rapid plate movements and abundant volcanic activity (Bergström et al., 2004) providing plentiful of nutrients. For instance, the explosive volcanism eruptions were common at that time, spreading ash deposits generally over the seafloor (Saltzman et al., 2003; Huff, 2008; Sell and Samson, 2011). According to Harper (2006), the Ordovician is considered as the greatest and most sustained interval of diversification of life on Earth. This dynamic palaeoeography might have induced great changes in the ocean and atmosphere geochemistry during the Ordovician, which are thought to have initiated one of the major episodes of climate and biodiversity changes of the Phanerozoic (e.g. Servais et al., 2010).

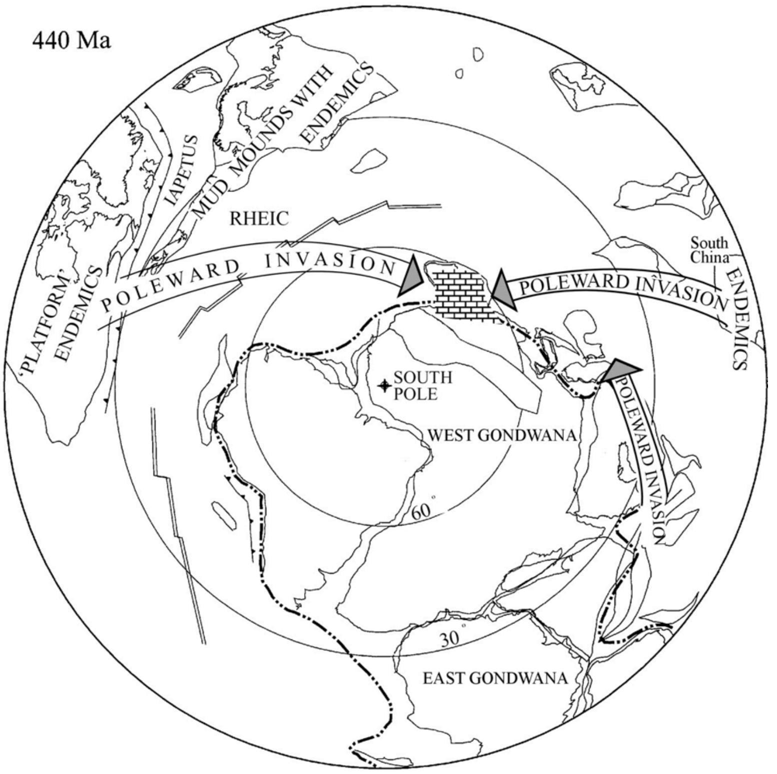

Fig. 1.2. Palaeogeographical reconstructions from the Upper Ordovician-Early Silurian. After Fortey and Cocks (2005).

2.2 Biodiversification and Ordovician mass extinction

The Ordovician observed the greatest marine diversification record, but also one of the Big Five mass extinctions (Raup and Sepkoski, 1982) associated with an important glacial event, the Hirnantian glaciation at the end of the Ordovician (Sepkoski and Sheehan, 2001; Fig. 1.3). After the Cambrian Explosion, marine invertebrates clearly strongly diversified during the GOBE (Great Ordovician Biodiversification Event) (Webby et al., 2004; Harper, 2006), giving place to the Palaeozoic Evolutionary Fauna described by Sepkoski (1981). The GOBE comprises increasing diversities in most groups of organisms during the Ordovician (Webby et al., 2004b). According to Servais et al. (2008), an increase in primary production, specifically microphytoplankton, was possible one of the main causes of the GOBE. This event involved a stronger growth in diversity and the emergence of more complex ecosystems (Sepkoski, 1995; Harper, 2006), and modern trophic chains developed (Signor and Vermeij, 1994).

The Ordovician was long considered to be a super-greenhouse world interrupted only by a short glaciation at the end of the Period, during the Hirnantian Stage (Brenchley et al., 1994, 2003). Currently, new evidence suggests that prolonged cooling must have preceded the end Ordovician glaciation and perhaps favorable conditions for the creation of the GOBE (i.e. Trotter et al., 2008; Rasmussen et al., 2016).

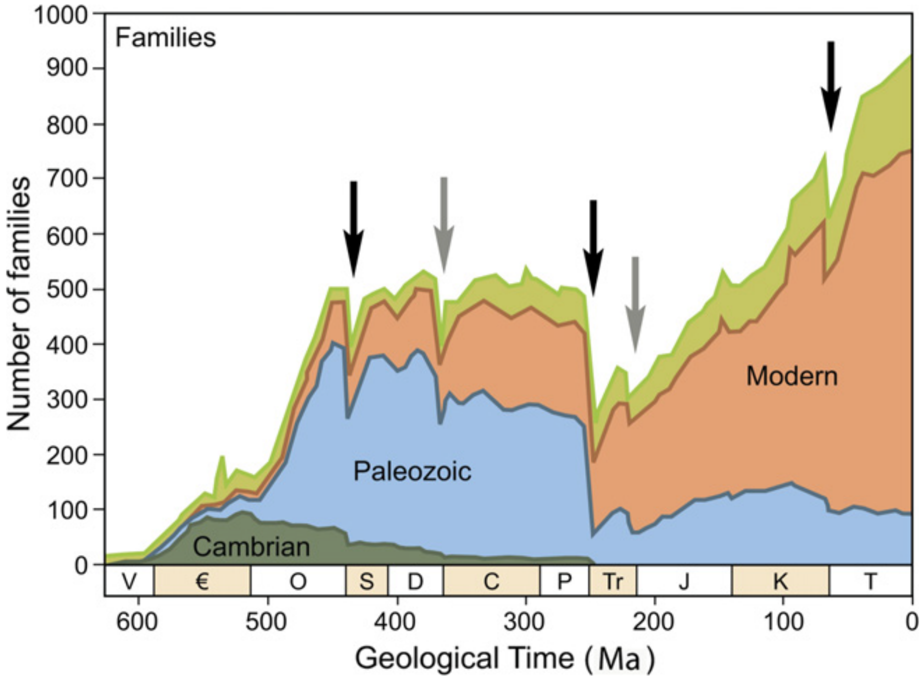

Fig. 1.3. The Big Five Mass Extinctions on Earth's history. After Harper et al. (2013).

According to Achab and Paris (2007), the occupation of new ecological niches, the temporary geographical isolation of faunas, and the contrasting climatic belts of the Late Ordovician, largely contributed to the development of one of the highest Palaeozoic faunal diversities. Figure 1.4 illustrates the diversity trends of the chitinozoans from different palaeocontinents.

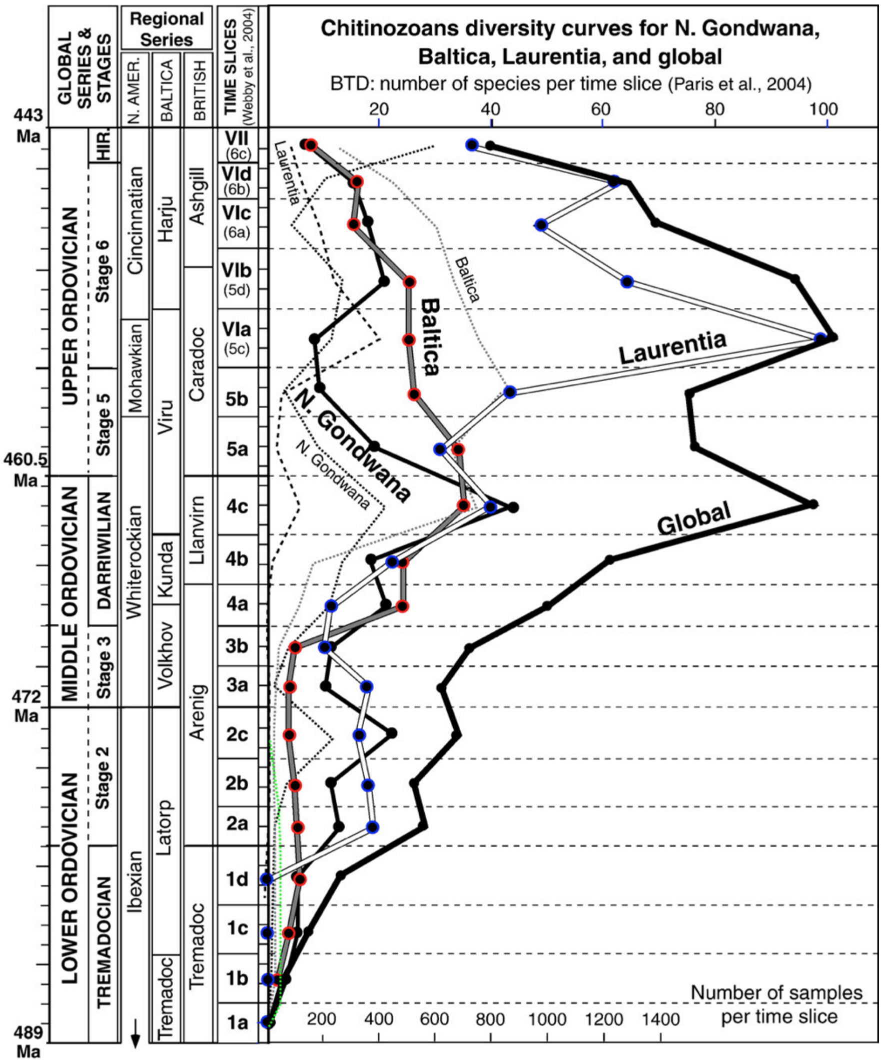

Fig. 1.4. Ordovician chitinozoan diversity curves of North Gondwana (black line), Baltica (black line with red dots), Laurentia (black line with blue dots), and the Global one (thick black line). After Achab & Paris (2007).

It is not proven yet whether the increasing diversity of phytoplankton can be related to bioproductivity, but it shows major changes in the trophic chain, which is why we also speak of "plankton revolution" (Servais et al., 2010).

The Ordovician radiation was interrupted by the end Ordovician mass extinction, one of the most severe extinctions of the Phanerozoic (Fig. 1.3; Sepkoski, 1981; Sheehan, 2001; and references therein) correlated to the Hirnantian glaciation, although the relation between cooling and extinction is currently debated (Hammarlund et al., 2012; Harper et al., 2014; Ghienne et al., 2014; Vandenbroucke et al., 2015). About 20% of the families, 40% of the genera and up to 85% of the species went extinct (Harper et al., 2014). The phytoplankton and zooplankton, forming the base of the food chain and playing an important role in driving the Great Ordovician Biodiversification Event (GOBE), were severely affected (Figs. 1.4, 1.5).

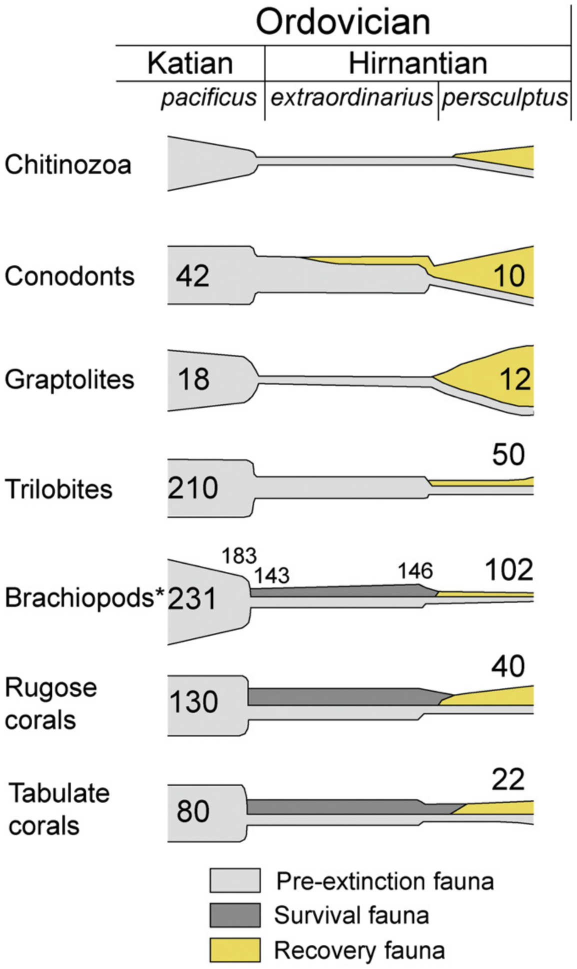

Fig. 1.5. Biodiversity changes of micro- and macro-faunas. After Harper et al. (2013).

The end Ordovician extinction is generally thought to comprise 2 pulses (Brenchley, 1984; Brenchley et al., 2006); the first one is just below the *Normalograptus extraordinarius* graptolite Biozone, which mainly affected the nektonic and planktonic organisms living on the shelf and deep sea. The second pulse, within the *Normalograptus persculptus* Biozone, had a more global effect on all organisms (Fig. 1.5; Harper et al., 2014). The diving mechanism of the first extinction pulse is still a matter of debate, as the timing of the events, such as temperature and sea-level drop, are not clear, but there is an agreement that the second pulse corresponds to a widespread transgression due to the melting ice cap, with an exception of the Anticosti area. The two pulses composing the extinction were followed by the establishment of a recovery fauna during the *Normalograptus persculptus* graptolite Biozone and in the lowermost Silurian *ascensus* graptolite Biozone (Finnegan et al., 2011;

Hammarlund et al., 2012; Ghienne et al., 2014; Melchin et al., 2013). The factors that have driven this glacial event and the timing of the events involved are debated, but in absence of a consensus on a single driving factor, the hypothesis of a combination of different causes is generally accepted (Harper et al., 2014).

2.3 Ordovician climate and sea level

The Ordovician was characterized by high sea levels, perhaps the highest in the Phanerozoic (Haq and Schutter, 2008). However, a period of major low sea levels is recorded, corresponding to the Hirnantian glacial events, with a maximum recognized in the "middle" Hirnantian (Webby et al., 2004; Melchin et al., 2013; Ghienne et al., 2014). In the palaeogeographic context, western Gondwana regions remained at high palaeolatitudes and underwent a cold climate during the onset of the Late Ordovician glaciation, especially during the Hirnantian glacial maximum. Laurentia, however, was in a warm equatorial position, whereas Baltica moved from a temperate palaeolatitude to a warmer subtropical position in the Late Ordovician.

Deep and surface oceanic circulations are responsible for the diffusion of the heat and the homogenization of the chemical composition of the ocean. The Ordovician oceanic circulations probably had an important impact on the biodiversification. Moreover, the Ordovician period was characterized as well by an odd distribution of lands and oceans. Indeed, during the Lower Ordovician, the northern hemisphere Panthalassic Ocean covered about half of the Earth surface and the Iapetus Ocean (separating Laurentia from Baltica) was at its maximum extent. Finally, the Rheic Ocean, latitudinally oriented, separated Gondwana from Avalonia and Baltica. According to Achab and Paris (2007), the geographical distribution of the large palaeoplates (Laurentia, Siberia and North China) composes an equatorial barrier causing a more or less independent circulation within each ocean.

The end Ordovician glaciation was first described in Mauritania and Algeria in the sixties. In Morocco, its consequences were identified by Destombes (1968a,b, 1971; Destombes et al., 1985), based on sedimentological evidence. Due to the exceptional Palaeozoic exposures and deposits preservation and its proximal location toward the ice-sheet, Morocco is considered one of the greatest places where the end-Ordovician glaciation can be studied. This glacial event was considered as very similar to more recent glaciations (e.g. during the Cenozoic, Ghienne et al., 2014)

Berner et al. (1990) included a combination of parameters, such as sedimentary burial of organic matter, silicate weathering, variation in ocean ridges and volcanoes degassing, and the position of carbon moving from platform to deep sea. They modeled a curve indicating high CO_2 for the Early Palaeozoic and Mesozoic and low CO_2 for the Permo-Carboniferous and Late Cenozoic. Brenchley et al. (1994) hypothesized that there were other parameters involved. They acquired new stable isotope data from Late Ordovician and early Silurian brachiopods to test the hypothesis of a glaciation during a greenhouse period. Their oxygen isotopes values show changes in sea-water temperature and ice-cap volume, which made them believe that there was a short glacial event, approximately 0,5 to 1,5 Myrs long, during the Hirnantian. The ice cap grew and melted very rapidly unlike the progressive growth in several cycles of the Cenozoic glaciation, which would be consistent with the high CO_2 levels. They also believed that a significant change in the carbon cycle may represent a reduction in $p\mathrm{CO}_2$ and may have triggered the glaciation.

New stable isotope data from several authors such as Ainsaar et al. (1999), Ludvigson et al. (2000, 2004), Saltzman and Young (2005), Bergström et al. (2006, 2009a, 2011), demonstrate that the Hirnantian glaciation was actually part of a “long-lived Late Ordovician glaciation” that was initiated during the Katian, if not earlier. Additionally, more recently some authors suggested an early cooling starting already during the Early-Middle Ordovician, such as Trotter et al. (2008) using $\delta^{18}O$ values from conodont apatite, suggesting decreasing temperature throughout the Tremadocian and the Floian. Rasmussen et al. (2016) used $\delta^{18}O$ and $\delta^{13}C$ data from brachiopods that suggest the onset of the Early Palaeozoic Ice age (EPI) during the middle Darriwilian.

The distribution of fossil groups that are SST-dependent, i.e. graptolites or chitinozoans, have been used to establish latitudinally controlled palaeoprovinces in the early Late Ordovician by Vandenbroucke et al. (2009, 2010a) (Figs. 1.6, 1.7), and confirm that the cooling trend toward the Hirnantian had started before or during the Sandbian (Vandenbroucke et al., 2010b; Figs. 1.6, 1.7).

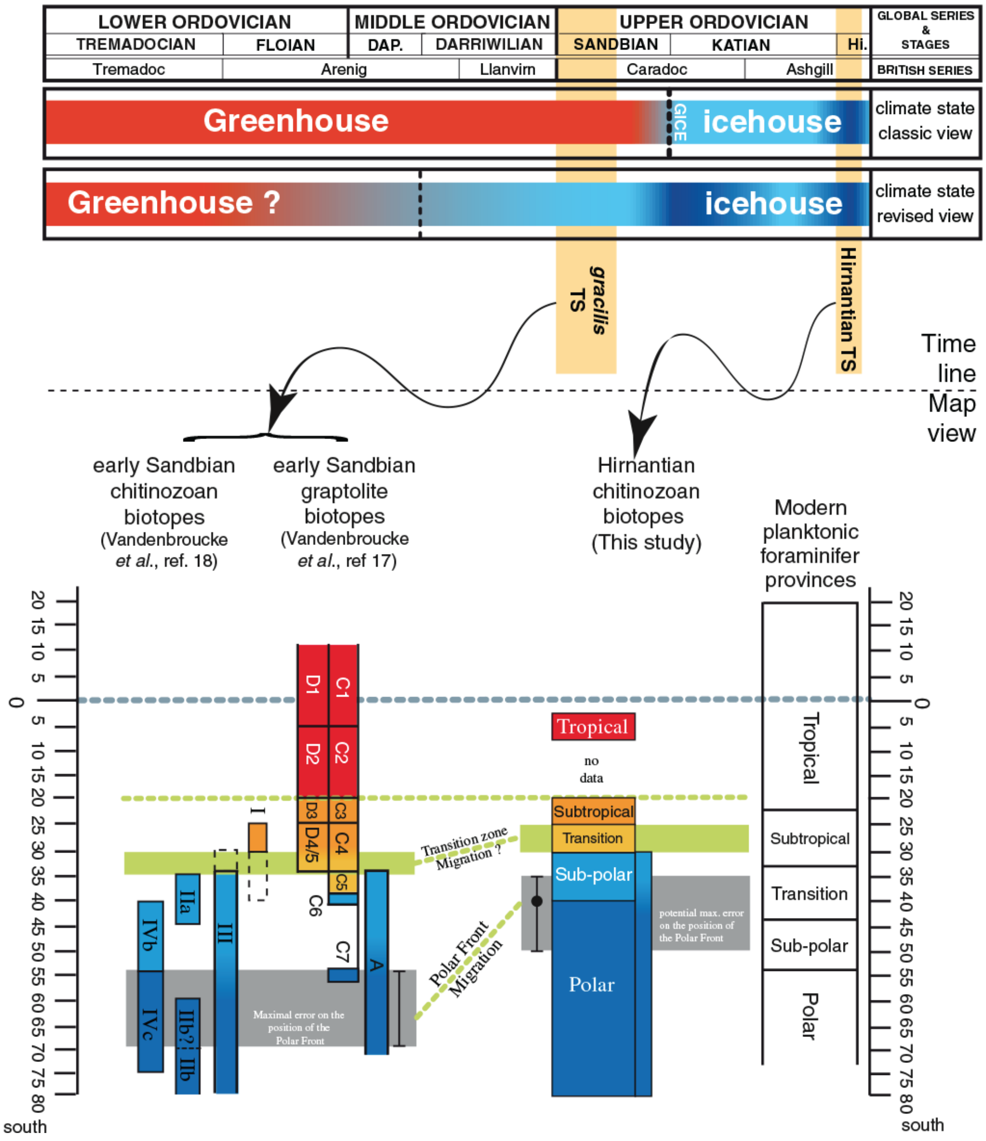

Fig. 1.6. Late Ordovician zooplankton distribution. Note that the latitudinal limits are not strictly defined as straight lines, but are more curved lines varying latitudinally. After Vandenbroucke et al. (2010).

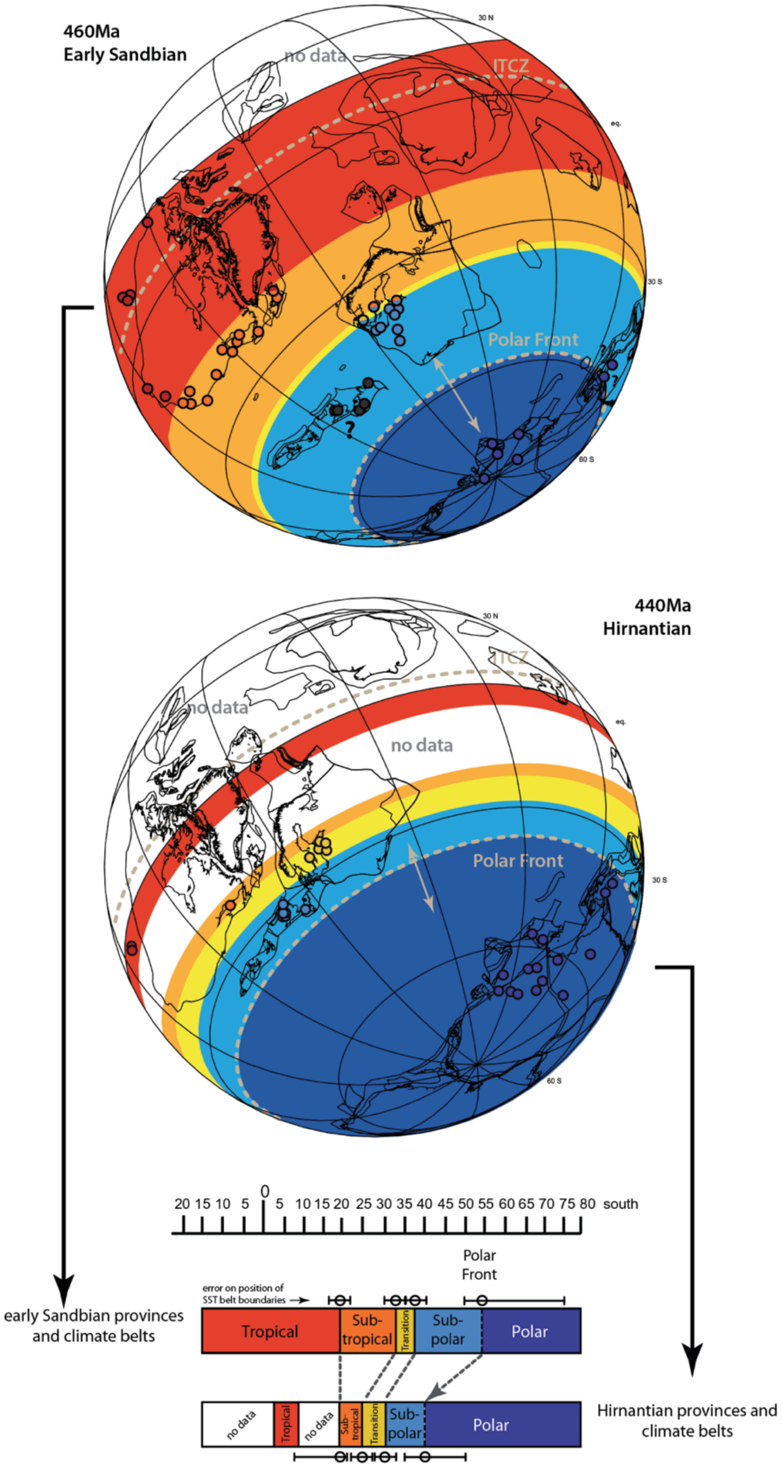

Fig. 1.7. Ordovician Climate. After Vandenbroucke (2010).

In addition, Ghienne et al. (2014) refined the timing of events in Gondwana during the Hirnantian glaciation proposing sequence stratigraphic correlations between the Anti-Atlas, Morocco (Gondwana) and sections on the Anticosti Island, Canada (Laurentia). This study considers three main Late Ordovician Glacial Cycles (LOGC 1, LOGC 2, and LOGC 3, Fig. 1.8) and multiple higher order cycles, suggesting a non-unique, Cenozoic-style, glaciation for the Hirnantian. It is clear that the Ordovician was not the long-assumed greenhouse state previously described (Brenchley et al., 1994, 2003), and that the Hirnantian is rather to be considered as the maximum expression of the EPI (Early Palaeozoic Icehouse) (Page et al., 2007).

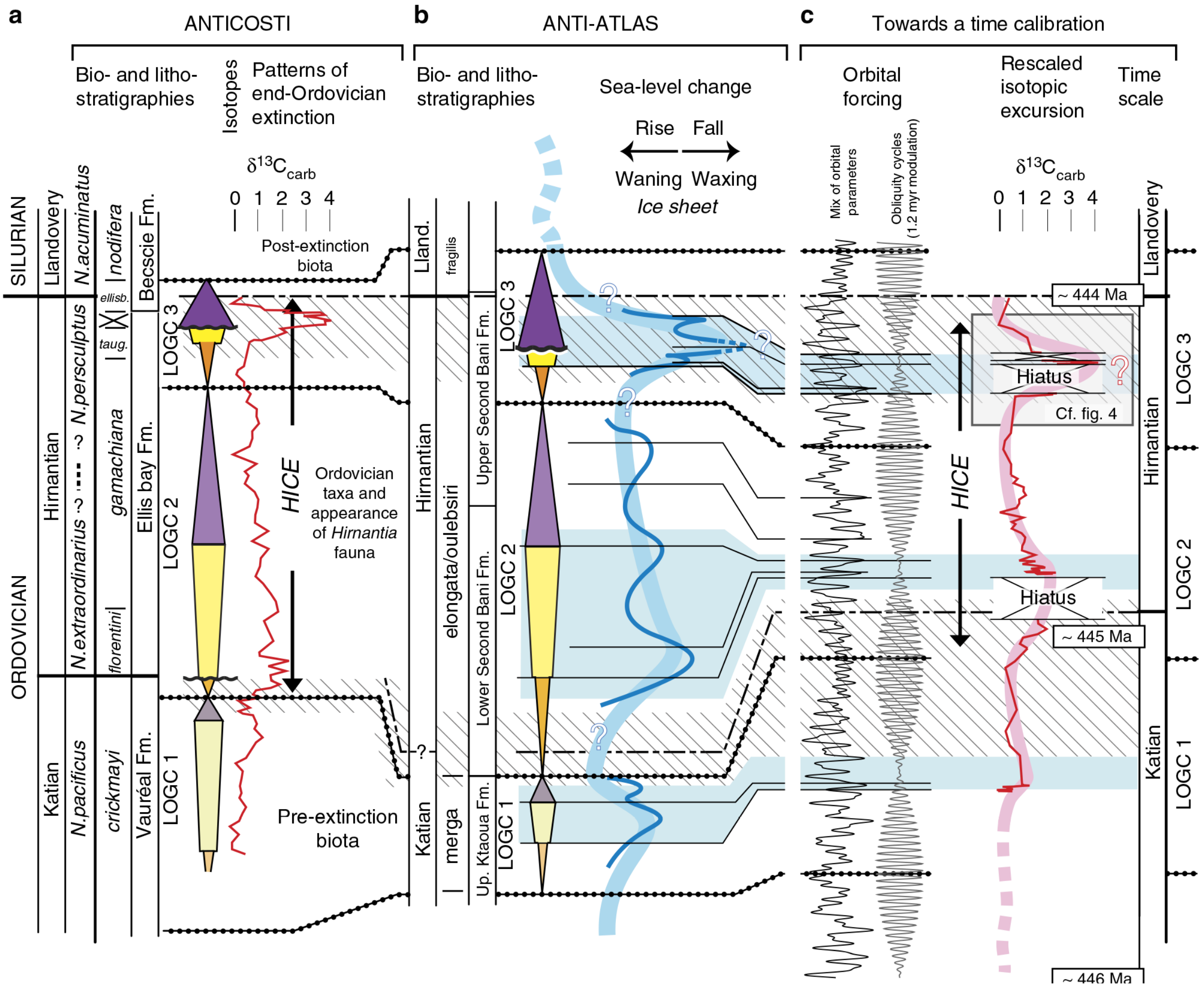

Fig. 1.8. Perspective of sequence sratigraphy. (a) Anticosti Island succession, (b) Anti-Atlas succession, (c) representation of a potential time calibration. Cycle hierarchy distinguishes LOGC1-3 (low-order, high-significance Late Ordovician Glacial Cycles represented by both coloured triangles and the thick, pale blue curve) from high-order cycles (thin, sark blue curve). LOGCs are bounded by major MFS (dotted lines). Blue shading highlights time intervals specifically characterized, or thought to be characterized by ice-sheet development stage. The dashed blue curve is a representation of the early Silurian eustatic background. Black, dashed lines are the inferred Katian to Hirnantian and Hirnantian to Llandovery boundaries. The dashed pink curve is a representation of the Katian isotopic background. After Ghienne et al. (2014).

3. Chitinozoans

The present PhD work is focused mainly on the study of a palynomorph group, the chitinozoans, which are an extinct group of organic-walled microfossils (Eisenack, 1931; Paris, 1996, 2006; Nolvak & Grahn, 1993; Grahn & Paris, 2010). The earliest known species appeared in the Early Ordovician (Tremadocian), and the group became extinct at the end of the Devonian (Webby et al., 2004). Ordovician chitinozoans have been reported from all continents, except Antarctica (see references in Miller, 1996; Paris, 1996). The chitinozoans are reported from most types of Ordovician marine sediments. However, their occurrence and preservation can be affected by high-energy hydrodynamic regimes, weathering, and medium- to high-grade metamorphism. Paris and Nõlvak (1999) postulated that chitinozoans are eggs of soft-bodied marine metazoans (Fig. 1.9) and consequently they can be used to document the biodiversification of their unknown producers. Chitinozoans diversified rapidly throughout the Ordovician Period (Fig. 1.10), even if the total generic and specific diversity is considered to be low. Only a few genera per sample are normally found, and the species rarely exceed 10 species on each sample. The abundance of chitinozoans, however, ranges from several hundred to a few thousand specimens per gram of rock for regions occupying high palaeolatitudes (e.g. Gondwana). Despite their inferred pelagic mode of distribution, chitinozoans display a definite provincialism during the Ordovician (Paris, 1981; Achab, 1991; Webby et al., 2004; Vandenbroucke et al., 2010).

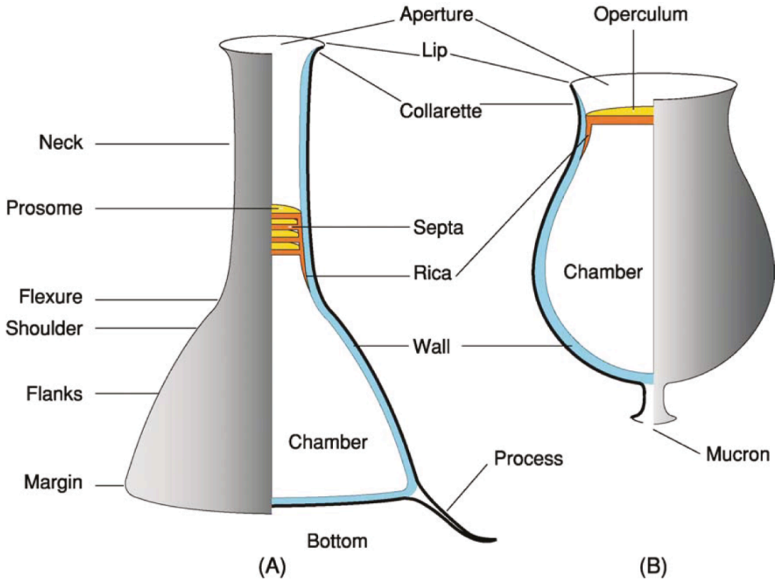

Fig. 1.9. Chitinozoan morphology and characteristics. After Paris (2006).

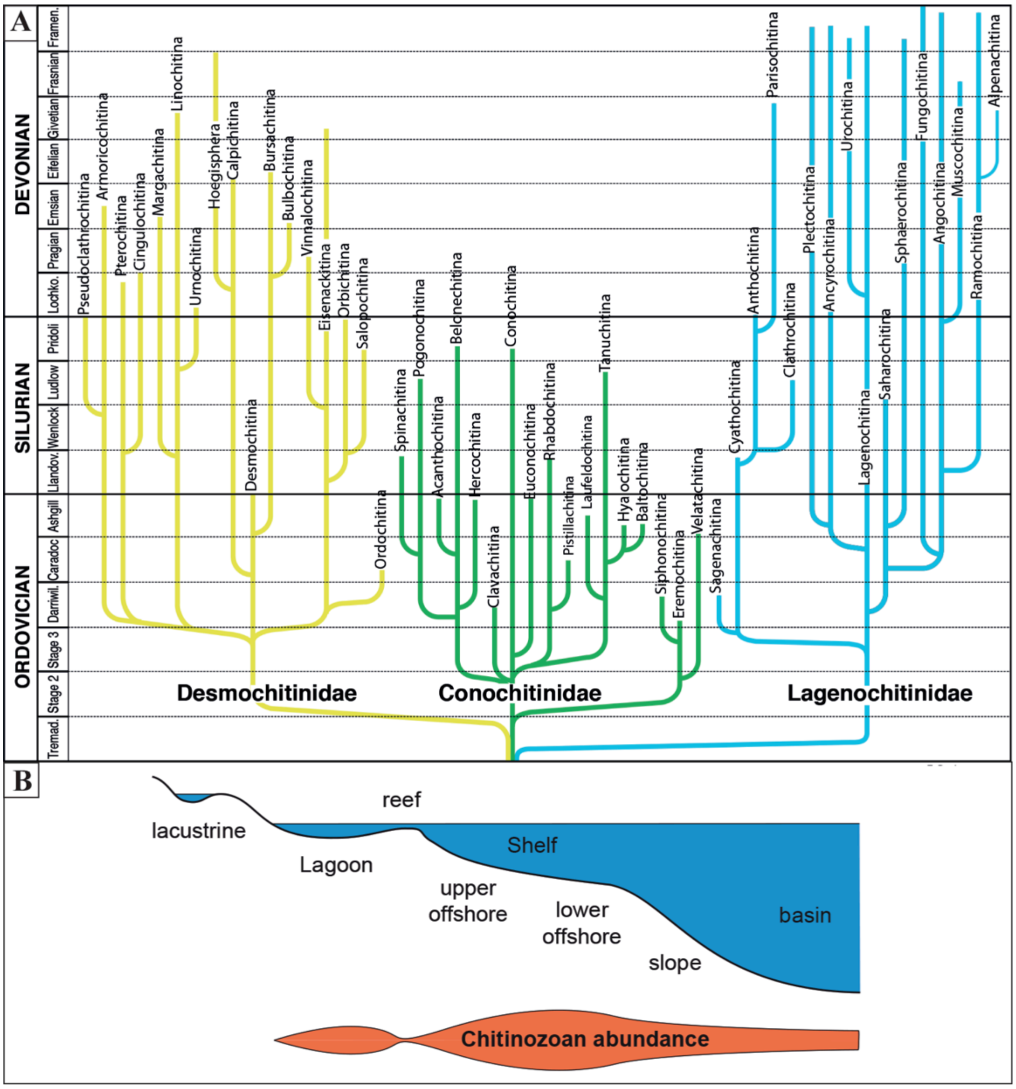

Fig. 1.10. Chitinozoans through time and space. **A** Distribution of chitinozoan groups from their appearance to their extinction; **B** Chitinozoan abundance on the shelf's deep. After Paris, (2006).

3.1 Regional Biodiversity – 'North' Gondwana

'North' Gondwana as mentioned above included the present-day northern Africa, the Middle East, and the southern part of Europe. Most of the Ordovician sequences investigated in these regions (Paris, 1998 and references therein) correspond to nearshore to outer-shelf environments at high or very high palaelatitudes during most of the Ordovician. According to Paris et al. (1995, 2000a), the Hirnantian glaciation, due to its erosive action, greatly affected the records of Ordovician chitinozoans in 'North' Gondwana. Recent works highlighted one of the effects of the erosion action, which is the reworking process of the chitinozoans (Paris et al., 2007, 2015).

The specific diversity of the 'North' Gondwanan Ordovician chitinozoans is fairly low when compared with those of other palaeoplates. In contrast, their abundance is much higher than on other palaeoplates. Meaningfully, chitinozoans display distribution patterns similar to those of modern pelagic marine fauna (Fig. 1.10, B), that is, low diversity but with high productivity in areas located at high latitudes (cold environment). A global chitinozoan biozonation has been created by Paris (2006) (Fig. 1.11) and it is constantly improved by more recent studies. Transgressions processes also seem to have had a positive impact on the diversity of chitinozoans. This is probably due to more open communication with Baltica. This is suggested by the occurrence of several typical Baltic species in the 'North' Gondwanan regions. The main transgressions registered in most of these regions are associated with increased chitinozoan originations.

The global BTD (balanced total diversity) curve is represented as a continuous diversification of the group from the early Tremadocian to a first peak in the late Darriwilian and then a short-lived lowering of diversity (Fig. 1.4). A second maximum diversification followed in the late Caradoc and then decreased progressively until the end of the Ordovician. The most dramatic extinction event occurs in the latest Ashgill.

The high biodiversity levels are not systematically synchrononous with the origination events and low diversity is not always related to extinction events. Each of these parameters must be shown separately in order to indicate more clearly the biodiversification patterns of the chitinozoans.

The differences observed between the regional and global curves highlight the existence of numerous levels of changes in the chitinozoan diversity during the Ordovician. The first-order trends are recorded in both the regional and the global curves, whereas the second-order trends are documented only regionally in one or two palaeoplates.

3.1.1 First-order features

The major feature of the chitinozoan diversification during the Ordovician is the radiation beginning in the Tremadocian (cf. Fig. 1.6) and a rather regular diversification up to the latest Darriwilian. Probably stable climatic conditions during the Early and Mid Ordovician and a large selection of niches available for pelagic organisms such as the "chitinozoan animals" have favored the radiation. The chitinozoan diversity declined during the Late Ordovician and was associated with the dramatic extinction event in the Hirnantian. It is noteworthy that the general decline is recorded in a pre-Hirnantian time interval (probably Ashgill) and it is not rigorously associated to the extinction *sensu stricto*. The Hirnantian crisis is simultaneous with a multi-cycle glaciation of the first magnitude. The glaciation is linked to a drastic fall in temperature and drop in sea level. However, the possible causes for the global change could be related to an increased of volcanic activity or a raised CO_2 levels. Nevertheless, this is not an explanation for the progressive global dropping of chitinozoan diversity through the Late Ordovician that remains uncertain.

3.1.2 Second-order features

The Second-order features are characterized by the large marine transgressions that are also believed to have increased chitinozoan diversity and/or preservation. Indeed, these favorite argillaceaous sedimentation facies, in a more distal environment, are suitable for the preservation and the registration of chitinozoans (Webby et al., 2004).

The most recent chitinozoan zonation (Paris et al., 2000; Achab and Paris, 2006) distinguishes 25 chitinozoan biozones within the Ordovician of the northern Gondwana margins. Paris et al. (1999, 2000) worked in detail on the northern Gonwana margin and defined the upper Katian and Hirnantian biozones characterizing the Ordovicican nothern Africa chitinozoans. These biozones have been defined thanks to the FADs of the index species. According to Paris et al. (1999, 2000), a biozone from the upper Katian is the *merga* Biozone, and then the two others are found in the Hirnantian, which are *elongata* and *oulebsiri* (in ascending order). These biozones have been determined in absence of a graptolitic control and this is one of the main causes of the uncertainty calibration of the biozones against the chronostratigraphy and the graptolites biozones.

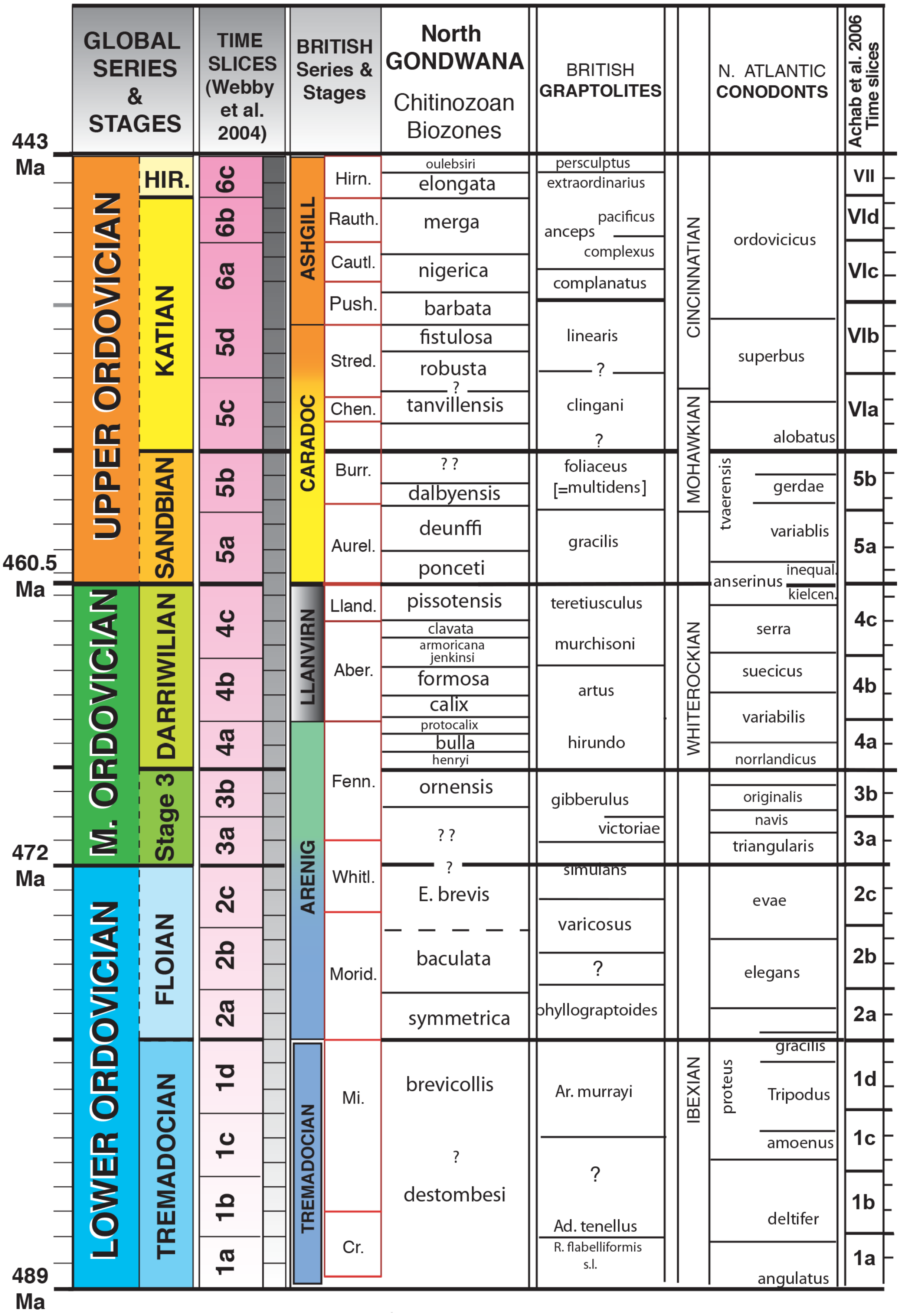

Fig. 1.11. Ordovician chitinozoan biozones for northern Gondwana and age assignment. After Paris (2006).

4. Outline of the manuscript

Following this overview, the PhD volume is divided into three main chapters that correspond to the three studied areas.

- In Chapter II is presented the study from the Central and Eastern Anti-Atlas, Southern Morocco, an ice-proximal area during the end-Ordovician glaciation. The work is focused on the chitinozoan biostratigraphy and local, regional, and global preliminary correlations are proposed.
- In Chapter III, the Northern Morocco domain (ice-distal area) is presented, with the study of the Tazekka Massif on palynological and geochemical points of view. The study of chitinozoan and of $\delta^{13}C_{org}$ permitted to refine the temporal framework. Additionally a local, regional, and global correlation is shown and discussed.
- In Chapter IV, a relatively low-palaeolatitude area is presented. The study of palynomorphs (chitinozoans) in the Wangjiawan Riverside section, South China revealed the possibility to draw preliminary worldwide correlations during the Hirnantian.

Finally, the main conclusions and perspectives of this thesis constitute a fifth chapter.

CHAPTER II

THE RECORD OF END-ORDOVICIAN GLACIAL AND FAUNAL EVENTS IN THE CENTRAL ANTI-ATLAS (SOUTHERN MOROCCO):

THE CHITINOZOAN CASE

Preamble

In chapter 2, chitinozoan distribution of the Central Anti-Atlas, southern Morocco, is investigated. This location reports on a very ice-marginal, pro- to sub-glacial position with restricted marine environments during the end-Ordovician glacial maximum, yet ‘normal’ shelf environments characterize most of the Hirnantian prior to the glaciation acme. The Anti-Atlas was an essential study area in addition to the to the key area (Tazekka Massif, Chapter 3) in the framework of the SeqStrat-Ice project, as it includes the end-Ordovician type section (Bou Ingarf section, Bourahrouh et al., 2004; Loi et al., 2010). This is why the Anti-Atlas record is first presented. The reason for studying the microfauna of this basin is to see its distribution, ecological niches and significance, etc., at a basin-scale and more specifically through the Katian-Hirnantian boundary. It will be shown that the chitinozoans of the Central and Eastern Anti-Atlas have the potential to clarify stratigraphic relationships between southern, central, northern, and eastern sectors of the Anti-Atlas, and especially to date part of the incision infills —and incision formation— present in the northeastern part.

This chapter is written as a usual thesis’ chapter and it will develop into a publication in the near future. The publication will involve some other members of the SeqStrat-Ice project. Section and figure numbering are kept in line with preceding and following chapters of this thesis.

2.1 Introduction

The end-Ordovician glaciation is well known for providing the backdrop of the penecontemporaneous mass extinction(s) (Melchin et al., 2013; Ghienne et al., 2014) though a general agreement about a “cause and effect” scenario is currently not available (Finnegan et al., 2016). According to Finnegan et al. (2016), previous studies of the Late Ordovician Mass Extinction have implicated two major drivers of the extinction: first a leakage of species inhabiting shallow cratonic seaways that drained as Gondwanan glaciers grew, occurring just below the *Normalograptus extraordinarius* graptolite Zone (Brenchley, 1984; Brenchley et al., 2006), and second, within the *Normalograptus persculptus* graptolite Zone, a loss of species with narrow and/or relatively warm thermal tolerance ranges as the polar front advanced and the latitudinal temperature gradient steepened (Vandenbroucke et al., 2010, Finnegan et al., 2012; Harper et al., 2014). The Late Ordovician–Early Silurian climatic events looks as well to have been associated with major changes in oceanographic circulation, productivity and oxygenation of outer shelf and slope settings (Brenchley et al., 1994; Hammarlund et al., 2012). The changes in oxygenation have been suggested as a major additional agent of the extinction event, particularly for taxa with planktonic life stages (Chatterton et al., 1989; Finney et al., 1999; Xu et al., 2005; Melchin et al., 2013, Vandenbroucke et al., 2015). Additionally, a widespread transgression due to the melting ice cap is also considered as one of the causes of the extinction.

The Anti-Atlas in southern Morocco is one of the rare places in western Gondwana where extensive archives do exist and offers both a profuse faunal record and a glacial record (Destombes, 1968 a&b, Destombes et al., 1985; Sutcliffe et al., 2001; Villas et al., 2006; Loi et al., 2010; Ghienne et al., 2014). Here, a high-palaeolatitude, actively subsiding basin at the Northwest edge (present-day coordinates) of the Gondwana resulted in a thick (1000-2000 m), siliciclastic Ordovician succession; this constitutes the only end-Ordovician interval (latest Katian – Hirnantian) being represented by a more than 500 m pile of alternating fine-grained sediments (mudstones), condensed horizons and sandstones. Because the end-Ordovician glaciers did not reach the basinal area before the middle to late Hirnantian (Destombes, 1968; Ghienne et al., 2014), the Katian-Hirnantian time interval is here largely represented, having escaped ensuing glacial erosions in most places owing to the previously deposited thick lower Hirnantian strata.

In Chapter 2, we focus on the end-Ordovician chitinozoan record predating the glaciation of the Anti-Atlas, yet limited data also help in deciphering the stratigraphic architecture of the glacial record itself. According to the conventional chitinozoan biostratigraphy, this time interval corresponds to the *merga* and *elongata* chitinozoan biozones (Paris, 1990, 2006; Paris et al., 2000; Bourahrouh et al., 2004; Webby et al., 2004; Vandenbroucke et al., 2009), their interface generally parallelised with the Katian-Hirnantian boundary, though any formal calibration against a detailed graptolitic record is directly available (cf. Fig. 1.11; see also chapter 3, Fig. 3.7).

Paradoxically, from a chitinozoan perspective, no patent signal for an end-Ordovician mass extinction is available (Bouhrarouh et al., 2004; Achab & Paris, 2007). As an extension of the work of Bourahrouh et al. (2004), that extensively studied the Bou Ingarf type section (see also, Loi et al., 2010), we decided to explore specifically this *merga-elongata* boundary in several sections that will offer a vision on the chitinozoan distribution through time and space at basin scale, potentially contrasting the basin axis record (the Bou Ingarf section) with that of basin-edge areas. Questions addressed in this study are for example: Are we able to trace a basin-scale migration of chitinozoan assemblage driven by the glacio-eustatically driven sea-level changes? By comparison with neighbouring areas, are we able to fairly position the Katian-Hirnantian boundary? Is chitinozoan reworking during lowstand events widely detectable or only accidental (e.g., Paris et al., 2015)? In other words, can we take advantage of the widespread distribution of chitinozoans in clastic successions to proposed a refined scenario through the Katian-Hirnantian boundary and during the immediately overlying “lower Hirnantian”, a puzzling time interval marked by a major transgression and retrogradation of the facies belts, which is however paradoxically viewed as the onset of the end-Ordovician. So doing, the study of chitinozoan assemblages added some biostratigraphic constrains, allowing enigmatic stratigraphic units such as the Erfoud limestones, sometimes understood as the reflect of the Boda event, or large-scale, turbiditic incision infills to be repositioned in the regional-scale stratigraphic scheme.

2.2 The Anti-Atlas in the end-Ordovician

2.2.1 Geological setting

The end-Ordovician record of the Anti-Atlas is part of an up to 5 km thick Palaeozoic succession preserved on the northern limb of the Tindouf Basin, an epicontinental basin characterizing the northern part of the West African Craton (Fig. 2.1; Destombes et al., 1985;

Boote et al., 1998; Burkhard et al., 2006). It was folded during the Hercynian orogeny and currently offers a world-class record of predominantly shallow-marine Cambrian to Carboniferous depositional sequences.

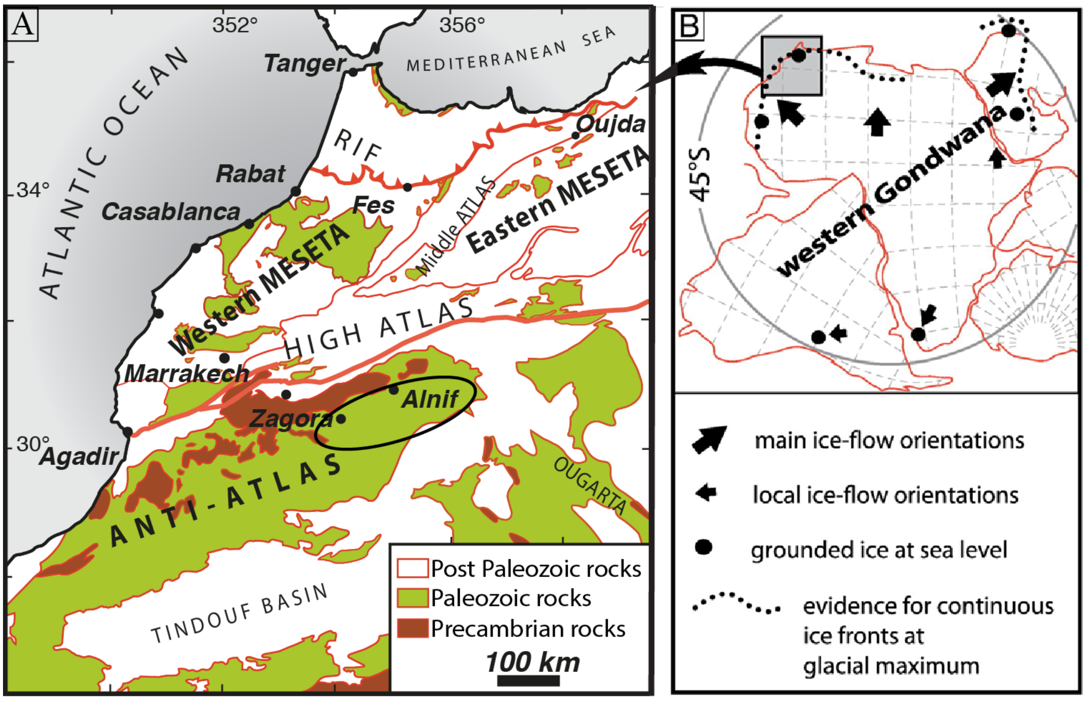

Fig. 2.1 A) Location of the study area, Central Anti-Atlas, southern Morocco (modified after Michard et al., 2008). B) Palaeogeographic and palaeoglacial setting of the study area during the Hirnantian (modified after Ghienne et al., 2007).

The Central Anti-Atlas was the location of a particularly active depocenter known as the Tagounite Trough (Destombes et al., 1985), which essentially individualized in the Late Ordovician. At the NW-SE oriented basin axis, the Ordovician succession is dominated by shallow-marine siliciclastic deposits and is up to 2 km in thickness (Fig. 2.2). During the latest Ordovician, offshore shales prevailed in the basin (Bou Ingarf/Tazzarine area; Loi et al., 2010). They graded laterally at basin edge, toward the SW and the NE into shoreface to tidal facies, which migrated basinward during regressive events. The Tagounite Trough therefore received clastics from various origins: from the SW (Rguibat Shield), from the SE via the Ougarta and Daoura depocenters in Algeria (Legrand, 1985; Ghienne et al., 2007), and from the NE or possibly even from the NNE, where a palaeohigh occurred in northwestern Algeria (Meddour, 2016).

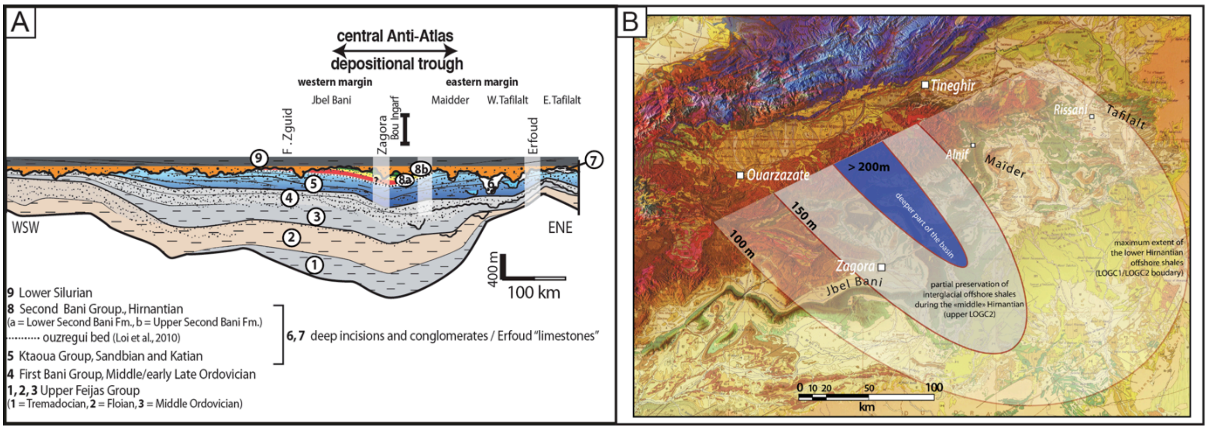

Fig. 2.2 The Tagounite Trough in the Anti-Atlas setting. (A) Generalized cross profile through the Ordovician strata of the Anti-Atlas (modified from Destombes et al., 1985; Burkhard et al., 2006; Ghienne et al., 2014); (B) Tentative map view of the Tagounite Trough.

2.2.2 Palaeoglacial setting

Hirnantian glacial strata have been formally identified and dated in the Anti-Atlas by J. Destombes at the end of the sixties (Destombes, 1968 a&b). No evidence for glaciers is available in the Anti-Atlas in the lower part of the Hirnantian record, suggesting that ice fronts did not reach southern Morocco before the middle to late Hirnantian (Destombes et al., 1985; Bourahrouh et al., 2004; Loi et al., 2010; Ghienne et al., 2014). It should be noted that in the absence of a formal subdivision of the Hirnantian, lower, middle and upper Hirnantian subdivisions are here relative to the sediment pile, rather than to a formal temporal calibration. According to Loi et al. (2010), most of the 1-2 Myrs of the Hirnantian time interval however occurred before the glaciation of the Anti-Atlas. In other words, the glacial record in the Anti-Atlas would be very short, solely corresponding to the acme of the end-Ordovician glaciation, when the ice sheet reached the Gondwana continental margin (Ghienne et al., 2007, 2014; Le Heron and Craig, 2008).

In the Anti-Atlas, the glacial record includes soft sediment subglacial shear zones, glaciomarine diamictites, glaciotectonic fold and thrust belts, tunnel valleys, periglacial deformations, etc., as in other parts of northern Africa (Sutcliffe et al., 2001; Ghienne et al., 2007, 2014; Le Heron, 2007; Clerc et al., 2013; Nutz et al., 2013; Ravier et al., 2015). Fluvial, deltaic and turbiditic sandstones are also recognized, as well as intercalation of offshore shales. Glacial striations and palaeovalley orientations suggest ice flows from the SE or from the W to SW. At time, it is not clear if these directions represent synchronous trends associated with a single, fluctuating ice sheet or distinct flow patterns relative to successive, major ice-sheet advances (Ghienne et al., 2007, 2014).

2.2.3 Stratigraphic setting

The end-Ordovician time interval is represented by the Upper Ktaoua Fm. in the upper part of the Ktaoua Group (Late Katian, more or less the pre-Hirnantian Ashgill strata) and by the Second Bani Group, inferred to be Hirnantian in age (Fig. 2.3A; see below). In the axis of the Tagounite Trough, the boundary between the Ktaoua and Second Bani groups is generally highlighted by a distinctive marker bed in the uppermost upper Ktaoua Fm. It is referred to as the ouzregui bed in Loi et al. (2010), which correlate northward with a unit characterized by a specific macrofauna including brachiopods, trilobites, etc. that are useful for extra-regional (wide) correlation (Destombes et al., 1985; Hamman and Leone, 1997, 2007) (Fig. 2.3 B&D). The Second Bani Group is itself subdivided in the Lower and Upper Second Bani formations (Fig. 2.2), the former essentially corresponding to Hirnantian pre-glacial strata, the latter including syn-glaciation and latest Ordovician post-glacial strata (Fig. 2.3 A&E). Hirnantian pre-glacial strata include a basal interval of fine-grained shales, inferred to record a major, platform-wide transgression. The lower boundary of the Upper Second Bani Fm. is best understood[1] as the composite end-Ordovician glacial erosion surface (Fig. 2.3). Recent work by SeqStrat-Ice collaborators in the Tazzarine area, north of the Bou Ingarf section, was conducted to unravel the pre-glacial Hirnantian record. Three coarsening-upward and laterally continuous (>50 km) units, bounded by transgressive condensed horizons have been identified. From the base to the top, they are informally referred to as the red, yellow and green units (which could be identified as a lower, middle and upper members of the Lower Second Bani Group Fm., respectively) (Figs. 2.3 C&D, 2.4 & 2.5). It should be noted that in the Bou Ingarf section (Fig. 2.4; Loi et al., 2010) the green and the upper yellow units are not identified, at least in part eroded beneath the glacial erosion surface.

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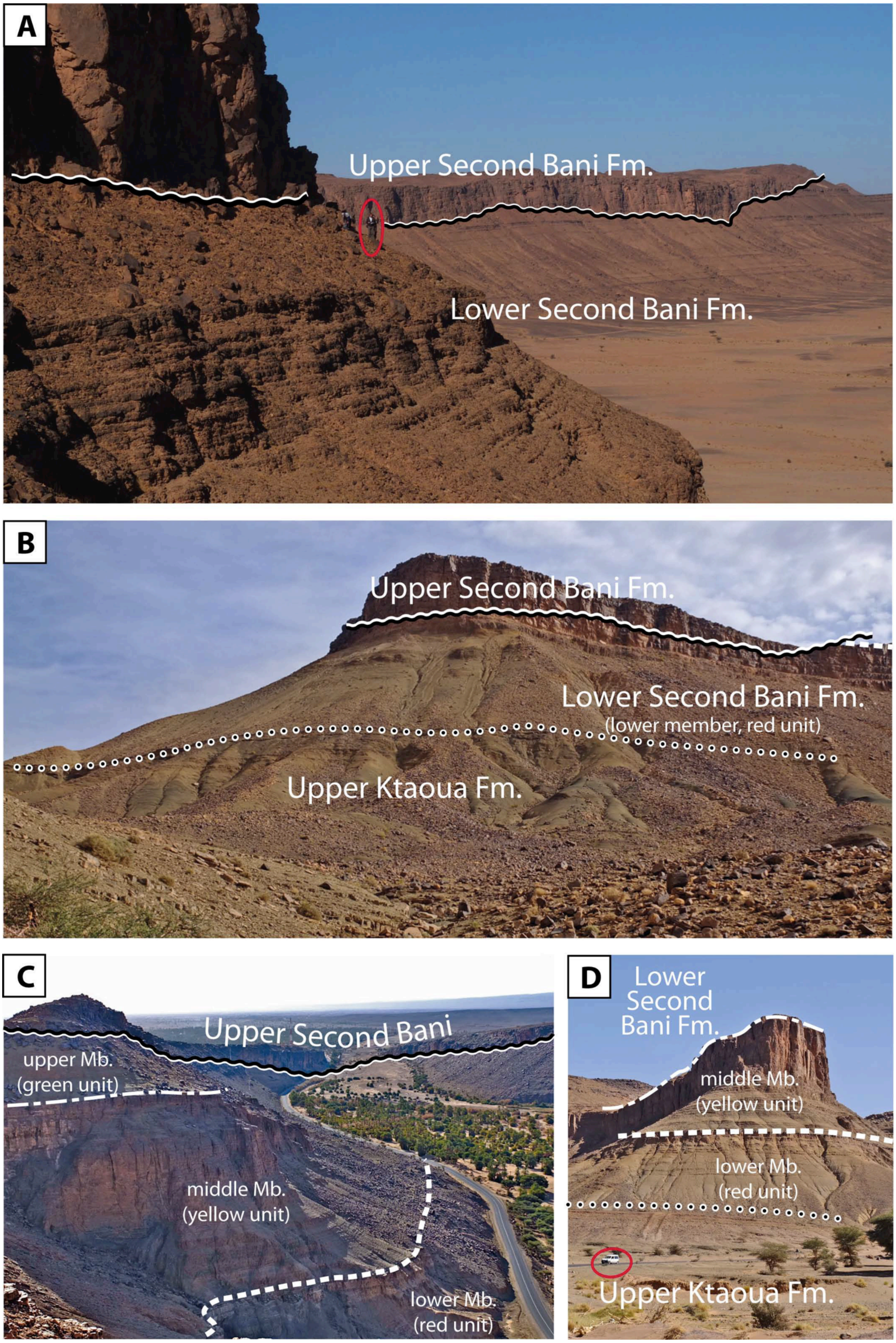
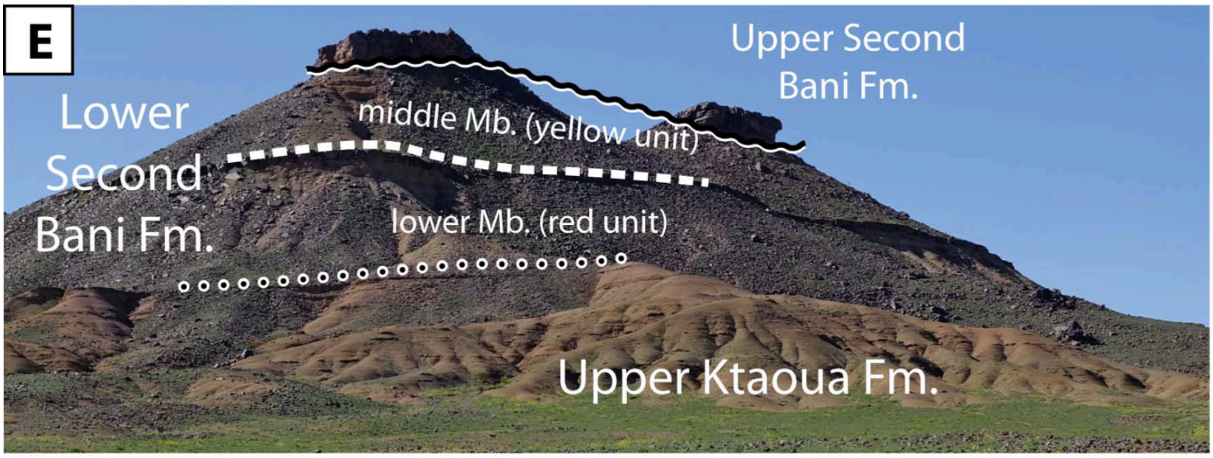
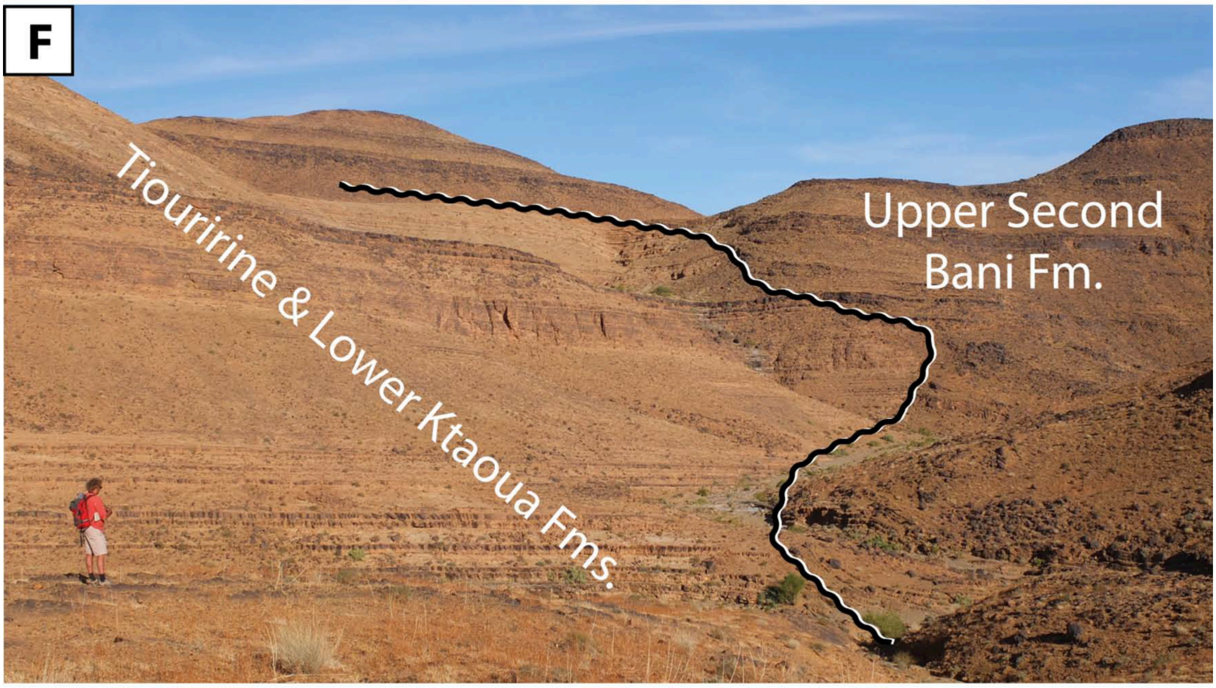
[1] This is in contrast with Loi et al., 2010, who positioned the boundary between the Lower and Upper Second Bani Fms at a major flooding surface (mid-Hirnantian interval in Ghienne et al., 2007), which was initially misunderstood as the glacial erosion surface (Bourahrouh et al., 2004), but which lies in fact significantly beneath the glacial erosion surface as demonstrated by recent work (Fig. 2.5).


A
Upper Second Bani Fm.
Lower Second Bani Fm.
B
Upper Second Bani Fm.
Lower Second Bani Fm.
(lower member, red unit)
Upper Ktaoua Fm.
C
Upper Second Bani
upper Mb.
(green unit)
middle Mb.
(yellow unit)
lower Mb.
(red unit)
D
Lower
Second
Bani Fm.
middle Mb.
(yellow unit)
lower Mb.
(red unit)
Upper Ktaoua Fm.


E
Lower
Second
Bani Fm.
middle Mb. (yellow unit)
lower Mb. (red unit)
Upper Second
Bani Fm.
Upper Ktaoua Fm.


F
Tiouririne & Lower Ktaoua Fms.
Upper Second
Bani Fm.

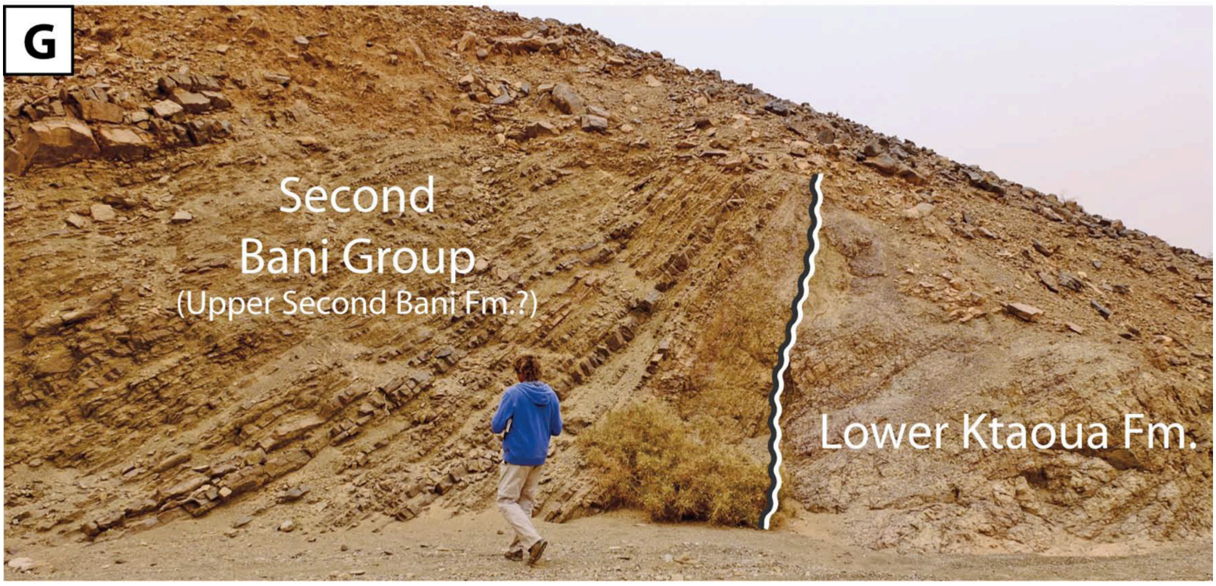

G
Second
Bani Group
(Upper Second Bani Fm.?)
Lower Ktaoua Fm.

Fig. 2.3 End-Ordovician strata of the Anti-Atlas, from the West to the East. (A) Erosional surface at the base of the Upper Second Bani Fm., truncating bioturbated sandstones of the Lower Second Bani Fm. nearby Tagounite, western part of the Central Anti-Atlas Basin (persons for scale). (B) The Bou Ingarf type section (Bourahrouh et al., 2004; Loi et al., 2010; Fig. 2.4) at the axis of the Central Anti-Atlas Basin. Only the lower Mb. of the Second Bani Fm. is here illustrated above the ouzregui Bed (dots); this segment of the end-Ordovician record is ascribed to a pre-glaciation —considering the Anti-Atlas—, "lower" Hirnantian time interval, yet including a major lowstand to transgressive sand wedge in its upper part. (C) The Second Bani Group in the Tazzarine area, with identification of the three members of the Lower Second Bani Fm. (Fig. 2.5) above the ouzregui Bed (dots), and bounded by flooding surfaces (dashes line). Note that the thick lowstand to transgressive sand wedge of the middle member is here reduced to thinly bedded sandstones and a condensed, Fe-rich horizon. Thickness of the middle member is c. 50 m. (D) Same place as in (C), showing the basal contact of the Second Bani Group above the Upper Ktaoua Fm.; the ouzregui Bed is here much thinner than in the Bou Ingarf section. (E) The Upper Ktaoua Fm. and Second Bani Group near Emin Bou M'Zur. The upper member of the Lower Second Bani Fm. has been eroded by the glacially related Upper Second Bani Fm. The middle member is thinner (c. 30 m) than in the Tazzarine area (D). (F) A sharp truncation surface at the base of an incision, cutting down to Middle Katian to Sandbian strata of the Lower Ktaoua Fm., north of Alnif. Sandstones of the Upper Second Bani Fm. are dominated by turbiditic deposits, but also include glaciogenics. (G) The base of a very deep incision in the Jbel Amessoui area (Fig. 2.7), truncating down to the lower part of the Lower Ktaoua Fm. (Sandbian). Overlying heterolitics yield a chitinozoan fauna of the *elongata* Biozone. Here, the entire Katian is missing.

This lithostratigraphic scheme is generally extrapolated toward basin edges, in the SW and in the NE. Destombes et al. (1985) recognized that the Lower Second Bani Fm. progressively disappeared in these two directions beneath the glacial erosion surface. Therefore, to the West of the Jbel Bani and in the Maïder and Tafilalt area, the Upper Second Bani Fm. superimposed directly the Upper Ktaoua Fm (Figs. 2.6 and 2.7). This pattern is a consequence of lesser subsidence rates rather than enhanced glacial erosion at basin edges. However, some difficulties arose when basin-edge successions have to be correlated with that of the Tagounite Trough at the basin axis, for which the Bou Ingarf section is representative (Bourahrouh et al., 2004).

West of the Draa River (Fig. 2.6) and associated Quaternary deposit, physical continuity is lost and the ouzregui bed is no longer a marker bed. Destombes et al. (1985) decided to parallelize the ouzregui bed with a bryozoan-bearing limy horizon marking the transition between an underlying shale succession and an overlying sandstone suite including a well-defined macrofauna. Such a correlation has suggested that the shales corresponded to the Ktaoua Fm. while the sandstones were ascribed to the Second Bani Group. Such a correlation has been questioned on the basis of chitinozoan biostratigraphy (Florentin Paris, pers. comm., in Ghienne et al., 2014).

Eastward, the relatively simple layer-cake stratigraphy that typifies the Tagounite Trough disappears. Instead, a succession of incisions and correlative infills occurred throughout the Upper Ordovician strata (Figs. 2.2, 2.3 F&G and 2.7; Meddour, 2016). Some of them are clearly positioned within the Ktaoua Group; others are tied to the base of the glaciation-related deposits. However, in the Tafilalt area, two additional occurrences of incisions are recognized, which the age and position within the regional stratigraphy are not straightforward. In the western Tafilalt, deep incisions, potentially in excess of 400 m, are identified (Razin et al., 2015). They are underlined by conglomerates and infilled by shallow-marine to turbiditic deposits, their initial infill being not related to any glacial depositional system. Razin et al. (2015) interpreted such incisions as canyons truncating the shelf in a continental margin setting. In the eastern Tafilalt, much shallower incisions (<75 m) are identified (Figs. 2.2 & 2.7). Interestingly, they are tied to the occurrence of the Erfoud Limestones (Destombes et al., 1985; El Maazouz and Hamoumi, 2007), the age of which is poorly constrained. They essentially correspond to two cross-bedded sandy units including a high concentration of reworked bryozoans, which are separated by presence of shaly horizon including bryozoans-rich horizons in living position (Meddour, 2016 pp. 191-213). Caradoc to Ashgill ages have been proposed, and a link with the Boda Event has been suggested by analogy with other North-Gondwanan comparable units recognized in Spain (Urbana Limestone), Sardinia (Iglesiente), Austria (Carnic Alps) or Libya (Tripolitaine).

Uppermost Ordovician, post-glaciation strata are most often sandstones throughout the Anti-Atlas. Some of them include a *Hirnantia* Fauna (Destombes et al., 1985; Sutcliffe et al., 2001), which represents a postglacial recovery distinct from the earlier *Hirnantia* Fauna that predates the occurrence of glacial surfaces. They are however devoid of fine-grained, chitinozoan-bearing horizons, possibly with one exception (sample TVDB 13-021, Fig. 2.4). Overlying thin, sandstone-dominated transgressive units, Silurian strata are characterized by bioturbated siltstones and black shales, yet a severe stratigraphic hiatus is usually identified, the lowest graptolite-rich shales being late Llandovery in age (Destombes et al., 1985; Luning et al., 2000; Nutz et al., 2013). Notable exceptions are the western Anti-Atlas and a single underfilled incision in the western Tafilalt, where lowermost Silurian (Rhuddanian) deposits are identified (Destombes et al., 1985; Willefert et al., 1988).

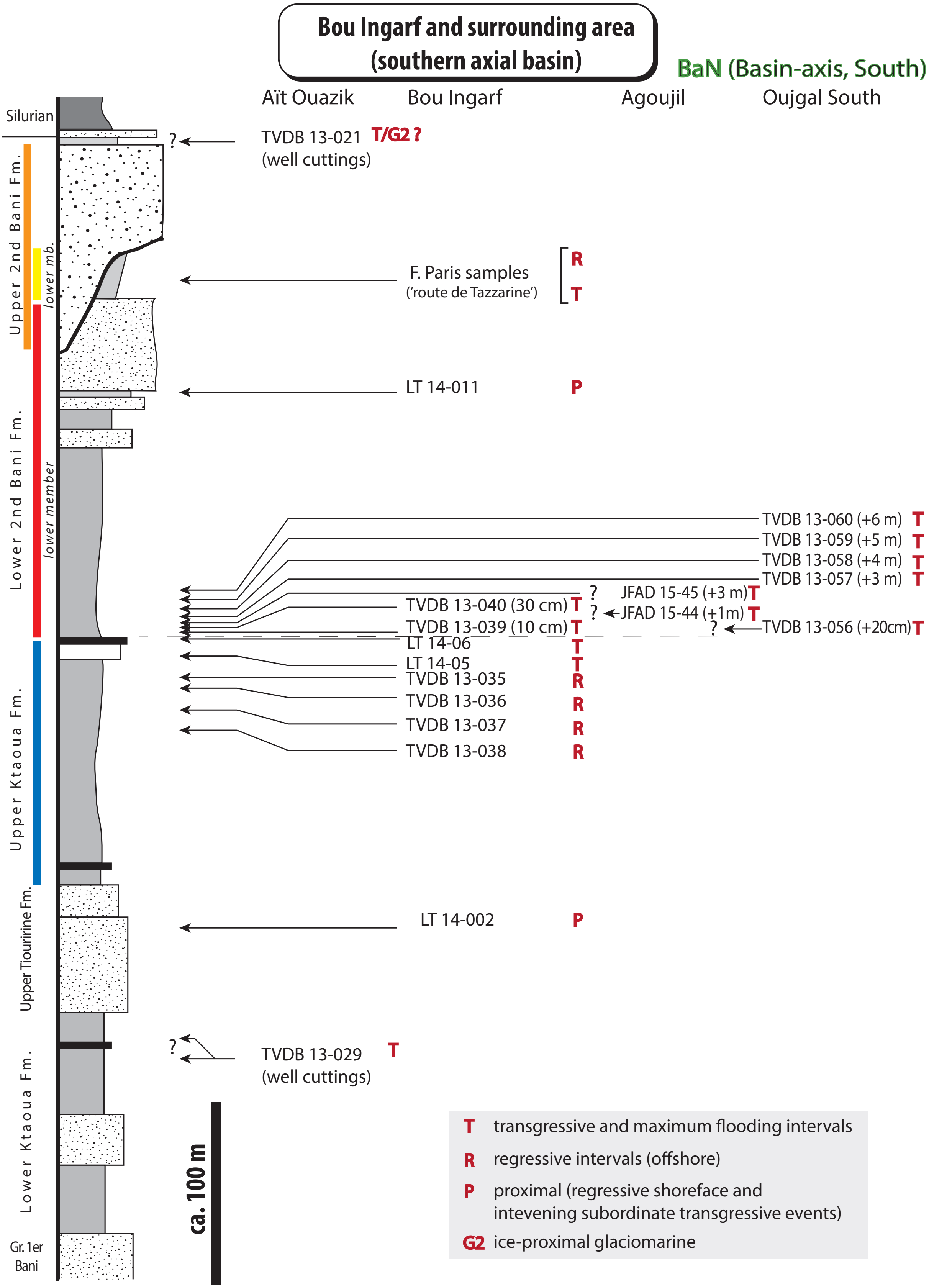


Fig. 2.4 Synthetic stratigraphy and sample distribution in the southern axial basin (Bou Ingarf area and surroundings). Selection of best samples placed on the synthetic section following their location sampling (Aït Ouazik, Bou Ingarf, Agoujil, and Oujgal South).

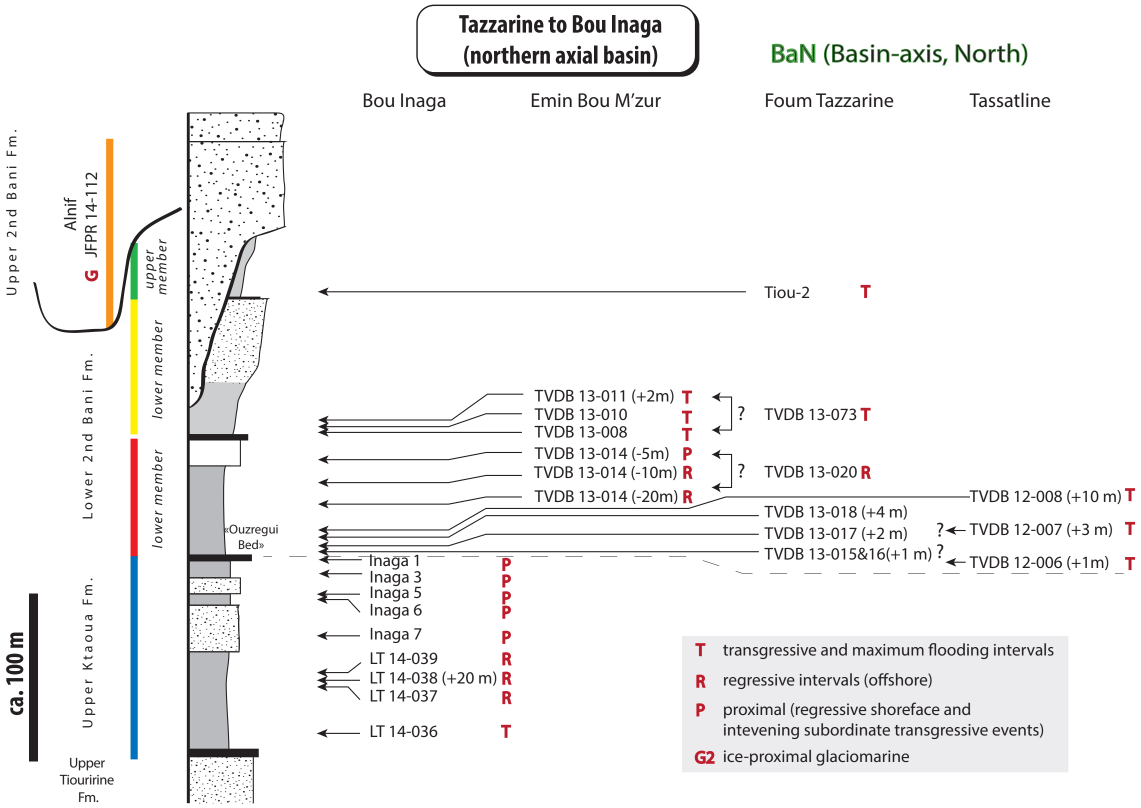


Fig. 2.5 Synthetic stratigraphy and sample distribution in the northern axial basin (Tazzarine area to Bou Inaga). Selection of best samples placed on the synthetic section following their location sampling (Bou Inaga, Emin Bou M'Zur, Foum Tazzarine, and Tassatline).

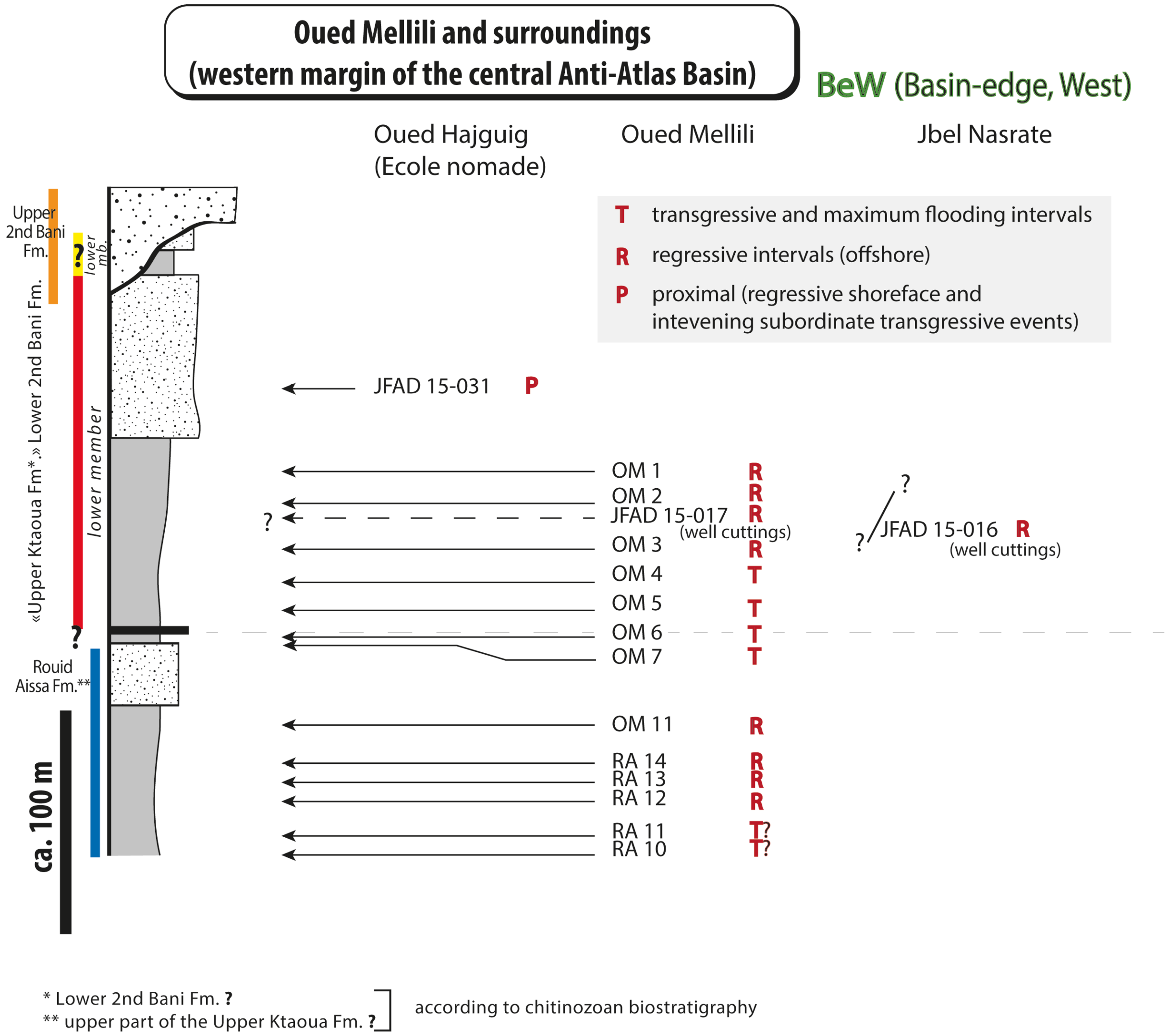


Fig. 2.6 Synthetic stratigraphy and sample distribution at the western edge of the Central Anti-Atlas basin (Oued Mellili area and surroundings). Selection of best samples placed on the synthetic section following their location sampling (Oued Hajguig (Ecole Nomade), Oued Mellili, Jbel Nasrate).

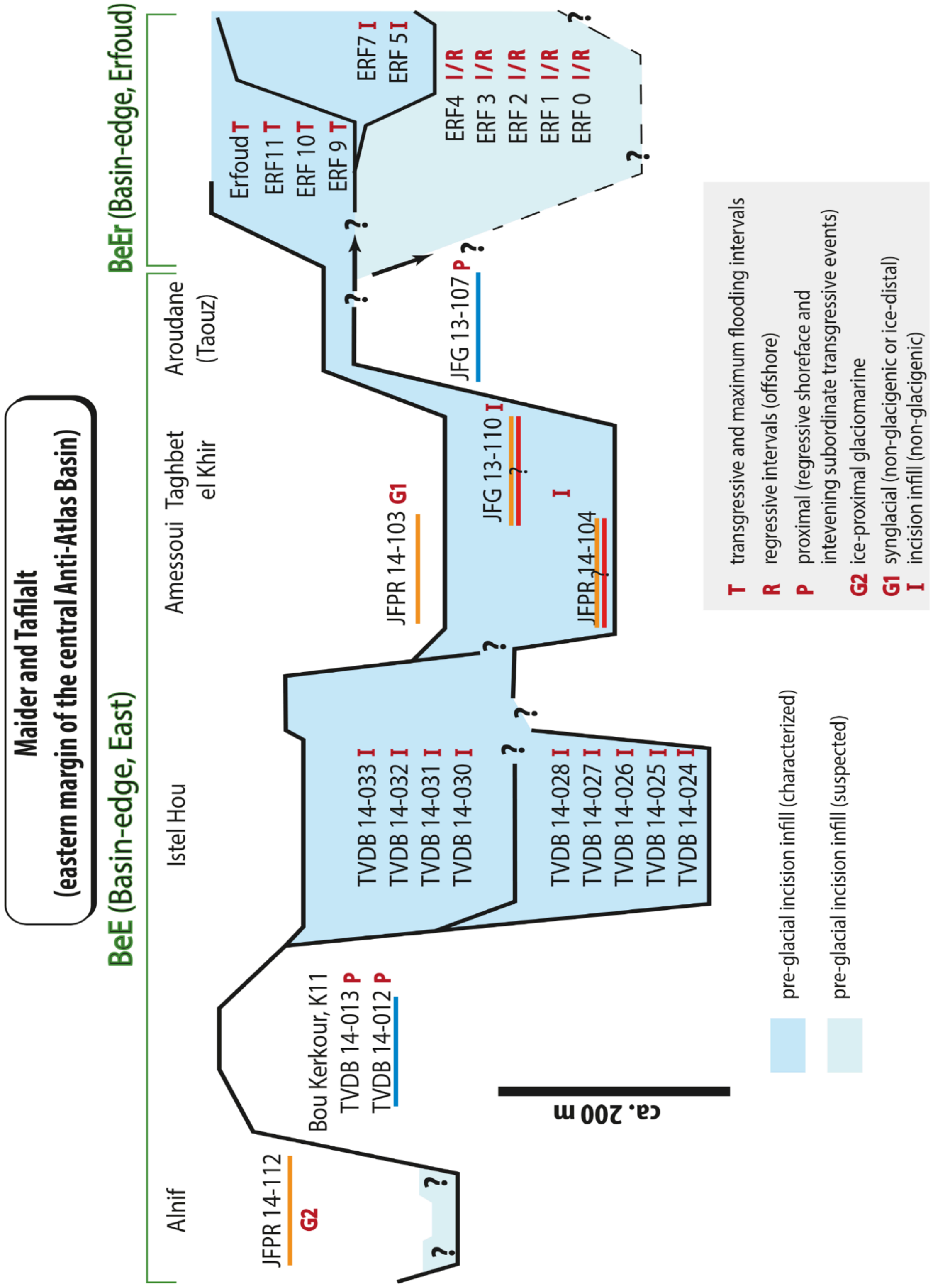


Fig. 2.7 Sample and incision distributions at the eastern edge of the Central Anti-Atlas basin, up to the Erfoud limestones (Maïder and Tafilalt). Selection of best samples placed on the synthetic section following their location sampling (Alnif, Bou Kerkour, Istel Hou, Amessoui, Taghbet el Khir, Aroudane (Taouz), and Erfoud). Blue, orange, and red corresponding to the different units defined in the other 3 regions of the Anti-Atlas basin.

2.2.4 Studied material and methods

Sample locations. A total of 166 samples from 26 localities (Fig. 2.8) were analysed and studied in detail for palynomorphs (mainly chitinozoans), amongst which 114 samples yielded 13,089 chitinozoans. Most of them were taken from the Upper Ktaoua and Lower Second Bani formations in central Tagounite Trough; other samples coming from the western and eastern margins of the basins. For sake of clarity, we divided the about 300 km of sections into 3 large areas (Figs. 2.2, 2.8): The Tagounite Trough axis, i.e. the centre of the Central Anti-Atlas basin, further subdivided into (i) a southern (Bou Ingarf and surroundings) part and (ii) a northern (Tazzarine to Bou Inaga) part, (iii) the western edge of the Central Anti-Atlas basin (Oued Mellili and surroundings), and (iv) the eastern edge of the Central Anti-Atlas basin (Maïder and Tafilalt), up to the Erfoud Limestones, and including several poorly dated incision. Stratigrahic distributions of the samples that provided valuable information are given along 4 synthetic sections (Figs. 2.4 to 2.7).

The samples were taken at a field-depth of few decimetres (when possible) or in well cuttings in order to avoid highly weathered material and debris of wells. A large amount of the organic-walled microfossils are flattened, except those extracted from calcareous or phosphatic samples. Nevertheless, in general the chitinozoans can be identified at species level (see Plates I-V). The description of the chitinozoan fauna for each area will help to the general overview of the chitinozoan distribution in the Anti-Atlas through space and time.

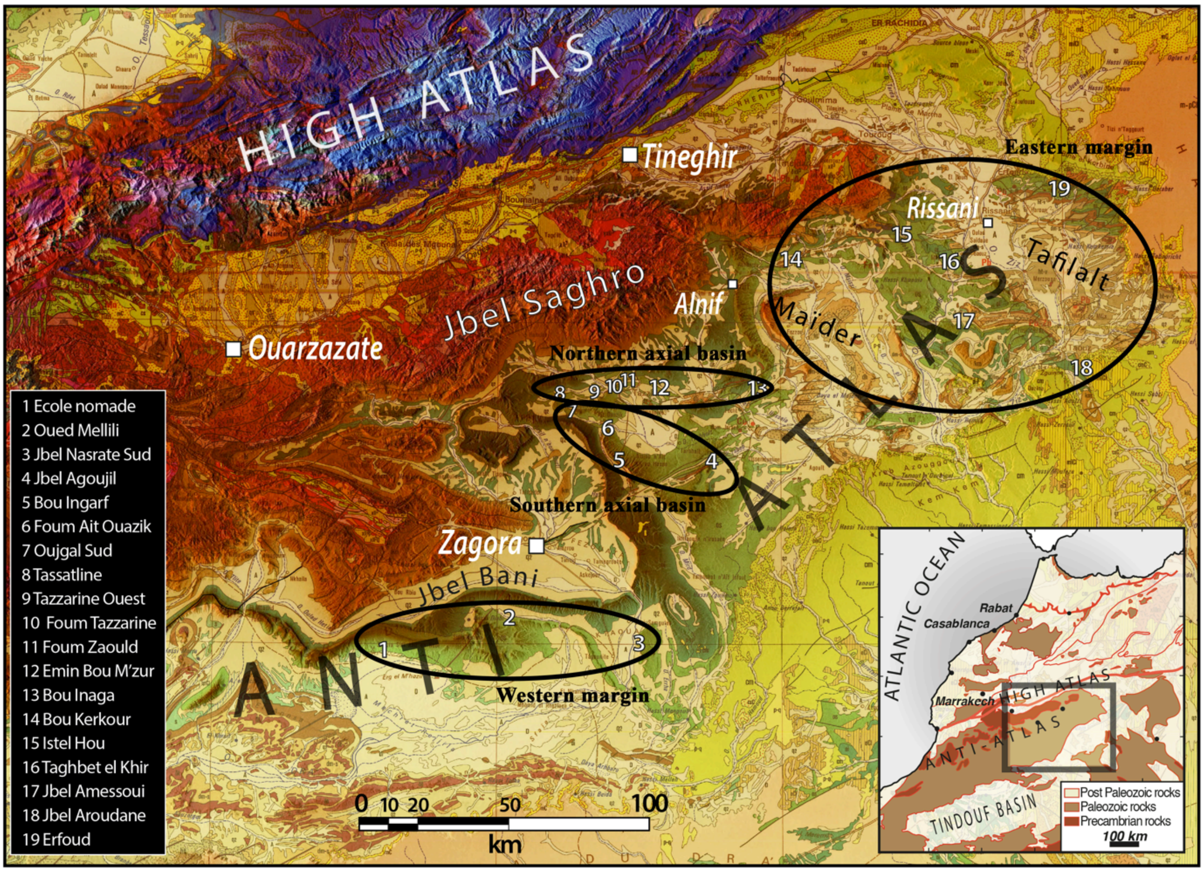


Fig. 2.8 Map of studied localities and the four main areas (Western margin, Southern axial basin, Northern axial basin, and Eastern margin).

Palynological preparation. All samples have been processed for the palynological analyses at the University of Lille (France). Depending on the available rock sample size, we used c. 40g of rock for the black shales and c. 100g for the calcareous or phosphatic samples. The analytical protocol comprises crushing the rock samples into 0.5 cm pieces followed by a first acid treatment with 38% HCl over 24h. Afterwards, the residue is washed with demineralized water, and subject to a second acid treatment with c. 200 ml 40-45% HF, while being agitated during 12h to 24h. Subsequently, the residues are treated once again with warm 38% HCl to remove any newly formed F-compounds. Finally, the samples are neutralized and filtered at 51µm. The residues on the filters were handpicked using a binocular microscope at 32-63 times magnification, and then studied with a FEI Quanta 200 and LEO 435VP Scanning Electron Microscope (SEM).

2.3 Chitinozoan biostratigraphy

The Global Ordovician terminology in series and stages is used here for the description of the chitinozoan assemblages of the Anti-Atlas. According to Bourahrouh et al. (2004), the biostratigraphic subdivisions identified in the Upper Ordovician succession in the Central Anti-Atlas are referred to the northern Gondwana chitinozoans biozones established by Paris (1990) and later completed (Paris et al., 2000) by data from several other regions such as Mauritania (Paris et al., 1998), Algeria (Oulebsir and Paris, 1995; Paris et al., 2000a), and Saudi Arabia (Paris et al., 2000b). Moreover, the Paris et al. (2015) study on the Tchad area added several information concerning the Hirnantian chitinozoan biozonation (see Fig. 1.11).

2.3.1 The southern axial basin: Bou Ingarf and surroundings

The Bou Ingarf area is the most well-sampled and studied (e.g. Bourahrouh et al., 2004). It is a historical key section of the Central Anti-Atlas with a large continuity through the succession. Moreover, Loi et al. (2010) added a sequence stratigraphic framework, which increased the understanding relative to the first study of Bourahrouh et al. (2004). In the southern axial basin three additional locations have been considered for palynomorphs, and finally studied locations are: Aït Ouazik, Bou Ingarf, Jbel Agoujil, and Oujgal South (Fig. 2.4). Together, they yielded a total of 5,324 chitinozoan.

In the Lower Ktaoua Fm. a single test sample (TVDB 13-029, Figs. 2.4 and 2.9A) display a chitinozoan assemblage dominated by *Belonechitina* spp., followed by *Angochitina* spp., and *Euconochitina* spp. Other species are also present, which are *Calpichitina lenticularis*, *Desmochitina* spp., *Acanthochitina* spp., *Conochitina* spp., *Rhabdochitina* spp., *Rhabdochitina magna*, *Cyathochitina kuckersiana*, *Fungochitina* spp., *Lagenochitina* spp. In the Upper Tiouririne Fm. another test sample (LT 14-002, Figs. 2.4 and 2.9A) yielded a chitinozoan fauna composed by a similar assemblage that the previous one, but in this case there is a dominance of *Angochitina* spp. Moreover, other species such as *Armoricochitina* spp., *Belonechitina micracantha*, *Rhabdochitina gracilis*, *Rhabdochitina claviformis*, *Tanuchitina* spp., *Cyathochitina* spp., *Cyathochitina campanulaeformis*, *Lagenochitina* *baltica*, and *Lagenochitina prussica* are also present. The disappearance of *Acanthochitina* spp., *Euconochitina* spp., *Cyathochitina kuckersiana*, and *Fungochitina* spp. is noted.

In the upper part of the Upper Ktaoua Fm. several samples have been collected that yielded an assemblage dominated by *Rhabdochitina gracilis*. They contain as well *Belonechitina* spp*., Armoricochitina* spp*., Calpichitina lenticularis, Desmochitina* spp*., Desmochitina minor, Belonechitina micracantha, Conochitina* spp*., Euconochitina* spp*., Rhabdochitina* spp*., Rhabdochitina magna, Rhabdochitina claviformis, Spinachitina* spp*., Spinachitina coronata, Spinachitina ?fossensis, Spinachitina multiradiata, Tanuchitina* spp*., Tanuchitina* cf*. elongata, Tanuchitina elongata, Ancyrochitina* spp*., Ancyrochitina merga, Cyathochitina* spp*., Lagenochitina* spp*., Lagenochitina prussica,* and *Lagenochitina baltica*. These samples are all located from c. 50m to few cm below the ouzregui bed (Fig. 2.9A). It is noteworthy that specimens of *T. elongata* have been found at the very top of the Upper Ktaoua Fm., in the closest sample beneath the ouzregui bed, and thus at a lower level than previously reported (Bourarouh et al., 2004).

The samples from the base of the Lower 2nd Bani Fm. are located from 10 cm to 6 m above the ouzregui bed (Fig. 2.9A) and they show an assemblage dominated by *Euconochitina* spp., *Rhabdochitina gracilis*, *Ancyrochitina* spp., and *Belonechitina* spp. Additionnaly, they contain an important amount of *Tanuchitina* spp., *Calpichitina lenticularis*, and *Fungochitina* spp. associated to *Armoricochitina nigerica*, *Desmochitina* spp., *Desmochitina minor*, *Acanthochitina* spp., *Belonechitina micracantha*, *Conochitina* spp., *Rhabdochitina magna*, *Rhabdochitina claviformis*, *Spinachitina* spp., *Tanuchitina elongata*, *Tanuchitina* cf. *elongata*, *Ancyrochitina merga*, *Angochitina* spp., *Cyathochitina kuckersiana*, *Lagenochitina* spp. *Lagenochitina prussica*, *Lagenochitina baltica* species.

A single sample from the upper Lower 2nd Bani Fm. (LT 14-011) yielded a large amount of chitinozoan and a general assemblage composed by *Calpichitina lenticularis, Desmochitina* spp*., Delochitina minor, Belonechitina* spp*., Belonechitina micracantha, Belonechitina wesenbergenesis, Conochitina* spp*., Euconochitina* spp*., Rhabdochitina magna, Tanuchitina* spp*., Tanuchitina* cf*. elongata, Tanuchitina elongata, Ancyrochitina merga, Angochitina communis, Lagenochitina* spp*., Lagenochitina prussica, and Lagenochitina baltica,* and mainly dominated by *Ancyrochitina* spp*., Rhabdochitina gracilis,* and *Armoricochitina nigerica*. It differs from the lower assemblages by the large amount of *Ancyrochitina* sp. and *Armoricochitina nigerica*, that where poorly or not represented.

No samples were available higher in the Lower Second Bani Fm. in the Bou Ingarf area. However, unpublished data from F. Paris display at the base of middle member of the

Lower 2nd Bani Fm. (yellow unit) a general assemblage composed by a dominance of *Spinachitina* spp. associated to *Spinachitina oulebsiri*, *Spinachitina verniersi*, *Spinachitina* cf. *taugourdeaui*, *Armoricochitina nigerica*, *Calpichitina lenticularis*, *Euconochitina* spp., *Conochitina* spp., *Rhabdochitina* spp., *Rhabdochitina gracilis*, *Acanthochitina* spp., *Tanuchitina* spp., *Tanuchitina elongata*, *Ancyrochitina* spp., *Ancyrochitina* sp. aff. *merga*, and *Desmochitina* gr. *minor*.

Finally, in the uppermost part of the section, within the Upper 2nd Bani Fm. and above the glacially-related strata, a single sample from well cuttings (TVDB 13-021) from Aït Ouazik, shows a chitinozoan fauna composed by a dominance of *Belonechitina* sp. and *Calpichitina lenticularis*. Additionally, species like *Armoricochitina nigerica*, *Desmochitina minor*, *Belonechitina hirsuta*, *Conochitina* sp., *Euconochitina* sp., *Euconochitina lepta*, *Pogonochitina* n. sp., *Rhabdochitina gracilis*, *Rhabdochitina claviformis*, *Spinachitina* sp., *Tanuchitina* sp., *Tanuchitina elongata*, *Fungochitina* sp., *Lagenochitina prussica*, and *Lagenochitina baltica*.

In this area the biodiversity values displayed in Fig. 2.9A vary from 3 to 19. The two samples from the Lower Ktaoua Fm. and Upper Tiouririne Fm. show intermediate values concerning the chitinozoan diversity. However, the condensed horizon (Ouzregui), between the Upper Ktaoua Fm. and the base of the Lower 2nd Bani Fm., displays a highly variable biodiversity. Biodiversity is still high in the sample characterizing the sandstone-dominated succession at the upper part of the lower member of the Lower Second Bani Fm (Fig. 2.4).

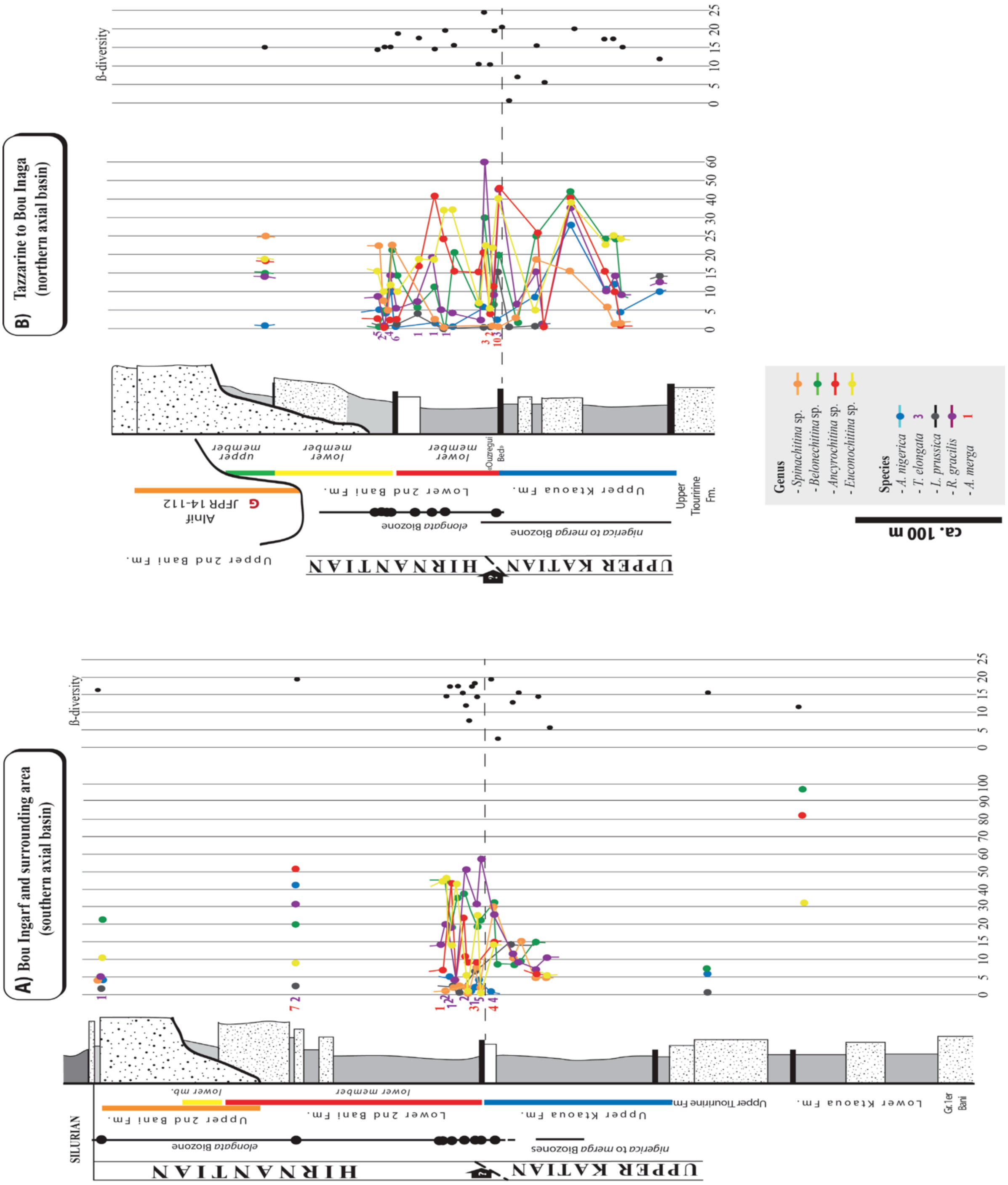


Fig. 2.9 Southern and northern axial basin. (A) Bou Ingarf and surroundings chitinozoan and biodiversity curve; (B) Tazzarine to Bou Inaga chitinozoan and biodiversity curve.


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Plate I. Late Ordovician chitinozoans from southern axial basin of the Central Anti-Atlas (Aït Ouazik, Bou Ingarf, Agoujil, Oujgal Sud), South Morocco. The scale bar represents 100µm and double scale bar represents 50µm. A) *Rhabdochitina magna* (LT 14-002_047); B) and F) *Tanuchitina elongata* (TVDB 13-032_022, TVDB 13-060_038); C) and H) *Spinachitina* spp. (LT 14-006_015, TVDB 13-035_015); D) *Spinachitina multiradiata* (LT 14-006_251); E) *Spinachitina kourneidaensis* (TVDB 13-036_003); G) and L) *Belonechitina micracantha* (LT 14-011_050, TVDB 13-036_076); I) *Euconochitina lepta* (LT 14-006_049); J*) Rhabdochitina gracilis* (TVDB 13-036_032); K) *Fungochitina* spp. (TVDB 13-058_038); M) *Belonechitina wesenbergensis* (TVDB 13-039a_068); N) *Rhabdochitina claviformis* (LT 14-004_024); O) *Conochitina* spp. (TVDB 13-039b_135); P) and R) *Ancyrochitina merga* (LT 14-011_093, TVDB 13-057_391); Q) *Desmochitina minor* (LT 14-006_090); S) *Cyathochitina campanulaeformirs* (LT 14-002_066); T) *Lagenochitina baltica* (TVDB 13-036_050); U) *Armoricochitina nigerica* (LT 14-011_306); V) *Lagenochitina prussica* (TVDB 13-040b_136).

2.3.2 The northern axial basin: Tazzarine to Bou Inaga zone

The northern axial basin, and especially the Tazzarine and Emin Bou M'zur sections are representative of an area, which is considered as more distal compare to the above-described zone (Bou Ingarf and surroundings). Two others locations, the Bou Inaga and Tassatline sections, have been inspected. They are as well located to the North of Bou Ingarf, as well, but are more proximal than the Tazzarine and Emin Bou M'zur sections.

In this zone 58 samples from four localities (Figs. 2.5 and 2.9B) have been collected and yielded a total of 5,198 chitinozoan that have been handpicked and identified.

In the Upper Ktaoua Fm. two assemblages can be distinguished. The lower one is dominated by *Belonechitina* spp*.*, *Euconochitina* spp*.*, associated to *Armoricochitina nigerica, Conochitina* spp*., Rhabdochitina magna, Rhabdochitina gracilis, and Ancyrochitina* spp. are present as well: *Calpichitina lenticularis, Desmochitina* spp*., Desmochitina minor, Desmochitina juglandiformis, Acanthochitina* spp*., Belonechitina micracantha, Belonechitina robusta?, Rhabdochitina claviformis, , Spinachitina* spp*., Tanuchitina* spp*., Angochitina communis, Cyathochitina* spp*., Fungochitina* spp*., Lagenochitina* spp*., Lagenochitina prussica, Lagenochitina baltica*, and *Sphaerochitina* spp.

The upper part of the Fm. shows samples that are located close to the suggested "ouzregui bed" and they are generally dominated by *Ancyrochitina* spp., *Belonechitina* spp*.,* and *Rhabdochitina gracilis*. The rest of the assemblage is comparable to that of the lower part, with the exception of presence of *Cyathochitina campanulaeformis* and the absence of *Sphaerochitina* spp. This difference is probably due to the fact that the samples from the lower part of the section comes from a more proximal location (Bou Inaga) compare to the upper part (Foum Tazzarine), which is in a more distal depositional setting.

The base of the Lower 2nd Bani Fm. (lower part of the lower member, red unit) is characterized by samples from the Tazzarine and Emin Bou M'zur sections and shows an intermediate abundance of chitinozoan. The samples are dominated mainly by *Rhabdochitina gracilis*, *Ancyrochitina* spp., and *Euconochitina* spp. The rest of the assemblage is composed by *Armoricochitina* spp., *Armoricochitina nigerica*, *Calpichitina lenticularis*, *Desmochitina* spp., *Desmochitina minor*, *Desmochitina typica*, *Belonechitina* spp., *Belonechitina micracantha*, *Belonechitina wesenbergensis*, *Conochitina* spp., *Euconochitina lepta*, *Rhabdochitina* spp., *Rhabdochitina magna*, *Rhabdochitina claviformis*, *Spinachitina* spp., *Tanuchitina* spp., *Tanuchitina* cf. *elongata*, *Tanuchitina elongata*, *Ancyrochitina merga*, *Ancyrochitina longispina*, *Angochitina communis*, *Cyathochitina* spp., *Cyathochitina campanulaeformis*, *Lagenochitina* spp., *Lagenochitina prussica*, *Lagenochitina baltica*. In the lowest sample of the Lower 2nd Bani Fm., at c. 1 m above the ouzregui bed, the lowest *T. elongata* specimen has been recorded and a significant proportion of *A. merga*.

In the upper part of the red unit (lower member of the Lower 2nd Bani Fm.) the chitinozoan assemblage is the same as in the lower part with a dominance of *Euconochitina* spp. and *Ancyrochtina* spp., but however with disappearance of *E. lepta*, *A. merga*, and appearance of *Fungochitina* spp. Moreover, the *T. elongata* is present in more specimens pro sample.

The base of the yellow unit, middle Lower 2nd Bani Fm., shows a similar assemblage as the rest of the Fm., but here an important appearance *Spinachitina* spp. is recorded. In previous study a pick of *Spinachitina* spp. has already been documented (F. Paris, pers. comm.) at this level in the Bou Ingarf area (see above), which is confirmed here with our data. Additionally, several species have disappeared in this part of the section, such as *B. wesenbergensis*, *R. magna*, *R. claviformis*, and *Angochitina* spp.

The green unit of the uppermost Lower 2nd Bani Fm. ("upper member") is characterized by a single sample from Tazzarine (Tiou 2, Figs. 2.5 & 2.9B), which shows a particular and abundant fauna. Indeed, here a new species *Pogonochitina* n. spp. and a large abundance of *Spinachitina* spp. characterize this sample. The not so favourable lithology (immediately beneath the ice-proximal glaciomarine) did not permit to identify most of the specimens due to their poor preservation and their fragmentation. However, with the poorly abundant identified specimens, it has been possible to determine a small chitinozoan assemblage. Concerning the biodiversity curve (Fig. 2.9B) of the Tazzarine area, it shows an increase in biodiversity at the beginning of the section, followed by a decrease approaching the ouzregui bed and then an increase to values from 10 to 20 in average for the rest of the section above the marker bed. All this is due to the condensation process, indeed the biodiversity increase through the condensation (retrogradation phase).

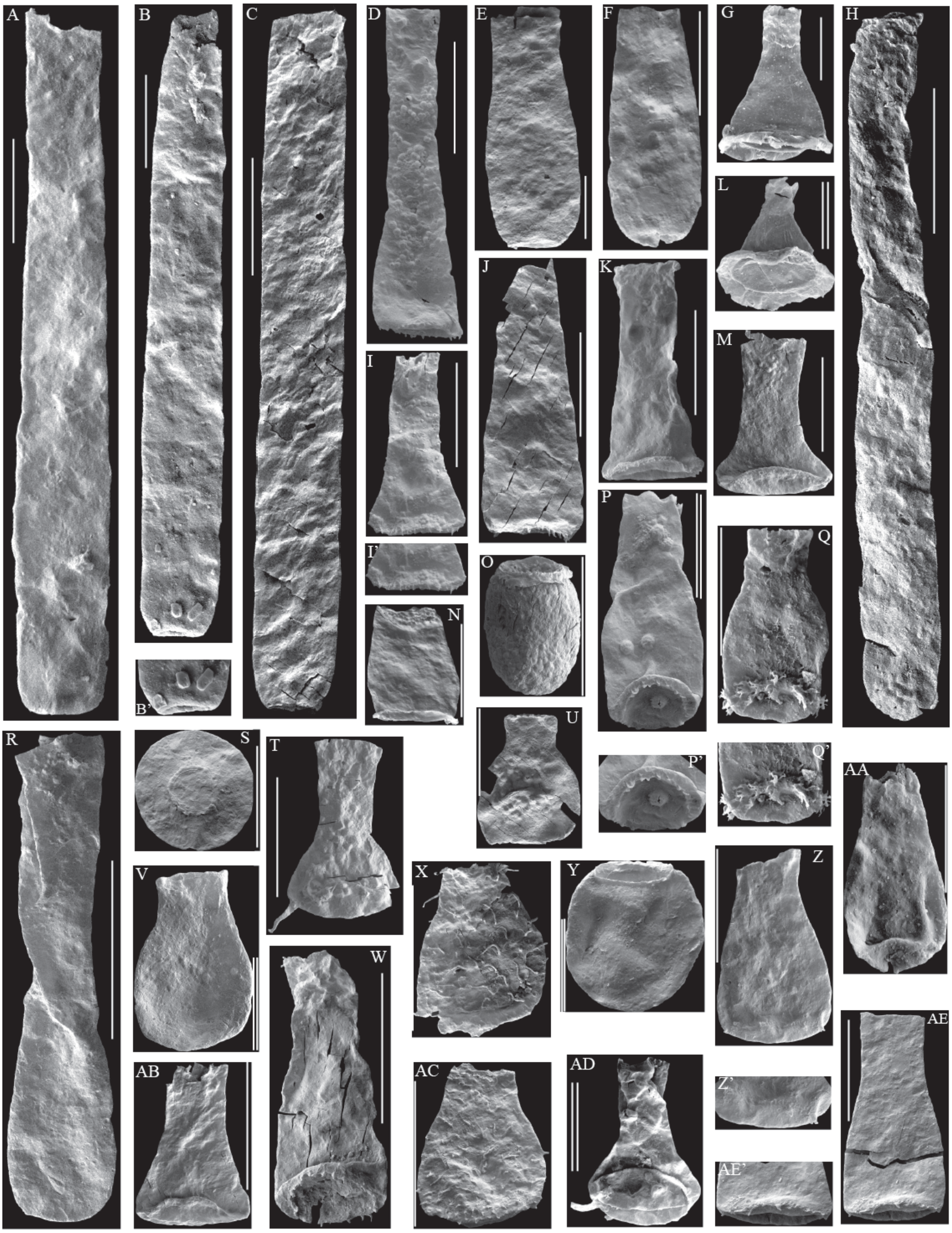

Plate II. Late Ordovician chitinozoans from the northern axial basin of the Central Anti-Atlas (Tassatline, Foum Tazzarine, Emin Bou M'Zur, Bou Inaga), South Morocco. The scale bar represents 100µm, the double scale bar represents 50µm. A) *Rhabdochitina magna* (Tiou2_1_088); B) and C) *Tanuchitina elongata* (Tiou2_1_197, TVDB 13-002_100); D) *Spinachitina kourneidaensis* (naga7_122); E) and F) *Conochitina* spp. (naga7_411, naga7_452); G) and L) *Cyathochitina campanulaeformis* (Tiou2_006, Tiou2_008); H) *Rhabdochitina gracilis*

(TVDB 13-013b_115); I) *Spinachitina multiradiata* (Tiou2_1_406); J) *Spinachitina* spp. (TVDB 13-003_091); K) *Belonechitina micracantha* (Tiou2_1_296); M) *Fungochitina* spp. (TVDB 13-012b_063); N) *Armoricochitina nigerica* (naga7_432); O) *Desmochitina typica* (TVDB 13-016_064); P) *Spinachitina verniersi* (TVDB 13-008_081); Q) *Pogonochitina* spp. (Tiou2_1_051); R) *Rhabdochitina claviformis* (TVDB 13-014A_051); S) *Calpichitina lenticularis* (TVDB 13-010_019); T) and AD) *Ancyrochitina merga* (TDVB 13-018_007, Tiou2_1_010); U) *Lagenochitina prussica* (TVDB 13-018_040); V) *Lagenochitina baltica* (TVDB 13-011_132); W) *Spinachitina* spp. (TVDB 13-003_018); X) and AC) *Angochitina communis* (TVDB 13-020_005, TVDB 13-018_063); Y) *Desmochitina minor* (TVDB 13-008_085); Z) *Spinachitina* spp. (TVDB 13-011_096); AA) *Conochitina* spp. (Tiou2_1_041); AB) *Euconochitina lepta* (TVDB 13-001_035); AE) *Spinachitina* spp. (TVDB 13-011_162).

2.3.3 Western margin of the Central Anti-Atlas Basin

The area (Jbel Bani) cover c. 100km and 3 locations have been sampled (Fig. 2.8), with the goal to characterize patterns of the chitinozoan assemblage in a basin margin context. A total of 7 samples were collected, this low amount is due mainly to the unfavourable lithology for palynomorphs; only 3 samples, from Oued Hajguig (Ecole Nomade), Oued Mellili, and Jbel Nsrate Sud locations, yield some interesting fauna (Plate III). A total of 231 chitinozoans have been handpicked and identified. The samples contain a large amount of fragments, which were unfortunately unidentifiable.

The three samples are located in the Lower 2nd Bani Fm. and they show a general assemblage dominated by *Conochitina* spp., *Armoricochitina nigerica, Euconochitina* spp., and *Rhabdochitina magna, Rhabdochitina gracilis*. They contain as well other species: *Desmochitina minor, Belonechitina micracantha, Euconochitina lepta, Cyathochitina* spp., *Fungochitina* spp., *Lagenohitina baltica,* and *Lagenochitina prussica*.

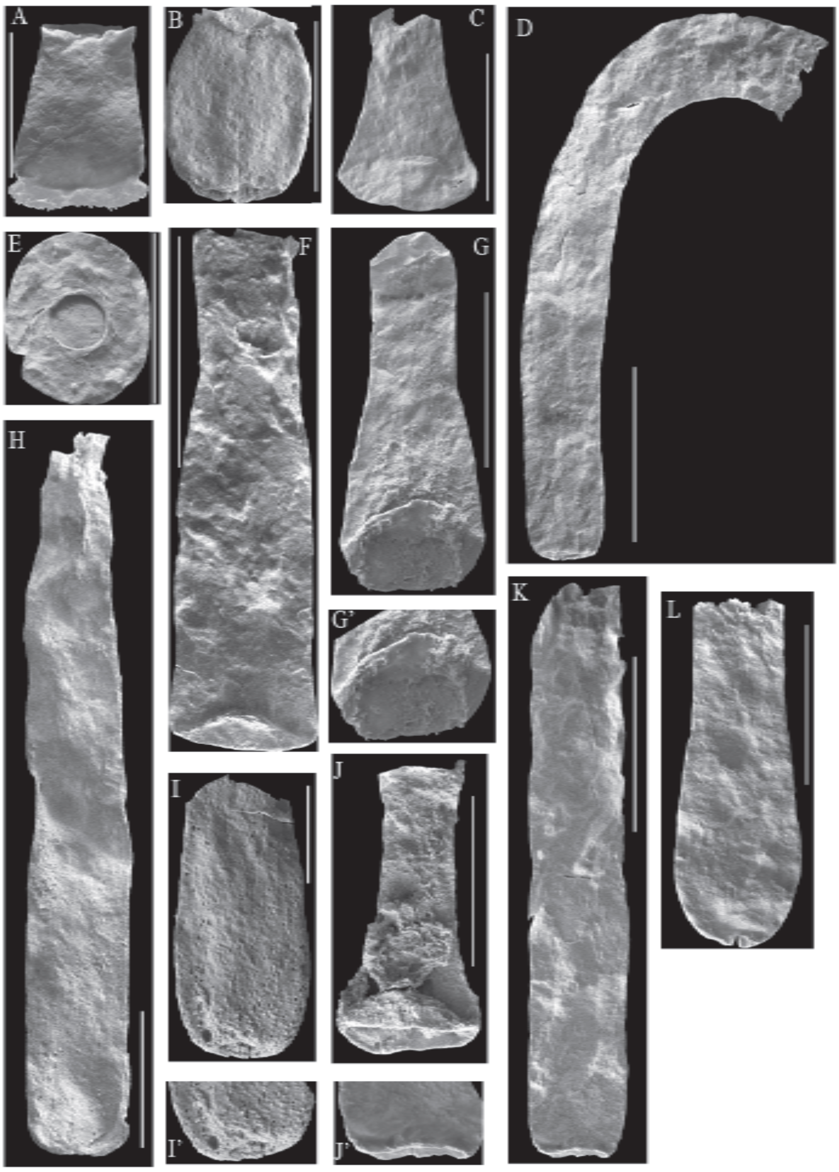

Plate III. Late Ordovician chitinozoans from the western margin of the Central Anti-Atlas Basin (Ecole Nomade, Oued Mellili, and Jbel Nsrate Sud), South Morocco The scale bar represents 100µm, the double scale bar represents 50µm. A) *Armoricochitina nigerica* (JFAD 15-031_015); B) *Calpichitina lenticularis* (JFAD 15-031_090); C) *Belonechitina micracantha* (JFAD 15-031_107); D) *Belonechitina* spp. (JFAD 15-017_020 and JFAD 15-017_020a); E) *Desmochitina minor* (JFAD 15-017_009); F) *Conochitina* spp. (JFAD 15-031_168); G) *Euconochitina lepta* (JFAD 15-031_143); H) *Fungochitina* spp. (JFAD 15-017_008); I) *Rhabdochitina gracilis* (JFAD 15-031_160); J) *Rhabdochitina magna* (JFAD 15-017_024); K) *Tanuchitina* cf. *elongata* (JFAD 15-031_179 and JFAD 15-031_179a); L) *Spinachitina verniersi* (JFAD 15-017_025 and JFAD 15-017_025a); M) *Cyathochitina* spp.(JFAD 15-031_057).

2.3.4 The eastern margin of the Central Anti-Atlas: Maïder-Tafilalt

This fourth region has been studied for several reasons. Firstly, it was necessary to add biostratigraphical constrains and particularly to determine the ages of the incisions. If the Alnif Valley and Jbel Amessoui incision include glaciation-related facies in their infill, strongly suggesting a Hirnantian age by correlation with the basin-axis stratigraphy, the status of the Istel Hou and Taghbet el Khir regions remained problematic. Bou Kerkour and Jbel Aroudane are considered as interfluve area relative to the incisions. Secondly, the datation of the "limestones" of the Erfoud area and associated shallow incisions will position these singular depositional facies in the regional biostratigraphic framework. The eastern margin data set is split and presented into four subsections: A) the interfluves of Bou Kerkour and Jbel Aroudane, B) the incisions with glaciomarine deposits of Alnif and Jbel Amessoui, C) the doubtful incisions of Istel Hou and Taghbet el Khir, and D) the Erfoud area.

A) Interfluves of Bou Kerkour and Jbel Aroudane

In Bou Kerkour, located c. 30 km West of Istel Hou, 2 samples yielded 211 chitinozoans. These samples are characteristics because they permit to date a large area laterally adjacent to the deep Istel Hou incision. However, only one sample (TVDB 14-013) is relevant for chitinozoan biostratigraphy. This sample shows a dominance of *Rhabdochitina gracilis* and *Calpichitina lenticularis.* Additionally, it contains *Armoricochitina nigerica*, *Desmochitina minor*, *Desmochitina elongata*, *Acanthochitina* spp., *Belonechitina micracantha*, *Conochitina* spp., *Euconochitina* spp., *Rhabdochitina magna*, *Rhabdochitina claviformis*, *Ancyrochitina* spp., *Cyathochitina* spp., *Cyathochitina campanulaeformis*, *Fungochitina* spp., *Lagenochitina* spp., *Lagenochitina prussica*, *Lageonochitina baltica*, and *Sphaerochitina* n. spp.. The presence of *Sphaerochitina* n. spp. is noteworthy and it will be discussed later in the text.

Jbel Aroudane, which is located c. 100 km SE Bou Kerkour, yielded only 17 chitinozoan from the single sample (JFG 13-107) and shows a rather poor preservation. The identifiable specimens are dominated by *Rhabdochitina gracilis* with subordinate *Calpichitina lenticularis, Conochitina* spp.*, Rhabdochitina magna, Ancyrochitina* spp.*, Lagenochitina* spp.*, Sphaerochitina* n. spp.*,* and one *Ancyrochitina merga* that will be very useful for age assignement.

B) Incisions with glaciomarine deposits of Alnif and Jbel Amessoui

The single sample (JFPR 14-112) from the Upper 2nd Bani Fm. in Alnif, which is located within the glaciomarine strata of the Hirnantian glacial record, shows a poor chitinozoan fauna (27 specimens in total), but several species have been identified. The sample is dominated by *Euconochitina* spp. and *Cyathochitina* spp., and it contains as well *Calpichitina lenticularis*, *Belonechitina* spp., *Conochitina* spp., *Tanuchitina* spp., and *Ancyrochitina* spp. To our knowledge, it is the first time that chitinozoans from the glacial strata have been recorded in the Anti-Atlas.

Jbel Amessoui is situated ca. 90 km SEE from the Alnif's sample. Here two samples have been analysed that yielded a total of 197 chitinozoans. The lower sample (JFPR 14-104), characterizing the lowermost incision infill, is dominated by *Rhabdochitina gracilis*, which is associated to *Armoricochitina nigerica*, *Calpichitina lenticularis*, *Desmochitina minor*, *Desmochitina elongata*, *Belonechitina* spp., *Belonechitina micracantha*, *Euconochitina* spp., *Euconochitina lepta*, *Rhabdochitina magna*, *Rhabdochitina claviformis*, *Angochitina* spp., *Cyathochitina* spp., *Lageonchitina* spp., and *Sphaerochitina* n. spp. The upper sample (JFPR 14-103) is positioned in a depositional unit younger than the first glaciation-related deposits, approximately in the middle of the incision infill. Its chitinozoan assemblage is similar to the previous sample but without *E. lepta*, *R. claviformis*, and *Cyathochitina* spp. In addition it yields *Spinachitina* spp., *Tanuchitina* spp., *Tanuchitina elongata*, *Tanuchitina* cf. *elongata*.

C) The Istel Hou and Taghbet el Khir incisions

The Istel Hou samples belong to a section representative of a very thick incision infill, the temporal calibration of which was not determined. Here, 9 samples have been collected that yielded a total of 936 chitinozoans. Palynomorphs data suggest two distinct assemblages. The first lower assemblage concerns the first 5 samples and their 446 chitinozoans. The assemblage is composed by a dominance of *Belonechitina* spp. and *Armoricochitina nigerica*. Additionally, it contains *Calpichitina lenticularis*, *Desmochitina* spp., *Desmochitina juglandiformis*, *Desmochitina typica*, *Acanthochitina barbata*, *Belonechitina micracantha*, *Conochitina* spp., *Euconochitina* spp., *Rhabdochitina* spp., *Spinachitina* spp., *Tanuchitina* spp., *Ancyrochitina* spp., *Angochitina* spp., *Cyathochitina* spp., *Cyathochitina campanulaeformis*, *Fungochitina* spp., and *Sphaerochitina* n. spp. The second, upper assemblage (4 samples) is similar to the preceding one, with the notable absence of *D.*

juglandiformis and of *Spinachitina* n. spp.. In addition, the presence of *Belonechitina robusta* is noted.

The Taghbet el Khir section is located ca. 20 km SE of Istel Hou and it provides a single sample (JFG 13-110) that yields a total of 64 chitinozoans. The assemblage is composed by *Armoricochitina nigerica*, *Calpichitina lenticularis*, *Belonechitina* spp., *Conochitina* spp., *Euoconochitina* spp., *Rhabdochitina magna*, *Rhabdochitina gracilis*, *Tanuchitina* spp., *Tanuchitina elongata*, *Tanuchitina* cf. *elongata*, *Cyathochitina campanulaeformis*, and *Lagenochitina baltica*.

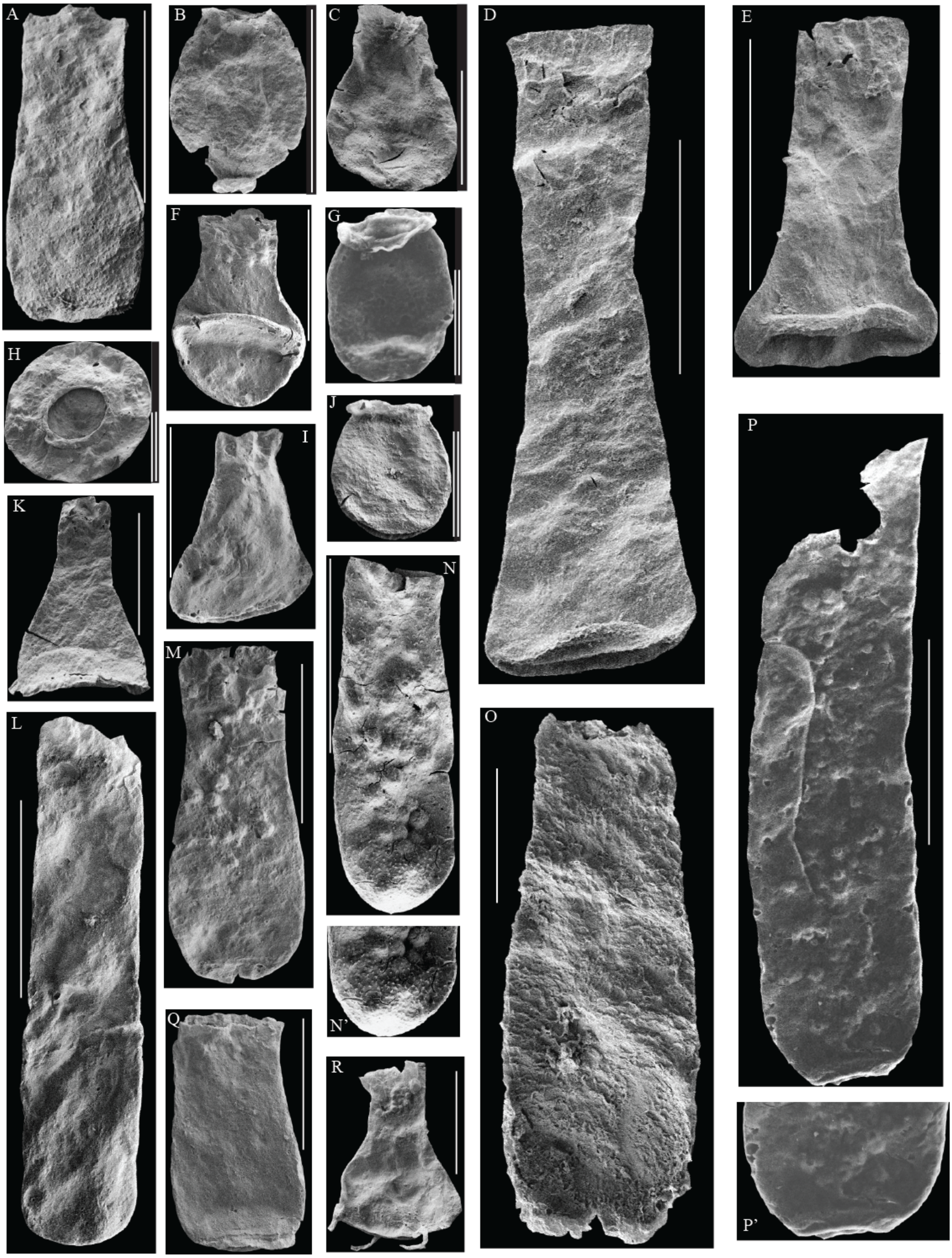

Plate IV. Late Ordovician chitinozoans from the eastern margin of the Central Anti-Atlas Basin (Maider and Tafilalt). Istel Hou incision. The scale bar represents 100µm, the double scale bar represents 50µm. A) and N) *Belonechitina* spp. (TVDB 14-032a_045, TVDB 030_018); B) *Desmochitina juglandiformis* (TVDB 14-024b_097); C) *Angochitina* spp. (TVDB 14-024a_098); D) *Belonechitina micracantha* (TVDB 14-025_035); E) *Fungochitina* spp. (TVDB 14-025_069); F) *Sphaerochitina* n. spp. (TVDB 14-026_045); G) *Desmochitina* *typica* (TVDB 14-026_112); H) *Calpichitina lenticularis* (TVDB 14-026_071); I) *Euoconochitina lepta* (TVDB 14-026_113); J) *Desmochitina minor* (TVDB 14-028_009); K) *Cyathochitina campanulaeformis* (TVDB 14-026_106); L) *Rhabdochitina gracilis* (TVDB 14-032a_016); M) *Conochitina* spp. (TVDB 14-032a_022); O) *Acanthochitina barbata* (TVDB 14-024a_006b); P) *Tanuchitina* spp. (TVDB 14-026_017); Q) *Armoricochitina nigerica* (TVDB 14-025_071); R) *Ancyrochitina merga* (TVDB 14-032a_041).

D) Erfoud

Erfoud is the most eastward area in our study, located some 50 km north Jbel Aroudane. The area is known for two distinctive "limestone" horizons —most often limy sandstones with reworked bryozoans—, their significance and age attribution remaining problematic. In addition, as demonstrated by A. Meddour (2016), these specific lithologies are related to the infill of shallow incisions. The sample set is designed to characterize strata beneath and in between the two main limestone horizons. Here, 13 samples have been collected that yielded a total of 1,379 chitinozoans.

Three assemblages are differentiated. The lower assemblage (ERF 0 to 4, Fig. 2.7) characterizes strata beneath the lower erosion surface. It contains a chitinozoan assemblage dominated by *Armoricochitina nigerica, Belonechitina* spp., and *Belonechitina micracantha,* associated to *Calpichitina lenticularis, Desmochitina* spp.*, Desmochitina minor, Desmochitina juglandiformis, Acanthochitina* spp.*, Belonechitina ghabensis, Conochitina* spp.*, Euconochitina* spp.*, Euconochitina lepta, Rhabdochitina* spp.*, Rhabdochitina magna, Rhabdochitina gracilis, Rhabdochitina claviformis, Tanuchitina* spp.*, Angochitina* spp.*, Cyathochitina* spp.*, Cyathochitina campanulaeformis, Fungochitina* spp.*, Lagenochitina* spp.*, Lagenochitina prussica, ?Ramochitina (Gotlandochitina)* spp., and *Sphaerochitina* n. spp.

The upper assemblage (ERF 9 to 11) is from the maximum flooding interval in between the two main limestone horizons. It revealed the following species: *Armoricochitina nigerica, Calpichitina lenticularis, Desmochitina* spp.*, Desmochitina minor, Belonechitina* spp.*, Belonechitina micracantha, Conochitina* spp.*, Euconochitina* spp.*, Euconochitina lepta, Rhabdochitina magna, Rhabdochitina claviformis, Spinachitina* spp.*, Spinachitina verniersi, Spinachitina kournaedensis, Tanuchitina elongata, Tanuchitina* cf. *elongata, Ancyrochitina merga, Ancyrochitina spongiosa, Angochitina* spp.*, Cyathochitina* spp.*, Fungochitina* spp., and a dominance of *Rhabdochitina gracilis, Tanuchitina* spp., and *Ancyrochitina* spp. The appearance of *T. elongata* is in agreement with a position in the younger strata.

The middle assemblage, from the lower incision infills, appears in samples ERF 5 and 7. It displays a dominance of *Belonechitina micracantha, Rhabdochitina gracilis,* and

Ancyrochitina spp. and it contains as well *Armoricochitina nigerica, Calpichitina lenticularis, Desmochitina* spp.*, Desmochitina minor, Belonechitina* spp.*, Conochitina* spp.*, Euconochitina* spp.*, Rhabdochitina* spp.*, Spinachitina* spp.*, Spinachitina verniersi, Spinachitina kournaeidaensis, Spinachitina coronata, Tanuchitina* spp.*, Tanuchitina* cf. *elongata, Ancyrochitina merga, Ancyrcohitina spongiosa, Cyathochitina* spp.*,* and *Lagenochitina prussica*. These samples differ from the preceding ones mainly by the appearance of *T.* cf. *elongata*, of several *Spinachitina* specimens, and the drastic drop of *A. nigerica*. Additionally, the *Spaherochitina* n. spp. disappeared as well as the *D. juglandiformis*, chitinozoans characterizing the older preceding assemblage.

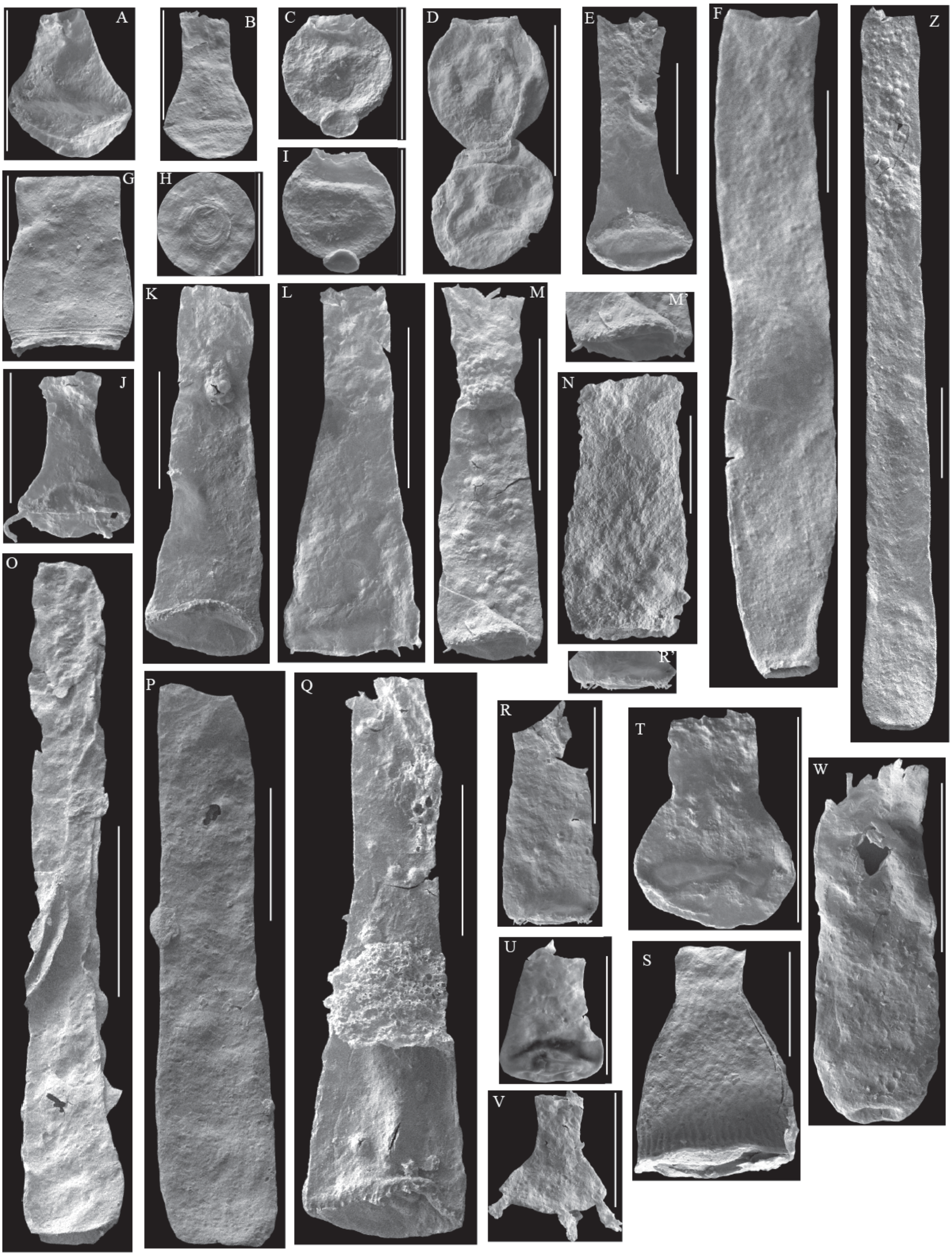

Plate V. Late Ordovician chitinozoans from the eastern margin of the Central Anti-Atlas Basin (Maider and Tafilalt). Erfoud section. The scale bar represents 100µm, the double scale bar represents 50µm. A) and B) *Sphaerochitina* n. spp. (ERF0_097, ERF1_119); C) and I) *Desmochitina juglandiformis* (ERF0_099, ERF3_057); D) *Desmochitina minor* (ERF1_098); E) *Fungochitina* spp. (ERF1_095); F) *Tanuchitina elongata* (ERF10_018); G) *Armoricochitina nigerica* (ERF1_001); H) *Calpichitina lenticularis* (ERF2_200); J)

Ancyrochitina merga (ERF9_043); K) and Q) *Belonechitina micracantha* (ERF7_144, ERF9_086); L), M), M'), R), and R') *Spinachitina* spp. (ERF7_075, ERF7_092, ERF7_110); N) *Acanthochitina* spp. (ERF2_030); O) *Rhabdochitina claviformis* (ERF9_075); P) *Rhabdochitina magna* (ERF9_113); S) *Cyathochitina campanulaeformis* (ERF0_137); T) *Lagenochitina prussica* (ERF2_202); U) *Euconochitina* spp. (ERF3_016); V) *Ancyrochitina spongiosa* (ERF9_045); W) *Conochitina* spp. (ERF9_084); Z) *Rhabdochitina gracilis* (ERF10_021).

2.4 A focus on the Katian-Hirnantian boundary in the Central Anti-Atlas Basin

The main goal of this study was to better define the Katian-Hirnantian boundary and our data permitted to identify the uppermost Katian Biozone (*merga*) and the lower Hirnantian Biozone (*elongata*). As it is possible to observe in Fig. 2.9, the *A. merga* specimens are found higher into the Hirnantian, and on the other hand we may see that the ouzregui bed does not bound the basal *T.elongata* Biozone. Indeed, few specimens are even been found just below it in the Bou Ingarf section (Fig. 2.9A), enlarging downward the stratal interval corresponding to the *T. elongata* Biozone as defined by the FAD of the index species. Theses informations do not totally permit to properly define the Katian-Hirnantian boundary because it has not been demonstrate until where (on the sections) the two key species are present, in order to fix the boundary. The only information we have is that the boundary might be somewhere around the ouzregui bed, provided the calibration of the *A. merga*/ *T. elongata* boundary effectively corresponds with the Katian-Hirnantian boundary (Paris, 2000, 2006).

In the conventional chitinozoan-based biostrartigraphic scheme, the main fact that distinguishes the uppermost Katian and the lowermost Hirnantian is not only the FAD of the index species (*T. elongata*), but as well their associated chitinozoan fauna (see Fig. 2.9). In the present study even if the definition of the Katian-Hirnantian boundary remains doubtful, it still possible to have an age assignment for the end-Ordovician formations from the Central Anti-Atlas. The Upper Ktaoua Fm. contains the key species *A.nigerica* and *A.merga* in ascending order. The boundary between the *nigerica* and *merga* biozones is not clearly defined with our data, but it is possible to say that Upper Ktaoua Fm. dates a *nigerica* to *merga* biozones, which are situated into the upper Katian time interval. The Lower 2nd Bani Fm., instead, contains a chitinozoan assemblage typical of the *elongata* Biozone, with the appearance of the index species *T. elongata* and as this biozone is located within the Hirnantian time as it will be presented in chapter III (Prague Basin section, Fig. 3.7). How far the Hirnantian may extend into the underlying Upper Ktaoua Fm. remains open to debate.

Several studies (Harper et al., 2006; see chapter 3) suggest a drop in biodiversity during the Hirnantian time interval. However, in the study areas, we did not record the same drop during the Hirnantian, but, instead, we observed a reduced chitinozoan fauna (in Bou Ingarf, Tazzarine, and Bou Inaga) just below the ouzregui bed. This may witness a decrease in biodiversity at this level, but it can also be only related to a fossil preservation issue. However, more sampling and further study is necessary to confirm our results. The question that the general Hirnantian biodiversity drop occurs at the Katian-Hirnantian boundary or not is open and need to find an answer with more studies in this part of Morocco. Additionally, to support the hypothesis of a faunal crisis between the Upper Ktaoua Fm. and the Lower 2nd Bani Fm., a recovery chitinozoan assemblage should be found. In this case, the chitinozoan assemblage at the base of the Lower Second Bani Fm. may represent such a recovery pattern, in contrast with younger Hirnantian assemblages.

According to several authors (e.g. Molyneux et al., 2006; Paris et al., 2007; Videt et al., 2010), who dated the main transgressif events in several world areas (Algerian Sahara, Oman) using the chitinozoans, they recognized several transgressif events during the Ordovician in North Gondwana margins. The datation of deposits by the biozonation of chitinozoan permitted to demonstrate a kind of synchronism of these events at regional level. Additionally the transgressives facies are favourable for the chitinozoan preservation, and it is in these facies that the biozones are defined. In the studied sections of the Central Anti-Atlas we identified three main units in the Lower 2nd Bani Fm. and each one has its own characteristic. The first unit (red, Fig. 2.9) is in the lowermost part of the Fm. and it is characterized by an abundant and quite diverse chitinozoan fauna. It is as well the first unit where the index species *T. elongata* of the homonymous biozone appear. The second unit (yellow) is characterized by a slightly decrease in biodiversity, but otherwise it displays a chitinozoan assemblage corresponding to the *elongata* Biozone and an important peak if *Spinachitina* sp. The uppermost member (green) of the Lower 2nd Bani Fm. is characterized by a small horizon of favourable lithology for the chitinozoans. It is generally difficult to find a proper assemblage. The recorded specimens display a similar biodiversity to the preceding units, but the 'assemblage' does not always permit to identify the uppermost *elongata* Biozone or the beginning of the *oulebsiri* Biozone.

It is possible to observe a general temporal evolution through the Hirnantian, when we look especially at the *T. elongata* species. Indeed, in the lowermost unit (red) it is recorded the appearance of *T. elongata*, with several specimens, but going upwards until the upper member (green) a general decrease of specimens is recorded. This 'disappearance' of *T. elongata* may confirms the end of the homonymous Biozone and the beginning of the *oulebsiri* Biozone at the base of the yellow unit, in the first transgressive facies (shales), even if we do not have evidence of *S. oulebsiri* in our study on Foum Tazzarine.

2.5 Age assignment of the Tafilalt incisions

Bou Kerkour and Jbel Aroudane constitute interfluves areas relative to the incisions and their datation was not defined. The two samples (TVDB 14-012 and JFG 13-107, Fig. 2.7) show a dominance of *R. gracilis* and both contain more or less (due to the poor preservation of the second sample) the same species. The first sample shows a *nigerica* Biozone, in absence of *A.merga* that would define the upper biozone. The second one suggests the *merga* Biozone. Additionally, both samples contain *Sphaerochitina* sp. that is here found higher up to the *merga* Biozone. Nevertheless, Bou Kerkour and Jbel Aroudane interfluves are now defined to be Upper Katian in age.

In the Tafilalt area, numerous incisions needed a detailed study for a chronostratigraphic definition. In general, no reworking fauna has been recorded from the interfluves or from the incisions with glaciomarine deposits. Nevertheless, the lower parts of Istel Hou and Erfoud display reworked chitinozoan assemblages. Istel Hou shows the coexistence of *A. nigerica*, *D. juglandiformis*, and *A. barbata*, in its lower part. These species normally do not coexist in a single biozone, as they are typical of three different time intervals. *A. nigerica* is characteristic of the upper Katian *nigerica* Biozone, *A. barbata* of the lower *barbata*/fistulosa ?? Biozone, and *D. juglandiformis* occur only in the *robusta* Biozone of the Sandbian-early Katian time interval (Paris, 2006). In Erfoud, it is as well in the lower part of the section that the reworking occurs. Here, there is coexistence in the same assemblage of *A. nigerica*, *D. juglandiformis*, and *Sphaerochitina* n. spp. As said above *D. juglandiformis* occurs in a relatively short time interval and it does not reach the *nigerica* Biozone. It is an evidence of the reworking effect. As corresponding deposits infill the lower part of deep incisions (Fig. 2.3 F&G), the reworking is thought to be directly related to the erosion processes, possibly indicating retrogressive, headward erosion concomitant with the initial infill of more distal portions of the incisions.

The Jbel Amessoui and Taghbet el Khir locations are close to each other, but they are in two different depositional setting. The first is for sure located in an incision with glaciomarine deposits and the second is situated eastward in a more doubtful incision, where no time definition was done yet. These two localities show in their lower part (JFPR 14-104 and JFG 13-110, Fig. 2.7) chitinozoan assemblages that are tied to the *elongata* Biozone. This is confirmed by the presence of the key species *T. elongata* in sample (JFG 13-110), but as well by the associated fauna. Species like *E. lepta*, *R. gracilis*, *A. nigerica*, *Belonechitina* spp., *B. micracantha*, etc. are as well present and usually associated to the *elongata* Biozone. An interesting point is that in JFPR 14-104 the chitinozoan fauna suggest the *elongata* Biozone, yet the key species is absent. On the other hand *Sphaerochitina* n. spp. is present and may suggest a return to previous conditions like in the *nigerica* Biozone, where normally this species is found. For the Taghbet el Khir sample there is no doubt, it suggests the *elongata* Biozone and so doing the Hirnantian age.

The Erfoud limestones are particular in their chitinozoan fauna. Indeed, they can be subdivided into three different depositional times. The first, at the base of the section, concern an assemblage that display the presence of *A. nigerica* suggesting that the samples are in an upper Katian time. Additionally, a reworked fauna is suggested because of the coexistence of mainly *A. nigerica, D. juglandiformis*, and *Sphaerochitina* n. spp. (see above). The higher assemblage (ERF 9 to 11) suggests the *elongata* Biozone due to the clear presence of the key species and so doing the Hirnantian time for the overlying upper limestone unit. The middle part of the section is composed by *A. nigerica*, *A. merga*, and *Spinachitina* specimens. These specimens usually compose the *elongata* Biozone, but here *T. elongata* is missing. This middle depositional portion can be considered as *merga* to *elongata* biozones, so a transition from the uppermost Katian to the Hirnantian. However, as it shows the characteristics species of *A. nigerica*, *A. merga*, *E. lepta*, *S. verniersi*, *S. kournaedensis,* a similarity with the upper and younger assemblage at the top of the section is noted, favouring the *T. elongata* Biozone. Once again provided the *elongata* Biozone characterizes the Hirnantian, the Erfoud limestones would thus be fully Hirnantian in age. This conclusion is however in conflict with conclusions derived from macrofaunas (Destombes et al., 1985). If true, our conclusion needs to reassess the significance of the Erfoud limestones and similar “Ashgill” s.l. carbonate platforms in the context of a warming Boda event (Cocks and Fortey, 2004) or of cool-water carbonates (Cherns and Wheeley, 2007).

2.6 Basin axis vs. Basin margins

The basin axis, which is composed of the two sub-zones northern and southern axis of the basin (Fig. 2.8), and its margins (western and eastern) show some differences. The basin axis shows a general abundance of chitinozoan fauna, especially in the Upper Ktaoua Fm. and in the lower member of the Lower 2nd Bani Fm. Additionally, the two zones are characterized by the presence of chitinozoan key species that define the Katian and Hirnantian *nigerica*, *merga*, and *elongata* biozones. In the upper member of the Lower 2nd Bani Fm. it has been found for the first time a chitinozoan assemblage, but a proper datation is difficult due to the absence of the index species *T. elongata* or *S. oulebsiri*. The definition of the Katian-Hirnantian boundary in this area is difficult, but it may be estimated to be close the ouzregui bed of Loi et al. (2010). Moreover, the Hirnantian chitinozoan fauna from the 2nd Bani Group are clearly different from the older one in the Ktaoua Fm. (upper Katian). Indeed, in the Hirnantian time interval the assemblage are clearly characterized by the typical specimens composing the *elongata* Biozone, which are generally of large size, with elaborate morphologies (see the *Spinachitina* genus or *T. elongata*, or others). On the other hand, in the Ktaoua Fm., the chitinozoan are characterized by specimens more simple, of smaller size and characteristics of older biozones (*merga, nigerica*). These differences in morphologies, size, etc., may suggest a Hirnantian faunal turnover and not a faunal migration from proximal to distal during lowstand periods.

Samples of the western margin permitted to identify only the lower member of the Lower 2nd Bani Fm., the chitinozoan fauna did not show the key species indicating the *elongata* Biozone, but the general assemblage suggests this time interval. This is confirmed by other studies in the Central Anti-Atlas (Paris et al., 2000; Bourharouh et al., 2004). On the other side, in the Maïder and Tafilalt area (eastern margin), the study of the chitinozoan fauna permitted to date the large incision of Istel Hou, its neighbouring Jbel Amessoui and Taghbet el Khir, and the easternmost limestones of Erfoud. Here, a reworked fauna in Istel Hou and in the lower part of Erfoud has been found. However, it is the only area in the Central and Eastern Anti-Atlas of this work, where a reworked fauna has been recorded. Nevertheless, the first datation of the Istel Hou incision and the limestones of Erfoud will permit a larger correlation through the entire basin.

On a regional point of view, it is possible to observe that in the Central Anti-Atlas the thick end-Ordovician outcrops permitted a more detailed study on the datation of the incisions as well as chitinozoan biozones determination, and an almost totally Katian-Hirnantian boundary definition. In the Tazekka Massif all these thick outcrops are condensed in few decades of metres. The lower member (red unit) of the Lower 2nd Bani Fm. and the Upper 2nd Bani Fm. are the two formations that correspond to the Tifarouine Fm. in the North Morocco area. The North Morocco chitinozoan biozones (*elongata* and *oulebsiri*) (cf. Figs. 3.6 and 3.7) have not been found both in the Tazekka Massif, but only the *elongata* Biozone. The *oulebsiri* Biozone in the Central Anti-Atlas has not been defined. The South Morocco area, considered as more proximal compare to North Morocco, permit to see all the upper Katian and lower-middle Hirnantian. On the other hand, the Tazekka Massif permits to complete the Central Anti-Atlas succession with the datation of the late Hirnantian time interval, in addition to the upper Katian and lower-middle Hirnantian. Moreover, the Katian-Hirnantian boundary can be more or less traced through the entire Central Anti-Atlas basin until the more distal environment of the Tazekka Massif, even if in North Morocco the boundary remains more doubtful than in the South.

2.7 Merit and pitfalls of the Hirnantian chitinozoan biozones

The Hirnantian chitinozoan biozones are very useful when trying to (relatively) date the end-Ordovician strata in the northern Gondwana margins and especially in areas where no graptolites have been found or no other domains may be helpful for datation. This is the case in Morocco, where graptolites are virtually absent and it exist a sequence stratigraphic succession analysis, but the chronostratigraphic definition of the deposits needs more precision. Thanks to the chitinozoans and their biozones it is possible to date the deposits, but the high dependence of index species that are often poorly preserved to non-existent, with several exception (see chapter 3), require a high systematic sampling, except some luck.

In the Central Anti-Atlas it was no possible to recognize the *oulebsiri* Biozone with our data. In order to support the *oulebsiri* Biozone as a proper unit and to not include it to the preceding biozone (*elongata*), a systematic study of the upper Hirnantian is necessary. Another characteristic of this study is that we recorded a larger time interval concerning the *merga* Biozone and that the *elongata* Biozone is thought to start in the Hirnantian, as it is the case in the Prague Basin. This hypothesis is not totally proved and more work on these two biozones are needed. However, until now, there is no evidence anywhere that *T. elongata* and its homonymous biozone start as early as in the Katian Stage.

2.8 Conclusions

To conclude, this study on the Central and Eastern Anti-Atlas, in South Morocco, revealed remarkable informations. The axial part of the basin permitted to identify mainly three chitinozoan biozones (*nigerica*, *merga*, and *elongata*) corresponding to the upper Katian up to the Hirnantian. On the other hand, the western margin of the basin lacks in palynomorphs and only a single Hirnantian biozone has been recorded (*elongata*). The eastern part of the basin displays several incisions and the easternmost limestones of Erfoud have been dated for the first time. Underlying strata revealed a reworked fauna in the Katian and a Hirnantian biozone (*elongata*) characterize the Erfoud limestones. These results permitted to establish a more complete correlation framework through the entire basin. Moreover, the definition of the Katian-Hirnantian boundary has been traced from the basin axis to the basin margins. At a regional level it is possible to see that the North Morocco (Tazekka Massif) record can complete the end-Ordovician succession of the Central Anti-Atlas, because it essentially shows the upper Hirnantian part, data that are missing in South Morocco due to the presence of thick, erosion-based glaciogenic deposits related to the glacial maximum.

CHAPTER III:

THE CHITINOZOAN RECORD IN THE TAZEKKA MASSIF, NORTHERN MOROCCO: A BENCHMARK FOR THE END-ORDOVICIAN GLACIATION?

Preamble

In chapter 3, the chitinozoan assemblages from the Tazekka Massif, northern Morocco, are investigated. This location represents a relatively deep (100's m), ice-distal depositional setting, which is currently understood as one of the most comprehensive records of the end-Ordovician glaciation. It was thus a key area in the development of the research agenda of the SeqStrat-Ice project. Preliminary results of geochemical analyses are presented as well. It will be shown that chitinozoans of the Tazekka Massif have the potential to fill in the correlative gap between more ice-proximal areas of the Gondwana hinterland and other peri-Gondwana terranes or far-field records (Avalonia and China).

This chapter is written as an article manuscript prepared for submission to *Gondwana Research.* It includes some other members of the SeqStrat-Ice project, as well as external collaborators (Petr Štorch for the study of graptolites; Matthias Sinnesael & Philippe Claeys for $\delta^{13}C_{org}$ analyses). The section and figure numbering are kept in line with preceding and following chapters of this thesis.

3. The chitinozoan record in the Tazekka Massif, northern Morocco: a benchmark for the end-Ordovician glaciation?

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Abstract

The end-Ordovician is well-known as a time interval enduring a widespread glaciation, major faunal turnovers and isotopic excursions. Several gaps, spatially and stratigraphically, affect the secular record of these events worldwide, and in order to fill in the gap between high- and low-palaeolatitude records, we decided to revisit the exposures of the Tazekka Massif in northern Morocco. The Tazekka Massif was close to the Gondwana continental margin and shows a thick (>600 m) Upper Ordovician succession. This near-field but ice-distal setting has the advantage of including direct indicators of the Ordovician ice-sheet activity. The up to 450 m thick, virtually continuous succession through the Katian-Hirnantian boundary and across the Hirnantian marks the Tazekka succession as one of the best places to study an end-Ordovician archive. In this study we specifically explore the potential of chitinozoan biostratigraphy in deciphering the glacial development. Preliminary results in our efforts to construct a $\delta^{13}C_{org}$ curve will also be presented in parallel.

In the study area five chitinozoans assemblages have been identified, corresponding to three successive environmental conditions. Two chitinozoan biozones have been accurately recognized through the Tazekka succession, i.e., the *nigerica* (in Tehar el Brehl Fm.) and *elongata* (in Tifarouine Fm.) biozones. The lowest assemblage corresponds to pre-glacial, Late Katian conditions, the second to the fourth biostratigraphic units correspond to the Hirnantian glacial conditions, and the fifth and highest one may record a recovery assemblage. The position of the Katian-Hirnantian boundary, however, remains debatable. The relatively abundant *Sphaerochitina* genus in the Tazekka Massif, in contrast to its near-absence in the substantially shallower Central Anti-Atlas domain, suggests a living environment such as an open-shelf/deep marine environment before the glaciation and in the early deglaciation. A detailed correlation across the end-Ordovician Gondwana margins — from Morocco to the Prague Basin— has been possible thanks to the presence of marker

fossils such as *T. elongata,* and by using $\delta^{13}C_{org}$ chemostratigraphy. In addition, the occurrence of *B. llangrannogensis* in our work, in Wales, and in South China allows us to suggest worldwide correlations. Finally, the indirect evidence for a glaciation (shifts in the $\delta^{13}C_{org}$ signal and related changes in microfossil assemblages) can be temporally calibrated against a stratigraphic signal directly impacted by the end-Ordovician glaciation.

Keywords

Hirnantian, Palynomorphs, Biostratigraphy, Continental Shelves, Moroccan Meseta, Organic Carbon isotopes.

3.1 Introduction

The end-Ordovician is a time interval enduring a widespread glaciation (Ghienne et al., 2007; Le Heron & Craig, 2008; Pohl et al., 2016), major faunal turnovers and stable isotopic excursions (Melchin et al. 2013; Rasmussen 2011; Hammarlund 2012). Temporal relationships however remain controversial (Delabroye and Vecoli, 2010; Finnegan et al., 2011; Ghienne et al., 2014) in absence of a coupled and comprehensive stratal record that would be comparable to the deep-sea archives exploited in Cenozoic palaeoclimate studies. On the one hand, low-palaeolatitude records, generally from carbonate shelves, show well-defined isotopic excursions and an abundant faunal record, but lack direct evidence of glaciation in the form of glaciogenic sediments. On the other hand, high (southern) palaeolatitude depositional successions preserve a rich glacial record (e.g. Girard et al., 2015), but with poor faunal and isotopic evidence. In both cases, the unravelmet of the glacial development, or the construction of a comprehensive and robust glacioeustatic record, is not straightforward. Major hiatuses related to glacial erosion surface, shelf emersions (incised valley, karst processes), transgressive ravinement surfaces, etc., are an inevitable part of the succession, and in some case poorly recognized. Close to the ice centers, the ice-sheet development is obscured owing to the intricate combination of glacial events from minor re-advances to extensive glacial cycles, and to interferences between the eustatic signal and isostatic processes.

To fill in the gap between these precious but uncompleted, high- and low-palaeolatitude records, we decided to revisit exposures of the Tazekka Massif, northern Morocco (Khoukhi and Hamoumi, 2001; Le Heron et al., 2007, 2008). In this area, lying close to the Gondwana continental margin (Michard et al. 2010), the very thick (> 600 m) Upper Ordovician succession is comprised of mudstones, heterolitics, and sandstones, within which no major erosion surface has been identified, at least not from the Middle Ordovician up to the upper Silurian. This near-field but ice-distal setting in intermediate to high palaeolatitudes has the advantage to include direct indicators of the Ordovician ice-sheet activity (occurrences of glaciomarine input, episodes of enhanced sediment supply highlighting nearby advancing ice fronts). Therefore, the Tazekka Massif is one of the best places to study an end-Ordovician glaciation-related sequence of events, which is here up to 450 m thick and virtually continuous through the Katian-Hirnantian boundary and up to the lowermost Silurian. While the sedimentology and others aspects tied to provenance studies (geochemistry, detrital zircons) will be the focus of companion papers, we more specifically explore in the present contribution the potential of chitinozoan biostratigraphy in deciphering the glaciation development. These organic microfossils have been recovered in large quantities throughout the whole succession, except in the sandstone units ("lowstand wedge" of Le Heron et al., 2008). Chitinozoan assemblages, as do all fossil assemblages, show a substantial degree of provincialism (Paris, 1990; Webby et al., 2004), a feature, which is exacerbated during globally cold conditions (Vandenbroucke et al., 2010). Nevertheless, their planktonic mode of distribution enables and wider spread elements of the faunas open the potential for long-distance correlations. Well-chosen stepping-stone sites between latitudinally distant localities, such as the Tazekka Massif, can be of great help for interlinking distant faunas and provinces. Key species such as *Tanuchitina elongata* or *Belonechitina llangrannogensis* found in the present study have already been found in South China (Wangjiawan) and Wales (Welsh Basin). These species are characteristic of the end-Ordovician and they permit global correlations.

Preliminary $\delta^{13}C_{org}$ results will also be presented in this paper. Trends in the isotopic curve allow us to suggest a detailed correlation with the Prague Basin (Czech Rep.), using the Tazekka record as a landmark between the Anti-Atlas (Gondwana landmass) and peri-Gondwana domains.

3.2 Stratigraphic setting

3.2.1 Geological Setting

From a Palaeozoic point of view, Morocco is comprised of two domains, the Anti-Atlas basin to the South and the Meseta area to the North. The boundary between the two domains essentially consists of fault zones running across the High Atlas (Fig. 3.1).

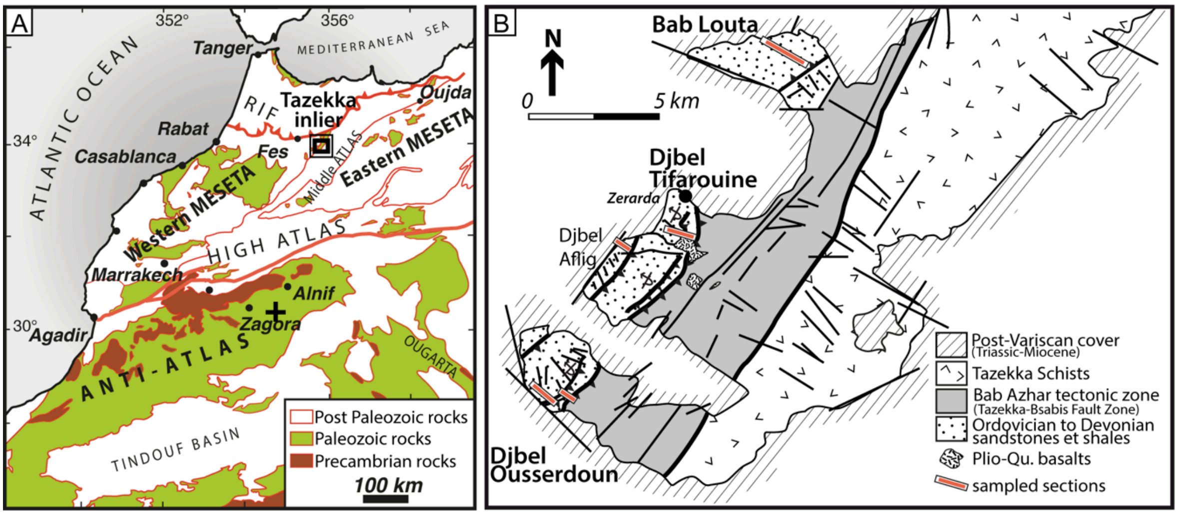

Fig. 3.1 Simplified geological maps of the study area modified from Michard et al., 2008 and Hoepffner, 1987. The black square in (A) locates the southern Tazekka inlier (detailed in B) and the black cross shows the position of the Bou Ingarf type section of the Central Anti-Atlas (Bourarouh et al., 2004 and Loi et al., 2010).

The Anti-Atlas is part of the West African Craton and Gondwana landmass, and the Meseta is a terrane, most often viewed as lying, during the Phanerozoic, northwards and outboard of the West African Craton, in close tectonostratigraphic connection with the Anti-Atlas (Hoepffner et al., 2005; Simancas et al., 2005; Michard et al., 2010; Von Raumer et al., 2015). The Meseta domain is further subdivided in the Western and Eastern Meseta sub-domains, the latter being characterized by an Eo-Variscan tectonic event associated with West to Northwest-verging folds and low-grade to amphibolite-facies metamorphism. Our study area is located in the Tazekka Massif, a Palaeozoic inlier to the West of the Eastern Meseta (Fig. 3.1). It includes three thrust sheets, showing increasing deformation from the West to the East. In the westernmost, less deformed thrust sheet, up to four slices separated by tectonic contacts have been delineated, from which an Ordovician to Devonian succession has been reconstructed (Destombes et al., 1985; Hoepffner, 1987; Amaouain, 1991; Khoukhi and Hamoumi, 2001).

In the Tazekka Massif, most of the Ordovician to Devonian strata record low-energy, shale-dominated depositional conditions. The uppermost Ordovician is a notable exception. At that time, thick, high-energy, relatively coarse-grained sandstones accumulated in relation with the end-Ordovician glaciation (Khoukhi and Hamoumi, 2001; Le Heron et al., 2007, 2008). The Ordovician succession is subdivided in: (i) the Lower to Middle Ordovician fine-grained Bou Chfâa Fm., (ii) the Middle Ordovician sandstones of the Bou Jam-Jam Fm., the Upper Ordovician (iii) fine-grained Tehar el Brehl and (iv) sandstone-dominated Tifarouine formations (Fig. 3.2; Hoepffner, 1987). Overlying the Tifarouine Fm., the Silurian strata are comprised of a relatively thin, condensed black-shale succession, lower Silurian phtanitic beds characterizing its base (see below).

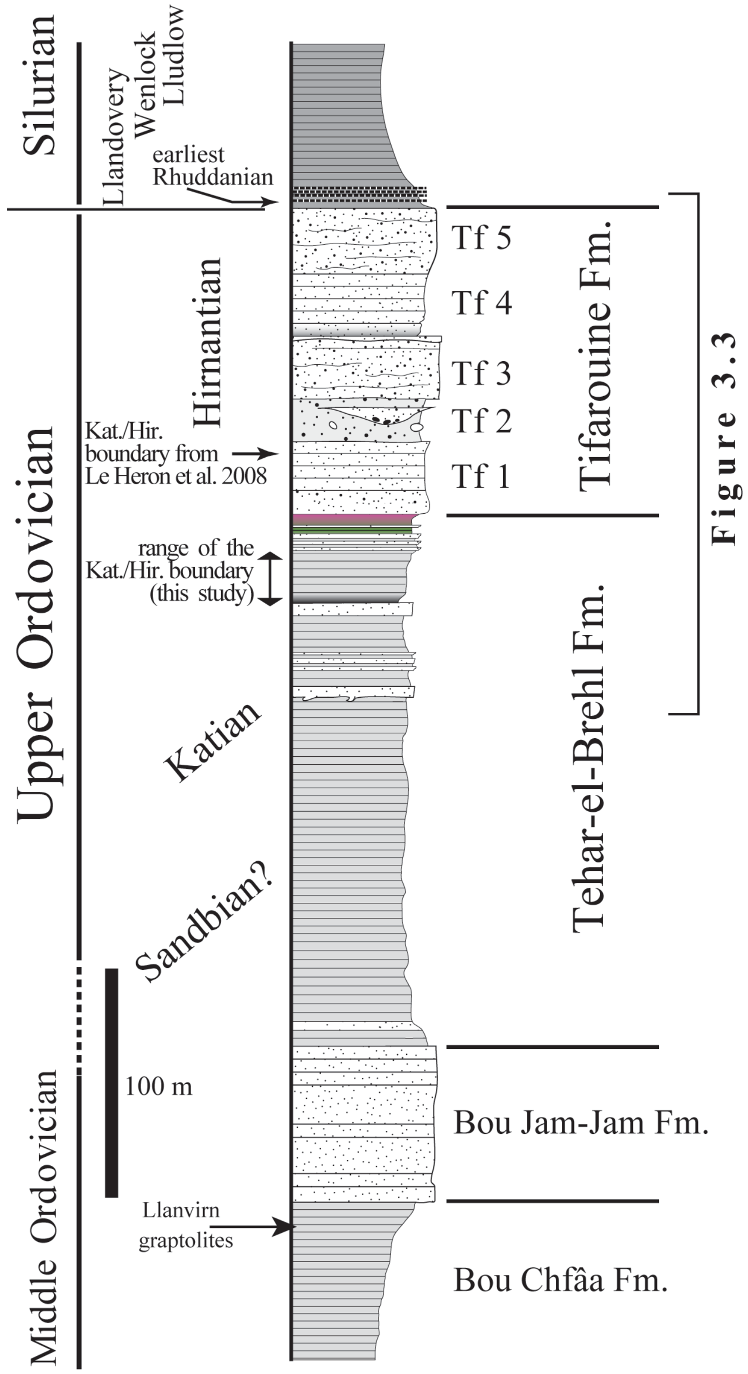

Fig. 3.2 An outline of the Ordovician in the Tazekka Massif (modified from Hoepffner, 1987)

At first order, the Tazekka Ordovician succession was deposited along the most distal, northwest corner of a north-dipping passive continental margin that extended from Morocco to Egypt (Selley, 1997; Boote et al., 1998). The exact status of the Eastern Meseta domain relative to the Gondwana landmass however remains debatable; in some reconstructions, this sub-domain formed an individual basin bounded to the West by the Western Meseta sub-domain and the South by the West African Craton (Khoukhi and Hamoumi, 2001; Le Heron et al., 2007).

3.2.2 The Bou Ayach-Tifarouine type section

In the western Tazekka Massif, Ordovician strata have subvertical to overturned dips. South of the village of Zerarda (Fig. 3.1), the Bou Ayach-Tifarouine exposure offers a thick (up to 600 m) section within a single, tectonic thrust, displaying the upper Tehar el Brehl Fm., the Tifarouine Fm. and the basal Silurian strata (Hoepffner, 1987). Most of the stratigraphic intervals missed in previous studies (e.g., covered areas in Le Heron et al., 2008) have been complemented thanks to additional short sections from nearby outcrops, resulting in a virtually continuous section from the upper Katian to the lowermost Silurian. The area has been logged in detail and extensively sampled for chitinozoan biostratigraphy. Four other main sections (Ousserdoune 1 and 2; Jbel Aflig; Bab Louta, Fig. 3.1) have been logged in order to recognize potential lateral facies changes and to sample additional fine-grained facies that were anticipated to be characterized by a better chitinozoan preservation. No important facies or thickness variations have been highlighted at the regional scale, neither along the 20 km long outcrop belt, nor from one tectonic thrust to another one. Granulometric trends, variations in bed thicknesses and degree of bed amalgamation, as well as limited palaeocurrent indications (ripples, flute-cast) suggest, however, that a proximal to distal gradient may be expressed from the West (NW to SW) to the East (SE to NE). The silty-shale-dominated, bioturbated Tehar el Brehl Fm. (Fig. 3.4, A) includes 4 sandstone intervals —referred to as TB(i)-(iv) horizons (Fig. 3.3)— and a distinctive but poorly outcropping one-meter thick finely laminated shale interval directly overlying TB(iii).

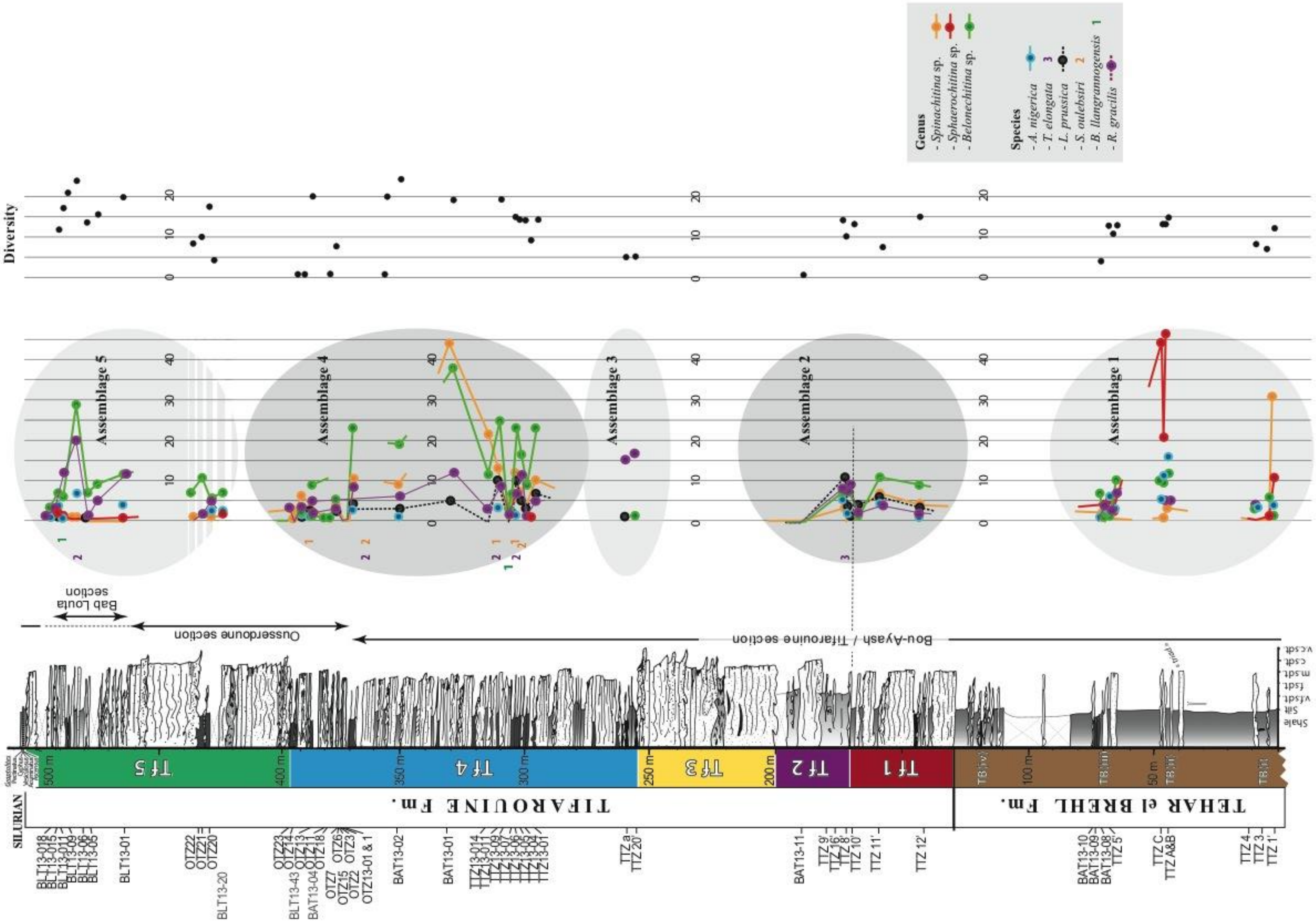

Fig. 3.3 Composite cross-section of the study area, mainly built from the Bou Ayach-Tifarouine type section (lower part; location in Fig. 3.1, A). Upper horizons are taken from the Ousserdoune and Bab Louta sections, which offer a better preserved chitinozoan record. Informal subdivisions are the TB (i)-(iv) sandstone-rich horizons of the Tehar el Brehl Fm., and the Tf1 to Tf5 units of the Tifarouine Fm. Only chitinozoan-bearing samples are reported here. Chitinozoan assemblages are figured, with selected genus and species (see Table 1 for details), and biodiversity curve on the right.

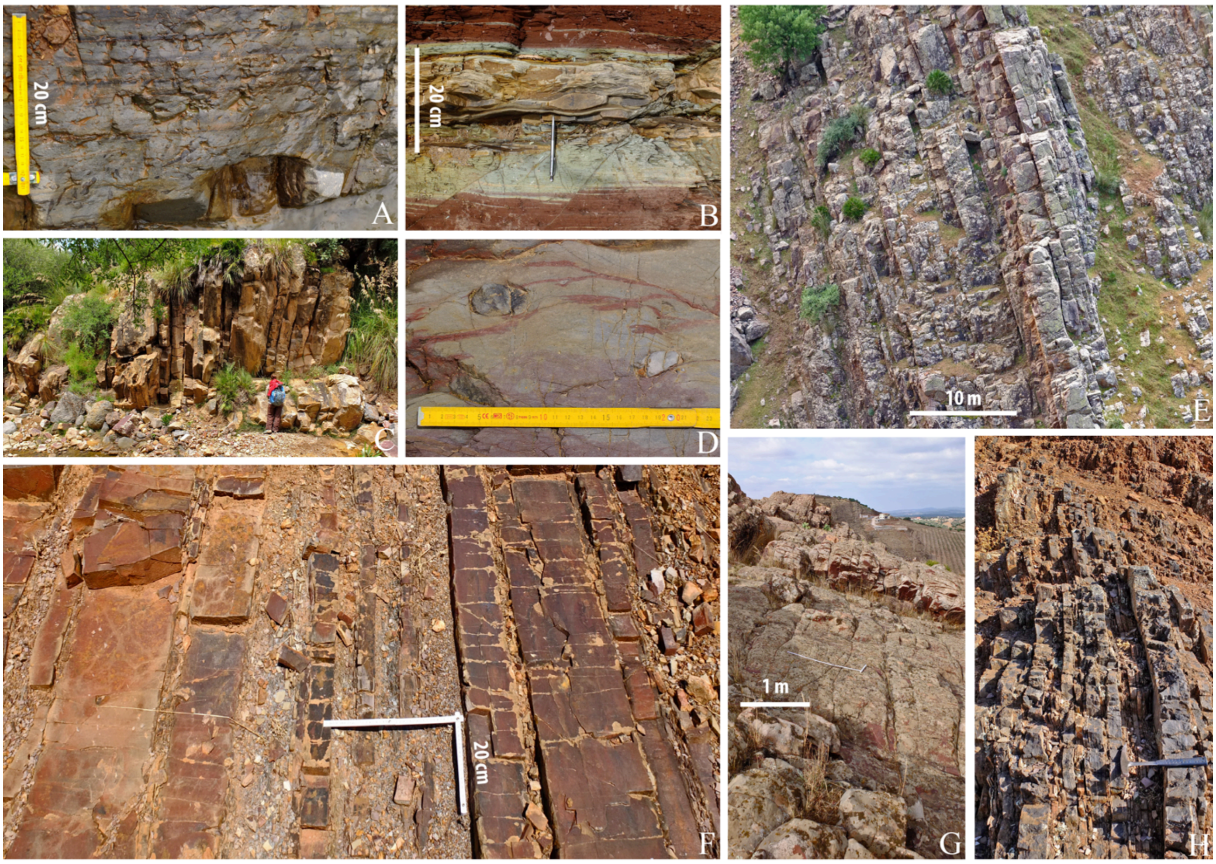

Fig. 3.4 An overview of depositional facies in the Tazekka Massif. (A) Mudstones of the Tehar el Brehl Fm., showing intense burrowing in the lower part of the photograph, and regularly spaced cm-thick darker shales in the upper part. (B) Ripple-cross laminated sandstone bed in the TB(iv) interval, intercalated in green to red siltstones. (C) Thin- to thick-bedded sandstones of the lower Tf1 unit in the Tifarouine Fm. Shaly interbeds provided chitinozoans. (D) Clast-bearing sandy argillaceous diamictite of the Tf2 unit. (E) Amalgamated sandstones beds of the Tf3 unit. Note the thick and erosion-based bedding. No chitinozoan were found in such strata. (F) Thin-bedded sandstones of the middle Tf4 unit, including numerous silty to shaly chitinozoan-bearing interbeds. (G) Amalgamated sandstones beds of the Tf3 unit. (H) Bedded chert, including graptolite-bearing shaly interbeds (Lower Silurian, Middle Rhuddanian). A-D & H: Bou Ayach wadi; E-G: Jbel Tifarouine.

Sandstone beds of TB(i)-(iv) horizons represent either turbiditic event beds or shallow-marine deposits related to lowstand events. A green to red transition is observed in the uppermost siltstones of the Tehar el Brehl Fm., in association with TB(iv) sandstones, which displays distinctive ripple cross-laminations (Fig. 3.4, B). The Tifarouine Fm. is subdivided for this study into five informal, 30 to 100 m thick, depositional units (Fig. 3.3): thin- to thick-bedded sandstones (Tf1, Tf4, Fig. 3.4, C & F), diamictites and sandstone channels (Tf2, Fig. 3.4, D) and amalgamated thick-sandstones beds (Tf3, Tf5, Fig. 3.4, E & G). Our composite cross-section has been built mainly from the Bou Ayach-Tifarouine section. At this particular location, chitinozoan recovery was however poor in the uppermost Tf4 and in Tf5. Our synthetic section thus had to incorporate data from the Ousserdoune (Tf4) and Bab Louta (Tf5) sections, respectively (Fig. 3.3).

It is worth noting that the position of the Katian-Hirnantian boundary is unclear (Fig. 3.2 & 3.6). Based on chitinozoan biostratigraphy, the Hirnantian (*elongata* Biozone) has been previously formally identified in the middle of the Tifarouine Fm. (basal part of our Tf4 unit), and the base of the Hirnantian has been arbitrarily positioned beneath the glaciomarine Tf2 unit (Le Heron et al., 2008). The lower part of the Tifarouine Fm. was thus indirectly attributed to the late Katian (*nigerica* Biozone), lower Ashgill, or time slice 6A of Webby et al. (2004) by comparison with chitinozoan assemblages of the Bou Ingarf section in the Anti-Atlas (Bourahrouh et al., 2004). In the following, we will see that the Katian-Hirnantian boundary in the Bou Ayach-Tifarouine section is suspected to be in a lower position, in the upper Tehar el Brehl Fm.

3.2.3 Depositional conditions

In line with Le Heron et al. (2007), we interpret the whole succession as a relatively deep-marine environment record dominated by low- to high-density turbiditic depositional processes. The pebble-rich diamictites of the Tf2 unit, including in places coarse-grained to conglomeratic sandstone channels bodies, reflect a time interval during which the Tazekka area was in close connection with a glaciomarine depositional environment. Tf1 and Tf4 consist of thin- to thick-bedded (5-50 cm, facies associations 4 & 5 of Le Heron et al., 2008) heterolitic sandstones, including Bouma-like sequences, and flute casts (Fig. 3.4). They relate to a relatively low-energy setting compared to Tf3 and Tf5 (see below), and possibly from turbiditic lobe deposits. Thick (0.3-2 m) amalgamated sandstone beds of Tf3 and Tf5 (facies association 6 of Le Heron et al., 2008) (Fig. 3.4), including subordinate debrite beds, are interpreted as deposition from higher-energy conditions in environments proximal to those of Tf1 and Tf4.

Regarding the overall depositional setting of the Tifarouine Fm., we discard the entirely shallow-marine to deltaic interpretations (Khoukhi and Hamoumi, 2001; Le Heron et al., 2008) on the basis of (i) depositional facies, (ii) the very thick succession relative to the short time interval —a maximum estimate being the 1-2 Myr duration of the Hirnantian stage, but most likely only a fraction of it—, which could only have been accommodated owing to a significant and inherited depositional depth, (iii) the absence of first-order vertical facies changes and of any significant erosion surface in spite of the thick, rapidly accumulated sediment pile, (iv) the occurrence of deep depositional facies beneath and above the glaciation-related Tifarouine Fm., (v) the notable absence of macrofauna, and (vi) the continuous sedimentation at the Ordovician-Silurian boundary (see below). However, whether the depositional setting was tied to an outer shelf or to a deeper setting (basin-floor fan, e.g. at the foot of shelf clinoforms) is at time unclear. Thick amalgamated sandstone successions would constitutes, for this two hypothesis, respectively delta-front “lowstand wedges” (Le Heron et al., 2008) or the proximal portion of a submarine fan (Le Heron et al., 2007). In the glaciation setting, they may be in close connection with subglacial meltwater networks and/or associated with the reworking of shelf material by upslope incisions of valley or canyon during glacio-eustatically-driven sea-level falls/lowstands. The detailed facies analysis of the Tazekka record will be the focus of a forthcoming paper by Girard F. and collaborators and is out of the scope of the present contribution. Independently from the facies interpretations, at least two episodes of enhanced sediment supply are highlighted by the Tf3 and Tf5 units (Le Heron et al. 2007, 2008), the former being more marked. The Tf2 glaciomarine unit may relate to an additional, individual glacial advance.

3.2.4 Lower Silurian strata in the Tazekka

Post-glacial stratigraphic continuity from latest Ordovician to lowest Silurian strata is an issue when dealing with North Gondwana records (e.g., Luning et al., 2000; Nutz et al., 2013). In the Meseta domain, a hiatus of the Rhuddanian is recurrently inferred, the oldest graptolite fauna being usually middle to late Llandovery in age (Destombes et al., 1985; Le Heron et al., 2008). In spite of Variscan tectonic décollement planes generally positioned in the lowermost Silurian shales, stratigraphic continuity is identified in places (Destombes et al., 1985; Willefert & Charrière, 1990), in agreement with (i) the observation of shales with glaciomarine input close to the Ordovician-Silurian transition, (ii) the occurrence of lower Silurian radiolarian-bearing phtanitic beds characterizing the most distal reaches of the Gondwana shelf where post-glaciation stratigraphic continuity is commonly inferred (Barca et al., 1996; Kozlu et al., 2002; Picarra et al. 2009; Ghienne et al., 2010; Martin et al., 2014). In the Tazekka, graptolites of the Rhuddanian were identified (Destombes et al., 1985), but this age assignment is not yet confirmed by palynomorphs (Le Heron et al., 2008). We re-sampled an Ordovician to Silurian succession, including phtanitic beds in a restricted tectonic slice of the Jbel Ousserdoune. Here, the *Akidograptus ascencus* Biozone and *Parakidograptus acuminatus* Biozone are formally identified based on our group's recent collections (P. Štorch, pers. com.) in a one-meter thick shaly interval immediately beneath the first phtanitic bed. It definitely identifies the occurrence of lowermost Silurian strata in the Tazekka area linked to a deep depositional setting. The overlying, graptolite-rich, late lower to upper

Silurian shales are observed in the Tifarouine area. Here, they are ca. 50 m thick and are notably devoid of sandstone or limestone.

3.3 Material and Methods

The investigated material is part of an extensive study and sampling including also the petrography, detrital zircon ages and a sedimentological analysis. Here, we essentially focus on the study of the palynology (chitinozoans) and on the preliminary results of the geochemistry ($\delta^{13}C_{org}$).

A total of 111 samples have been analyzed from the three main sections (Bou Ayach-Tifarouine, upper part of the Ousserdoune and Bab Louta sections), with additional, isolated samples. Sixty-five (58%) of them yielded a total of 5’125 chitinozoan that were individually handpicked and identified. Thermal alteration is responsible for dark to grey coloured vesicles.

All the provided samples have been processed for the palynological analyses at the University of Lille (France). Depending on the available rock sample size, we used ca. 40g of rock for the shales and ca. 100g for the diamictite samples (Tf2 unit and base of Tf4). The analytical protocol comprises crushing the rock samples into 0.5 cm pieces followed by a first acid treatment with 38% HCl over 24h. The residue is then washed with demineralized water, and subject to a second acid treatment with ca. 200 ml 40-45% HF, while being agitated during 12h to 24h. Afterwards, the residues are once again treated with warm 38% HCl to remove any newly formed F-compounds. Finally, the samples are neutralized and filtered at 51µm. The residues on the filters were handpicked using a binocular microscope at 32-63 times magnification, and then studied with a FEI Quanta 200 and LEO 435VP Scanning Electron Microscope (SEM).

The organic carbon isotopes ($\delta^{13}C_{org}$) measurements were carried out at the Vrije Universiteit Brussel (V.U.B.), Belgium. A total of 98 samples from the three main sections have been processed. In the Bou Ayach-Tifarouine section 58 samples have been analyzed (19 from the Tehar el Brehl Fm. and 39 from the Tifarouine Fm.), 21 samples from the Tifarouine Fm. in Ousserdoune, and 19 samples in Bab Louta (5 below the Tehar el Brehl Fm., 2 from the Tehar el Brehl Fm., and 13 from the Tifarouine Fm.).

Powdered samples were weighed (30-60 mg) in silver capsules and decarbonated by adding 5% HCl in steps of 4 hours, reaction in oven at 50°C, till no further reaction occurred. The $\delta^{13}C_{org}$ was measured using a Thermo1112 flash elemental analyzer coupled via a Con-Flo III interface to a Thermo DeltaV isotope ratio mass spectrometer. The international reference standard IAEA-CH-6 was used for calibration. Carbon isotope abundance is expressed as $\delta^{13}C_{org}$ (‰) relative to VPDB (Vienna Pee Dee Belemnite). Standard deviations (1σ) on replicate analyses ($n=3$) are <0.3‰.

3.4 Chitinozoan assemblages

The Bou Ayach-Tifarouine area displays a key section for the end-Ordovician in the study area, but its uppermost part does not yield enough information regarding chitinozoans owing to unfavorable lithologies for palynomorphs recovery. Therefore, data from the Ousserdoune and Bab Louta sections are used to characterize the chitinozoan record of the upper Tf4 and Tf5 units.

From the base to the top, we identify five chitinozoan assemblages (Fig. 3.3): the first one is essentially tied to pre-glacial environmental conditions (Tehar el Brehl Fm.), the second, third, and fourth assemblages correspond to various stages within the glaciation development (lower to middle Tifarouine Fm.). The fifth assemblage suggests a recovery assemblage (uppermost Tifarouine Fm.).

3.4.1 Bou Ayach-Tifarouine (Assemblages 1, 2, 3, and 4)

The Bou Ayach-Tifarouine section intersects the Katian-Hirnantian boundary (Figs 3.1 & 3.6). It yielded a large amount of palynomorphs such as chitinozoans (Plate I), acritarchs, and few scolecodonts (see Le Heron et al. 2008) and four of the five chitinozoan assemblages are identified (Fig. 3.3): Assemblage 1 (Tehar el Brehl Fm.), Assemblage 2 (lower Tifarouine Fm., Tf1 & Tf2), Assemblage 3 (lower Tf4), and Assemblage 4 (middle to upper Tf4). A total of 49 samples from the Tehar el Brehl Fm. to the Tifarouine Fm. were collected and 31 yielded a total of 3,332 chitinozoans (Table 1 and Plate I).

Samples	*Pogonochitina* sp.	*Desmochitina* sp.	*Spinachitina* sp.	*Ancyrochitina* sp.	*Fungochitina* sp.	*Sphaerochitina* sp.	*Tanuchitina* sp.	*Armoricochitina nigerica*	*Conochitina* sp.	*Lagenochitina* sp.	*Calpichitina lenticularis*	*Euconochitina* sp.	*Belonechitina* sp.	*Cyathochitina* sp.	*Desmochitina minor*	*Rhabdochitina gracilis*	*Belonechitina wesenbergensis*	*Cyathochitina campanulaeformis*	*Desmochitina elongata*	*Acanthochitina* sp.	*Angochitina* sp.	*Rhabdochitina magna*	*Angochitina communis*	*Cyathochitina protocalix?*	*Tanuchitina cf. elongata*	*Euconochitina lepta*	*Ancyrochitina merga*	*Belonechitina robusta*	*Lagenochitina baltica*	*Lagenochitina prussica*	*Rhabdochitina claviformis*	*Belonechitina micracantha*	*Tanuchitina elongata*	*Spinachitina oulebsiri*	*Cyathochitina Kuckersiana*	*Spinachitina kourneidaensis*	*Spinachitina verniersi*	*Belonechitina llangrannogensis*	Assemblage	Chitinozoan Biozone	Chronostratigraphy
BLT 13-18						X	X	X	X	X	X	X	X		X	X					X					X													5	*elongata*	HIRNANTIAN
BLT 13-15				X	X	X		X		X	X	X	X	X	X	X				X	X					X				X		X						X			
BLT 13-11			X	X		X	X	X	X	X	X	X	X	X	X	X					X		X		X	X			X		X	X						X			
BLT 13-09			X	X	X		X	X	X		X	X	X	X	X	X			X	X	X	X	X		X	X		X				X	X			X					
BLT 13-06				X					X	X		X	X		X	X			X	X	X								X		X		X									
BLT 13-05							X		X	X		X	X	X	X	X	X	X	X	X	X		X			X						X									
BLT 13-01				X		X		X	X	X	X	X	X	X	X	X		X	X		X	X				X		X	X	X		X									
OTZ 22			X							X		X	X		X													X									X				
OTZ 21		X							X	X		X	X			X	X	X								X		X				X									
OTZ 20			X	X				X	X		X	X	X		X	X							X			X						X			X		X				
BLT 13-20						X		X					X																												
OTZ 23			X								X	X				X																							4		
OTZ 14			X										X														X		X												
BLT 13-43			X						X		X	X	X		X	X			X						X					X		X									
OTZ 13			X	X				X	X		X	X	X			X						X								X		X				X					
BAT 13-04			X	X			X	X	X	X			X	X		X		X		X								X		X		X		X							
OTZ 11												X	X																												
OTZ 18			X						X				X																												
OTZ 7	X		X				X			X	X	X	X		X	X	X	X												X		X						X			
OTZ 6			X	X								X			X	X			X																						
OTZ 15																										X															
OTZ 3	X	X	X		X			X	X	X	X	X	X	X	X	X	X	X	X									X		X		X									
OTZ 2			X	X			X		X		X	X	X	X	X	X	X	X							X		X		X	X											
OTZ 1			X										X	X												X								X		X					
OTZ 13-01			X	X	X						X	X	X	X	X	X																X					X				
BAT 13-02	X		X	X				X	X	X	X	X	X	X	X	X	X	X								X	X	X		X	X	X	X	X		X					
BAT 13-01	X		X	X					X		X	X	X	X	X	X	X	X								X		X		X	X	X			X						
TTZ 13-14			X	X					X	X	X		X		X	X			X									X			X										
TTZ 13-11			X	X			X	X	X		X	X	X		X	X		X	X						X			X	X	X		X	X	X							
TTZ 13-09											X	X	X			X			X																						
TTZ 13-07			X	X							X		X	X	X	X														X											
TTZ 13-06			X					X	X		X	X	X		X	X		X	X				X							X		X	X	X							
TTZ 13-05		X	X								X	X	X		X	X			X		X				X			X		X		X		X							
TTZ 13-04			X			X					X		X		X	X										X				X		X									
TTZ 13-01			X								X	X	X		X	X		X			X				X			X	X	X		X									
TTZ a									X		X		X			X						X								X									3		
TTZ 20'											X				X	X													X												
TTZ 9'			X					X	X		X	X				X		X								X		X	X	X		X	X						2		
TTZ 16'								X	X			X	X	X		X		X										X		X		X									
TTZ 8'			X	X					X		X	X	X	X	X	X		X											X	X		X									
TTZ 10'										X	X		X	X		X													X	X											
TTZ 11'			X	X				X	X		X		X			X		X	X								X	X	X	X	X	X									
TTZ 12'			X	X			X	X	X		X	X	X			X		X		X					X	X	X	X	X	X											
BAT 13-10			X					X					X		X																								1	*nigerica to merga*	KATIAN
BAT 13-09						X	X	X	X	X	X	X	X			X			X			X			X	X															
BAT 13-08			X			X	X	X	X			X	X		X	X						X	X																		
TTZ 5'						X	X	X	X		X	X	X		X	X		X			X	X		X																	
TTZ C			X		X	X	X	X		X	X	X	X		X				X		X		X																		
TTZ B					X	X	X	X		X	X	X	X	X	X	X			X			X																			
TTZ A			X		X	X		X	X		X	X	X		X	X	X	X	X	X	X																				
TTZ 4								X	X	X	X	X	X		X	X																									
TTZ 3						X			X		X	X	X	X	X																										
TTZ 1'	X	X	X	X	X	X	X	X	X	X	X	X	X																												

Table 1 Chitinozoans species from the composite section. Colors highlight chitninozoan assemblages. Colors of the Samples column relate to the stratigraphic units as figured in Fig. 3.3, where samples position are plotted.

Assemblage 1. This assemblage is tied to the Tehar El Brehl Formation (Fig. 3.3). No sample was productive in the upper Tehar el Brehl Fm., most likely due to the alternance of green-red mudstones (Fig. 3.4, B), which commonly are unfavorable for chitinozoan preservation. Assemblage 1 is dominated by *Belonechitina* spp. and *Armoricochitina nigerica*, but it contains as well a medium to high amount of *Rhabdochitina gracilis* and *Spinachitina* spp. Most of the samples have *Sphaerochitina* n. spp. and some samples (BAT 13-01, at the very base of the section; TTZ A, B & C associated with TB(ii)) show a clearly significant amount of *Sphaerochitina* n. spp. (up to 50 specimens). The following associated species are represented in minor quantities: *Calpichitina lenticularis, Desmochitina minor, Desmochitina elongata, Acanthochitina* spp.*, Belonechitina wesenbergensis, Conochitina* spp.*, Euconochitina* spp.*, Rhabdochitina magna, Angochitina* spp.*, Cyathochitina* spp.*, Cyathochitina campanulaeformis, Fungochitina* spp.*, Lagenochitina* spp. (Plate I).

In summary, Assemblage 1 displays a medium to high abundance of chitinozoans and it is characterized by the presence of *Sphaerochitina* n. sp. and *Armoricochitina nigerica*. Assemblage 1 shows a medium ß-diversity in the 7-15 species range. The low diversity (4) of sample BAT 13-10 might be related to the poor preservation of the chitinozoan.

Assemblage 2. This assemblage is identified from the Tf 1 and Tf 2 units of the Tifarouine Fm. This assemblage shows a general dominance of *Belonechitina* spp., *Rhabdochitina gracilis,* and *Lagenochitina prussica,* associated to a medium abundance of *Spinachitina* spp. and *Armoricochitina nigerica.* Other species such as *Calpichitina lenticularis, Desmochitina minor, Belonechitina micracantha, Belonechitina robusta, Conochitina* spp.*, Euconochitina* spp.*, Euconochitina lepta, Tanuchitina elongata, Ancyrochitina* spp.*, Cyathochitina* spp.*, Cyathochitina campanulaeformis, Lagenochitina baltica* are also present, but in minor numbers (Plate I). The presence of three specimens of *Tanuchitina elongata* in the middle part of the assemblage, the absence of *Sphaerochitina* n. spp., and the relevant presence of *Lagenochitina prussica* that was totally absent from Assemblage 1, characterize this second assemblage. It is noteworthy that this chitinozoan assemblage is present from Tf1 to the lower Tf2, i.e., within a glaciomarine facies. However, a drawdown in chitinozoan biodiversity might be suggested by a single sample in the upper Tf2. From Assemblage 1 to 2, the ß-diversity does not change significantly. The disappearance of *Sphaerochitina* n. spp. from Assemblage 2 is worth noticing, suggesting a major change in the depositional environment.

Assemblage 3. The Assemblage 3 relates to only two samples at the base of Tf 4 unit, with poor chitinozoan preservation, one of them corresponding to a fine-grained diamictite (TTZ20'). The two samples however display a distinctive association showing the predominance of *Rhabdochitina gracilis*. They contain as well few specimens of *Calpichitina lenticularis, Desmochitina minor, Belonechitina* spp*., Conochitina* spp*., Rhabdochitina magna, Lagenochitina prussica,* and *Lagenochitina baltica* (Plate I). Assemblage 3 is characterized by the low amount of *Lagenochitina prussica* and the virtual absence of *Spinachitina* spp., species that dominated the Assemblage 2. *Spinachitina oulebsiri* and *Armoricochitina nigerica* have however been recorded from previous studies (cf. Le Heron et al. 2008) in the same level, which were missing in this work (probably due to samples preservation). The appearance of *Spinachitina oulebsiri* might thus be another characteristic of this assemblage, as this species seems to be absent from Assemblage 2. The ß-diversity of Assemblage 3 is reduced relative to other assemblages, but it is suspected that it essentially relates to the preservation of the fauna in this tectonically-deformed horizon, where most of the specimens are fragmented.

Assemblage 4. The last chitinozoan assemblage identified in the Bou Ayach-Tifarouine area corresponds to the lower part of Assemblage 4. Related samples are positioned in the lower to middle part of Tf 4. Assemblage 4 differs from the underlying one by a large abundance and diversified fauna (ß-diversity from 9 to 24) with a complete dominance of *Belonechitina* spp. and *Spinachitina* spp., their proportion in the assemblage being at least twice of that present in assemblages 2 and 3. *Rhabdochitina gracilis* and *Lagenochitina prussica* are the second most abundant species, followed by a series of minor species such as *Armoricochitina nigerica, Calpichitina lenticularis, Desmochitina minor, Desmochitina elongata, Belonechitina, micracantha, Belonechitina robusta, Belonechitina wesenbergensis, Belonechitina llangrannogensis, Conochitina* spp.*, Euconochitina* sp.*, Euconochitina lepta, Rhabdochitina magna, Rhabdochitina claviformis, Spinachitina oulebsiri, Tanuchitina elongata, Tanuchitina* cf. *elongata, Ancyrochitina* spp.*, Angochitina* spp.*, Angochitina communis, Cyathochitina* spp.*, Cyathochitina kuckersiana, Cyathochitina campanulaeformis, Lagenochitina* spp.*, Lagenochitina baltica* (Plate I). This lower part of Assemblage 4 is characterized not only by the large abundance of *Belonechitina* spp. and *Spinachitina* spp., but also by the presence of Hirnantian key species such as *Tanuchitina elongata, Spinachitina oulebsiri* (Bourahrouh et al., 2004; Paris et al. 2000), and *Belonechitina llangrannogensis* (Challands et al., 2014; see also Chapter 4).

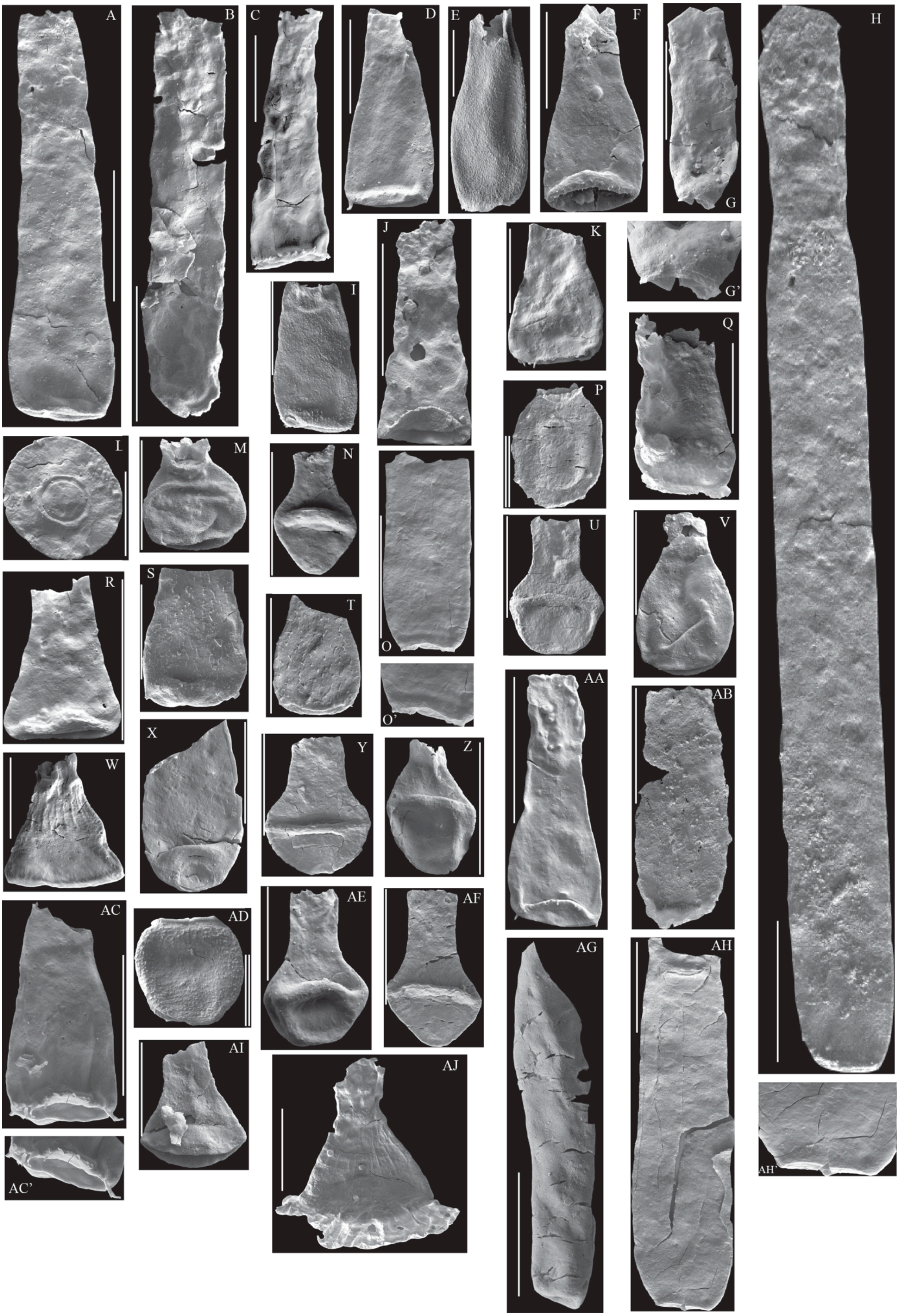
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Plate I

Plate I. Late Ordovician chitinozoans from the Bou Ayach-Tifarouine section, Tazekka Massif, northern Morocco. The scale bar represents 100µm, the double scale bar represents 50µm.

A: *Rhabdochitina claviformis* (BAT 13-01_030); B and AH: *Rhabdochitina gracilis* (BAT 13-01_177, TTZ C_084); C: *Spinachitina* spp. (BAT 13-02_078); D: *Spinachitina* spp. (BAT 13-04_001); E: *Acanthochitina* spp. (BAT 13-04_032); F: *Spinachitina* spp. (TTZ 1'_026); G and G', O and O', AG and AG': *Tanuchitina elongata* (TTZ 9_012, TTZ 13-11_134, TTZ 13-11_109); H: *Rhabdochitina magna* (TTZ a_040); I: *Belonechitina robusta* (BAT 13-02_105); J: *Belonechitina micracantha* (BAT 13-01_253); K: *Spinachitina* spp. (BAT 13-01_156); L: *Calpichitina lenticularis* (BAT 13-01_263); M: *Lagenochitina prussica* (BAT 13-04_027); N, U, Y, Z, AE, AF: *Sphaerochitina* n. spp. (TTZ 1'_265, TTZ C_084, BAT 1308_037, BAT 13-09_013, TTZ 1'_329, TTZ Bb_144); P: *Desmochitina elongata* (TTZ Bb_138); Q: *Armoricochitina nigerica* (BAT 13-09_022); R and AI: *Euconochitina lepta* (BAT 13-02_093, BAT 13-09_004); S and T: *Angochitina communis* (BAT 13-01_014, TTZ 13-06_018); V: *Lagenochitina baltica* (TTZ 11'_097); W: *Cyathochitina campanulaeformis* (TTZ 11'_120); X: *Conochitina* spp. (TTZ 13-06_024); AA: *Spinachitina ?verniersi* (TTZ 13'_169); AB: *Acanthochitina* spp. (TTZ 12'_064); AC and AC': *Spinachitina* spp. (TTZ 13'_038); AD: *Desmochitina minor* (TTZ 5_001); AJ: *Cyathochitna kuckersiana* (BAT 13-01_165).

3.4.2 Ousserdoune (Assemblages 4 & 5)

The Ousserdoune section is a complementary section that allows the investigation of the chitinozoan content of the Tf 4 and Tf 5 units of the Tifarouine Fm. A total of 32 samples have been analyzed, and 20 yielded a total of 671 chitinozoans (Tabel I; Plate II). In this section, we delineated the upper part of Assemblage 4 and the lower part of Assemblage 5 (Fig. 3.3).

Assemblage 4. In the upper Tf 4 unit, the chitinozoan assemblage is dominated by the *Spinachitina* sp., *Rhabdochitina gracilis*, and *Belonechitina* spp. species, which is the feature of Assemblage 4 in the Bou Ayach-Tifarouine section. In addition, it contains as well few *Armoricochitina nigerica, Calpichitina lenticularis, Desmochitina minor, Desmochitina elongata, Belonechitina micracantha, Belonechitina robusta, Belonechitina wesenbergensis, Belonechitina llangrannogensis, Conochitina* spp*., Euconochitina* spp*., Euconochitina lepta,* *Spinachitina verniersi, Tanuchitina* spp.*, Tanuchitina* cf. *elongata, Ancyrochitina* spp.*, Angochitina communis, Cyathochitina* spp.*, Cyathochitina campanulaeformis, Fungochitina* spp.*, Lagenochitina prussica,* and *Lagenochitina baltica.*

The assemblage 4 in Ousserdoune differs from that of Bou Ayach-Tifarouine first by a reduced abundance of chitinozoans and second by the near-disappearance of *Lagenochitina prussica*. The presence of a specimen of *Belonechitina llangrannogensis* is noted, but here the species *Spinachitina oulebsiri* and *Tanuchitina elongata* are absent. The ß-diversity curve in Ousserdoune is more irregular, ranging from 2 to 20. As depositional conditions are very comparable in the Bou Ayach-Tifarouine and the Ousserdoune area, these differences are considered to display a stratigraphic evolution associated with the upper Tf4.

Assemblage 5. The fine-grained interval in the otherwise sandstone-dominated lower Tf5 yield a chitinozoan assemblage referred to as Assemblage 5, as described from the Bab Louta section. In Ousserdoune, this assemblage shows a predominance of *Belonechitina* spp. and *Rhabdochitina gracilis*, though less abundant than in Assemblage 4. Other species such as *Calpichitina lenticularis, Desmochitina minor, Belonechitina micracantha, Belonechitina robusta, Conochitina* spp.*, Euconochitina* spp.*, Euconochitina lepta, Spinachitina* spp.*, Spinachitina verniersi, Ancyrochitina* spp.*, Angochitina communis, Cyathochitina kuckersiana, Cyathochitina campanulaeformis, Lagenochitina* spp.*, Lagenochitina prussica,* and *Lagenochitina baltica* are also present. However, the re-appearance of *Armoricochitina nigerica* and *Sphaerochitina* n. spp. is noted, which is a clear difference with Assemblage 4, making a transition with an upper Assemblage 5. Also, the Hirnantian key species (*Tanuchitina elongata*, *Spinachitina oulebsiri*, and *Belonechitina llangrannogensis*) are notably absent.

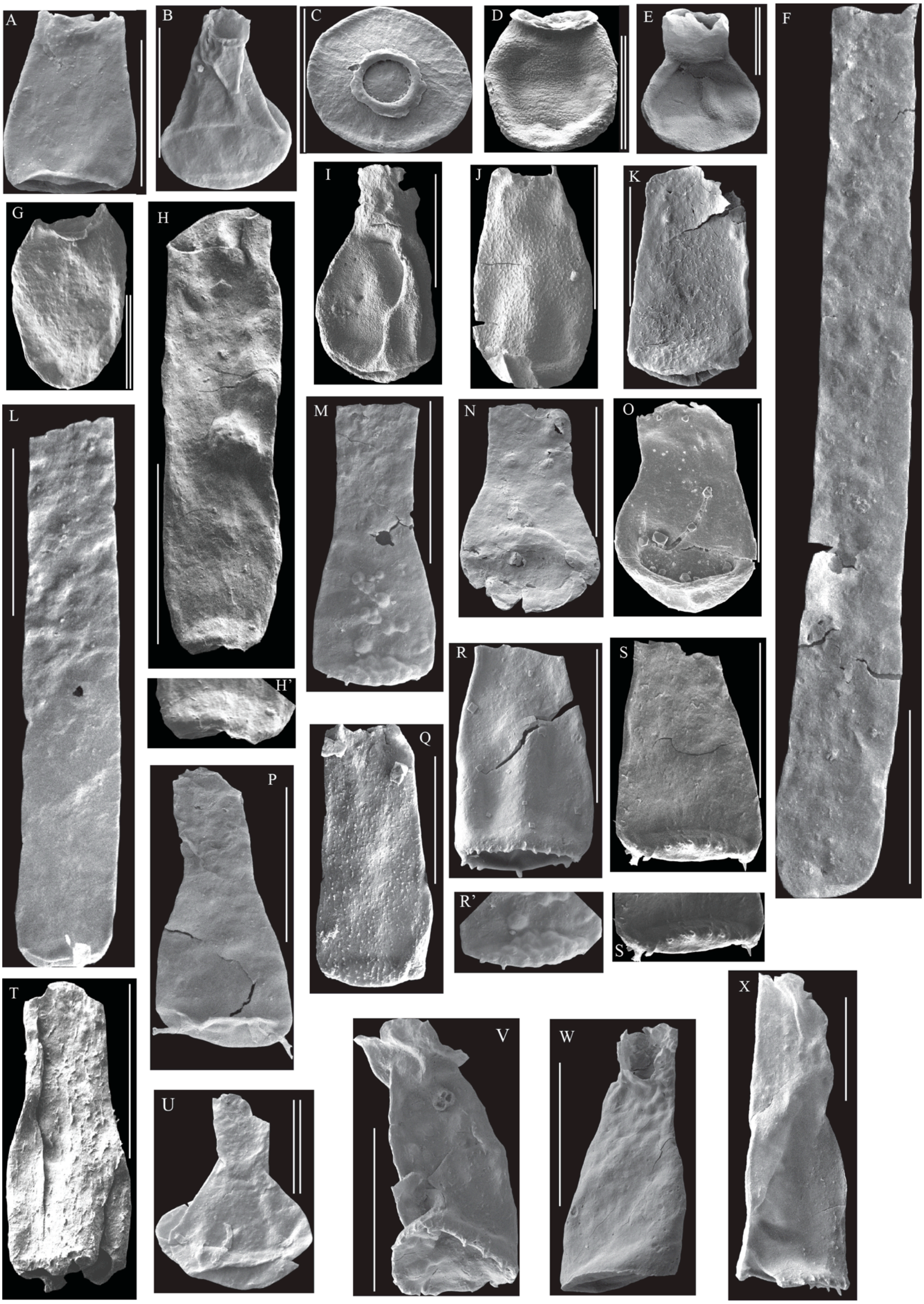

Plate II

Plate II Late Ordovician chitinozoans from the Ousserdoune section, Tazekka Massif, northern Morocco. The scale bar represents 100µm, the double scale bar represents 50µm.
A: *Armoricochitina nigerica* (OTZ 13_003); B: *Euconochitina lepta* (OTZ 1_004); C: *Calpichitina lenticularis* (OTZ 20_010); D: *Desmochitina minor* (OTZ 13-003_087); E: *Lagenochitina prussica* (OTZ 13-023); F: *Rhabdochitina magna* (OTZ 23_008); G: *Desmochitina elongata* (OTZ 6_029); H and H': *Tanuchitina elongata* (OTZ 2_071); I: *Lagenochitina baltica* (OTZ 13-003_058); J and Q: *Belonechitina robusta* (OTZ 13-03_115, OTZ 13-07_021); K: *Belonechitina* spp. (OTZ 22_020); L: *Rhabdochitina gracilis* (OTZ 23_014); M: *Spinachitina* cf. *oulebsiri* (OTZ 1_025); N and O: *Sphaerochitina* spp. (OTZ 20_008, OTZ 21_017); P: *Spinachitina* aff. *cervicornis* (OTZ 13_015); R, R', S, and S': *Spinachitina fossensis* (OTZ 13-01_031, OTZ 13-003_015); T: *Belonechitina wesenbergensis* (OTZ 2_0024); U: *Spinachitina* spp. (OTZ 20_020); V: *Spinachitina ?coronata* (OTZ 13_027); W: *Cyathochitina campanulaeformis* (OTZ 20_019); X: *Ancyrochitna* spp. (OTZ 14_029).

3.4.3 Bab Louta (Assemblage 5)

The Bab Louta section, in a likely more distal position compare to the two other sections (see 3.2.2), is used to characterize the chitinozoan assemblage in the uppermost horizons of the Tf5 unit (Fig. 3.3). A total of 29 samples have been analyzed, and 13 yielded a total of 941chitinozoans (Table 1; Plate III).

Assemblage 5. The assemblage is characterized by a large abundance of *Belonechitina* sp. and *Rhabdochitina gracilis*, associated to *Armoricochitina nigerica,* and in minor quantities *Calpichitina lenticularis, Desmochitina minor, Desmochitina elongata, Acanthochitina* spp.*, Belonechitina micracantha, Belonechitina robusta, Belonechitina wesenbergensis, Belonechitina llangrannogensis, Conochitina* spp.*, Euconochitina* spp.*, Euconochitina lepta, Rhabdochitina magna, Rhabdochitina claviformis, Spinachitina* spp.*, Spinachitina kourneidaensis, Tanuchitina* spp.*, Tanuchitina elongata, Tanuchitina* cf. *elongata, Ancyrochitina* spp.*, Angochitina* spp.*, Angochitina communis, Cyathochitina* spp.*, Cyathochitina campanulaeformis, Fungochitina* spp.*, Lagenochitina* spp.*, Lagenochitina prussica, Lagenochitina baltica and Sphaerochitina* n. spp.. Assemblage 5 in Bab Louta assemblage thus displays a diversified fauna with the presence of *Belonechitina llangrannogensis* and *Tanuchitina elongata*, but from which *Spinachitina oulebsiri* is absent.

The main differences between Assemblage 5 and Assemblage 4 are the large drop of *Spinachitina* spp., the almost disappearance of *Lagenochitina prussica*, the re-appearance of *Armoricochitina nigerica* and of *Sphaerochitina* n. spp., even if in small quantities, which featured Assemblage 1 (Tehar El Brehl Fm). Though the presence of *Sphaerochitina* n. spp. may relate to the more distal position of the Bab Louta section, the onset of Assemblage 5 in the proximal Ousserdoune section suggests that it relate to a temporal signal, rather than to a change in basin-scale distribution of the chitinozoan assemblage.

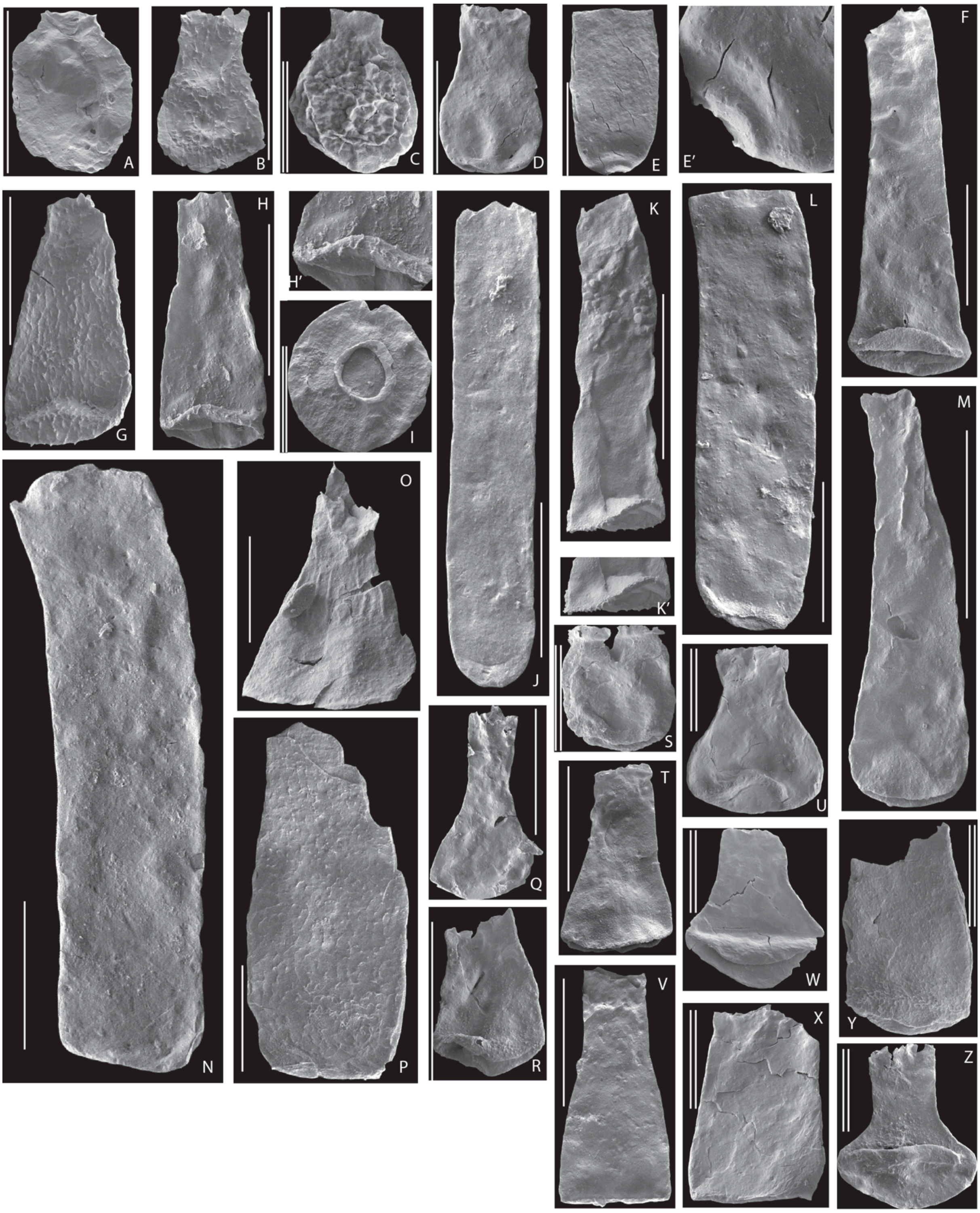

Plate III

Plate III Late Ordovician chitinozoans from the Bab Louta section, Tazekka Massif, northern Morocco. The scale bar represents 100µm, the double scale bar represents 50µm.

A: *Desmochitina elongata* (BLT 13-01_055); B: *Angochitina communis* (BLT 13-01_070); C: *Lagenochitina prussica* (BLT 13-06_054); D: *Lagenochitina baltica* (BLT 13-06_063); E and E': *Conochitina* spp. (BLT 13-06_076); F: *Belonechitina micracantha* (BLT 13-09_012); G: *Belonechitina wesenbergensis* (BLT 13-05_063);

H and H': *Spinachitina* spp. (BLT 13-09_057); I: *Calpichitna lenticularis* (BLT 13-09_079); J: *Rhabdochitina gracilis* (BLT 13-09_099); K and K': *Spinachitina* spp. (BLT 13-09_159); L: *Tanuchitina* cf. *elongata* (BLT 13-09_043); M: *Rhabdochitina claviformis* (BLT 13-11_065); N: *Rhabdochitina magna* (BLT 13-09_49); O and V: *Cyathochitna campanulaeformis* (BLT 13-09_106, BLT 13-09_144); P: *Belonechitina llangrannogensis* (BLT 13-09_087); Q: *Ancyrochitina* spp. (BLT 13-11_011); R: (BLT 13-09_058); S: *Desmochitina minor* (BLT 13-15_013); T and U: *Euconochitina lepta* (BLT 13-09_015, BLT 13-15_030); W and Z: *Spaherochitina* n. spp. (BLT 13-15_039, BLT 13-18_037); X: *Armoricochitina nigerica* (BLT 13-15_062); Y: Belone*chitina llangrannogensis?* (BLT 13-015_017).

3.5 Carbon isotopes

We collected 98 samples for $\delta^{13}C_{org}$ analyses from silty shale and diamictites of the Tehar el Brehl and the Tifarouine Fms. As for chitinozoans, samples are from three sections (Bou Ayach-Tifarouine, Ousserdoune and Bab Louta, Fig. 3.5), the combination of the three sets providing a composite isotopic signal through the upper Katian to the Hirnantian (Fig. 3.6). Isotopic values of organic carbon are comprised between -32 and -25‰, similar to those obtained worldwide in coeval strata (Underwood et al. 1997; Fan et al., 2009; Vecoli et al., 2009; Melchin et al., 2013). A number of fluctuations (or excursions?) are noted, which have magnitude higher than (i) variations noted on a selection of sample duplicates (<1‰), (ii) the range of sample-to-sample variations in one section (<2‰), and (iii) the range of sample-to-sample from one to another section. Our $\delta^{13}C_{org}$ values are thus viewed as a robust, representative isotopic signal at least at basin-scale.

$\delta^{13}C_{org}$ values decline rapidly in the lowermost part of the section, down to values around -30‰. Whether a baseline value can be identified or not is not clear from our data set since up to 2‰ fluctuations characterize the $\delta^{13}C_{org}$ values within the upper Tehar el Brehl Fm. Significantly higher $\delta^{13}C_{org}$ values are recorded in three samples of the uppermost Tehar el Brehl Fm., in association with the green to red transition in mudstone facies. The lower part of the Tifarouine Fm. (Tf1) displays a well-defined descending trend from -26.5 to -31‰, peaking in the basal glaciomarine diamictites of the Tf2 unit. However, a single sample in the diamictite unit in the Ousserdoune section shows the higher $\delta^{13}C_{org}$ value at -25.1‰. No isotopic signal is recorded in the sandstone-dominated Tf3 unit. Most of the Tf4 unit is characterized by relatively stable $\delta^{13}C_{org}$ values that essentially hover between -31 and -30‰, though sample-to sample variations typically reach 2‰. A strong, short-term excursion is recorded in the upper Tf4 unit, yet its rising limb is not captured. After a peak value at -25.3‰, a rapid recovery down to values around -30‰ is evidenced. A last fluctuation (drop in values) is recorded within the upper part of the Tf5 unit. In summary, and excluding the basal Tehar el Brehl record, there is an initial, positive excursion with a rising limb in the upper Tehar el Brehl Fm. and a descending limb in the lower Tifarouine Fm. Above, a slightly rising baseline from the lower Tf4 to the upper Tf5 units is noted, which is interrupted by two short-term positive fluctuations. The lower one is the more pronounced (ca. 5‰), comparable to other shifts commonly seen in isotopic Hirnantian records.

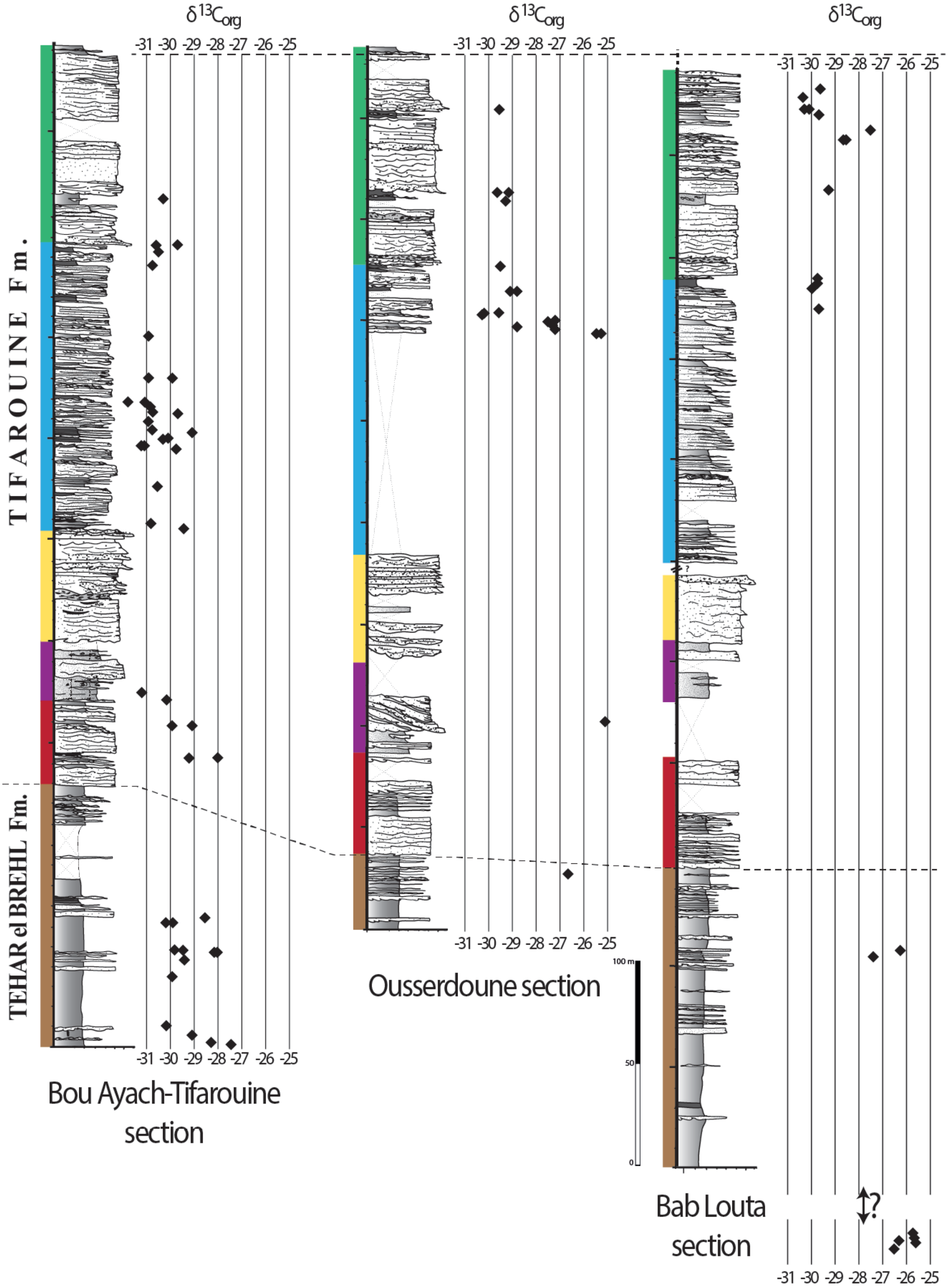

Fig. 3.5 $\delta^{13}C_{org}$ values from the three sections (Bou Ayach-Tifarouine, Ousserdoune, and Bab Louta).

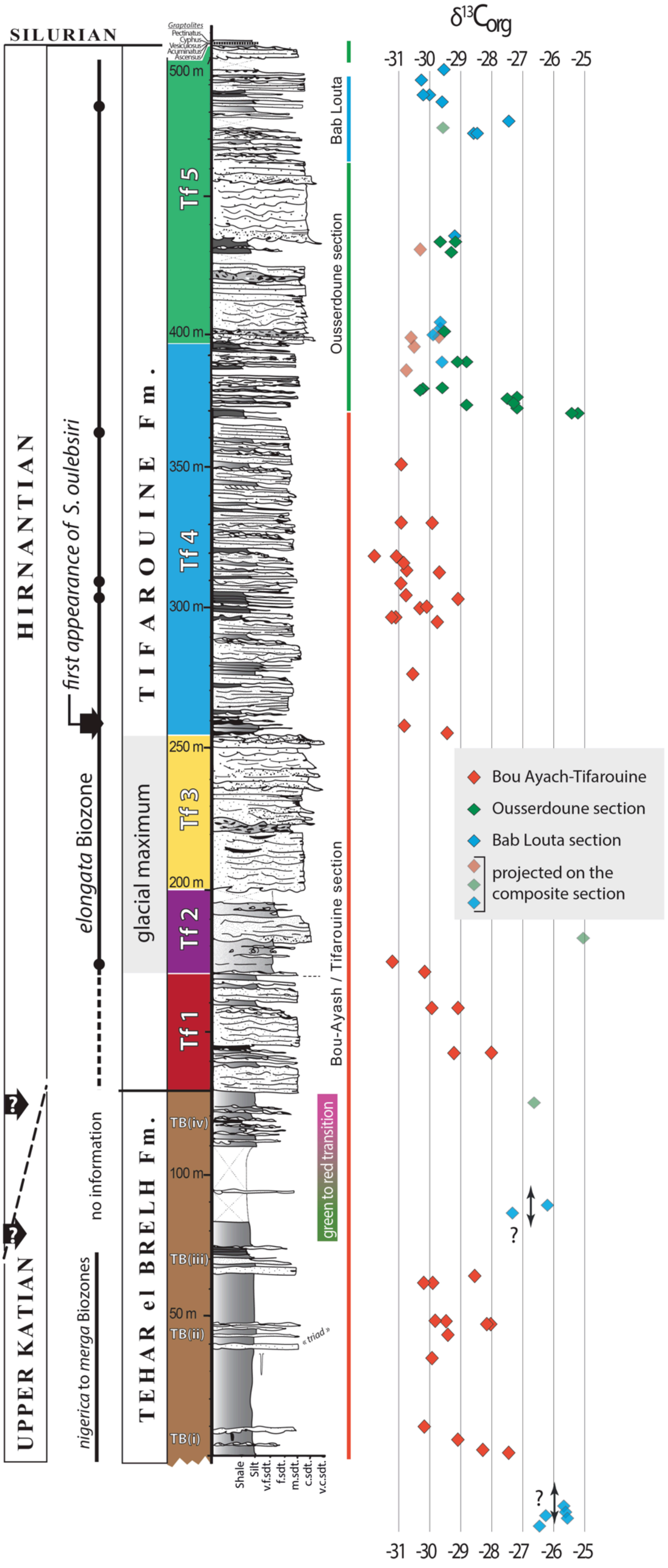

Fig. 3.6 Summary of $\delta^{13}C_{org}$ plotted relative to the composite stratigraphic section through the upper Katian to Hirnantian of the Tazekka Massif. Black arrows are potential position of the Katian-Hirnantian boundary as discussed in the text. The lower one will be favored, considering the correlation with the Prague Basin section (see section 3.9 and Fig. 3.7). TF 1 to 5 correspond to Tifarouine Fm. units and TB (i)-(iv) correspond to Tehar el Brehl Fm. units.

3.6 Age assignment

Originally, the sandstone-dominated Tifarouine Fm. was thought to be closely related to the end-Ordovician glaciation (Khoukhi and Hamoumi, 2001). According to palynomorphs, the Tifarouine Fm. was attributed to the upper Katian-Hirnantian, with a Katian-Hirnantian boundary placed within the Tifarouine Fm. at the base of the first thick sandstone horizon occurring immediately below the first glaciomarine deposits (Fig. 3.2; Le Heron et al., 2008). They formally identified the Hirnantian only high in the section (in the basal Tf4 unit), but in absence of the *T. elongata* index fossil.

A. nigerica is present in Assemblage 1, unambiguously characterizing the end-Ordovician, and possibly the upper Katian *nigerica* Biozone based on the numerous specimens of the key species (Paris, 1990; Paris et al., 2000; Webby et al., 2004). Therefore, contrary to Le Heron et al. (2008), who suggested that the Tehar el Brehl Fm. —and our associated Assemblage 1— represented the middle Katian *barbata/fistulosa* biozone, we here present evidence that the upper part of this formation is significantly younger. However, in the absence of *A. merga* or associated species (*E. lepta, L. prussica*, etc.), the uppermost Katian *merga* Biozone cannot be formally distinguished, even if the relative rarity of *A. nigerica* in the upper horizons displaying the Assemblage 1 may suggest that the Assemblage 1 includes successively the two upper Katian biozones.

Within the Tifarouine Fm., *T. elongata*, the index species of the homonymous biozone, is identified in Assemblages 2, 4 and 5. In North Gondwana, this species characterizes all the glaciation-related deposits, particularly the glaciomarine successions (Paris et al.1995; Vandenbroucke et al. 2010). However, it also characterizes in places —such as in the Central Anti-Atlas, southern Morocco— certain pre-glacial Hirnantian strata preceding the englaciation (Bourahrouh et al., 2004; Videt et al., 2010). Assemblage 2, which characterizes the whole Tf1 unit, starts very close to the base of the Tifarouine Fm., strongly suggesting the latter is entirely Hirnantian, in contrast with Le Heron et al. (2008). In addition, *S. oulebsiri* is recorded throughout Assemblage 4. It shows that the upper Tifarouine Fm. records the first appearance of the key species of the *oulebsiri* Biozone, "late" Hirnantian in age (Paris et al., 2000; Videt at al., 2010), yet its stratigraphic utility in the Tazekka context is questionable (see below). We will expand on the significance of *B. llangrannogensis* in Assemblages 4 and 5 later in section 3.9.

In Assemblage 5, there is no predominance of a *C. caputoi/C. kuckersiana* complex sensu Thusu et al. (2013) and/or *E. moussegoudaensis* (Le Hérissé et al., 2013; Thusu et al., 2013; Paris et al., 2013), and/or *S. oulebsiri* (Vandenbroucke et al., 2009) suggesting that Assemblage 5 (and Tf5) is probably not latest Hirnantian in age. The lowermost Silurian is identified owing to graptolites in overlying beds (see section 3.2.4 and Appendix), uppermost Hirnantian deposits are suspected to correspond to condensed horizons that we did not identify, unless the aforementioned fauna only characterized the most inner domains of the continental shelves.

According to our revised biostratigraphic scheme, the Katian-Hirnantian boundary is most likely positioned in between Assemblages 1 and 2, where no sample from any of the studied sections was productive. This interval, corresponding to the upper Tehar el Brehl Fm. is coincident with a major change assuming that the transition from green to red mudstones and other higher frequency red-green alternations (Fig. 3.4, B) are related to changing redox conditions in the basin (McLaughlin et al., 2012). Considering that the *elongata* Biozone starts well below the first sharp-based contact of shallow-marine deposits over offshore shales in Bou Ingarf, Central Anti-Atlas (Loi et al., 2010; Fig. 3.1, A), the Katian-Hirnantian boundary is most likely located within the upper Tehar el Brehl Fm., above the TB(iii) sandstone interval, or above or below TB(iv) (Fig. 3.6). As a working hypothesis, we proposed that the Katian-Hirnantian boundary would positioned closed to the black shale horizon just at top of the TB(iii) interval, which may be the signature of the major basal Hirnantian transgression, and considering that the higher ripple-cross laminated sandstones of TB(iv) may highlight the first arrival of glaciation-related clastics in the basin (Fig. 3.6). This view will be substantiated below using chemostratigraphy.

3.7. Biodiversity trends

In the Tazekka Massif, the biodiversity is similar to that observed in the more proximal Bou Ingarf section (Bourahrouh et al., 2004), however with some isolated samples in the upper Tifarouine Fm. showing higher values (>20) than in the Central Anti-Atlas. Combined with the lower Hirnantian chitinozoan record of Bou Ingarf section, which correspond to horizons not represented in the Tazekka section (see below), no drop in diversity is noted neither from the upper Katian to the 'lower' Hirnantian (Bou Ingarf record), nor from the 'lower' to the 'upper' (not uppermost) Hirnantian (Tazekka record). Thus, in what concerns the chitinozoan fossil record, we could not observe the signature typical of the classic Hirnantian faunal crisis tied to the end-Ordovician glaciation in this distal part of the north Gondwana continental margin. However, we cannot exclude that a short-lived event (with no long-term consequences) might have been missed in the upper Tehar el Brehl Fm. The distal, deep depositional setting of the Tazekka might have escaped significant perturbation of associated ecological niches owing to sea-level changes. However, this may be recorded in the proximal depositional setting of the Central Anti-Atlas. In addition, or alternatively, the lack of any significant hiatus in this section (Tazekka) that experienced a virtually continuous sedimentation, did not favored the expression of a disruption in the biodiversity curve. Our data set, which lacks middle Katian samples, does not allow us to outline the drop in diversity that globally characterizes the upper Katian preceding the end-Ordovician glaciation (Achab and Paris, 2007).

Another significant conclusion is that the glacial environment *sensu largo* is not especially unfavorable to the occurrence of chitinozoans. This is patent when considering that Assemblage 2 remains essentially unchanged from Tf1 to Tf2. In Assemblages 2 and 3, chitinozoan content and biodiversity do not change whether glaciomarine diamictites (Fig. 3.4, D) or 'regular' silty shale facies are investigated. The possibility of chitinozoan reworking has been here envisioned (e.g. Paris et al., 2015), but the occurrence of the index species *T. elongata* specifically in the glaciomarine facies, but absent from the underlying horizons, argues against this hypothesis.

Through the entire section, a general pattern in chitinozoan distribution characterizes the Tazekka Massif, i.e., the covariance of *Belonechitina* sp. and *R. gracilis* (Fig. 3.3), with prevalence of the former. The two samples of Assemblage 3 are the only exception. In Assemblages 2 and 4, this co-variance also includes *Spinachitina* sp. and *L. prussica.* In contrast, in Assemblage 1 and 5, where *L. prussica* is virtually absent, this co-variance does not involve anymore *Spinachitina* sp., which is a subordinate species (except in sample TTZ1'). Similar environmental conditions are inferred throughout the main part of the glacially-related Tifarouine Fm., with a final trend returning toward initial conditions that prevailed before the glaciation onset. The occurrence of *Sphaerochitina* n. sp. throughout Assemblage 1 (Tehar el Brehl Fm.), where it is predominant in silty shales associated with TB (i), and in Assemblage 5 reflects a similar signal. Relatively shallow and/or proximal (nearby shorelines) environments, or links with ocean geochemistry, may be suggested during deposition of the glaciation-related Tifarouine Fm. Whatever the explanation, the re-appearance of *Sphaerochitina* n. sp. and the decoupling of *Spinachitina* sp. relative to co-variance patterns at the top of the section is viewed as a late- to post-glacial recovery signal. Moreover, in this work there is no evidence for a reworking of fauna, which, in contrast, is a feature in some areas of the Anti-Atlas or other parts of the glacially-impacted North-Gondwana platform (Paris et al., 2007, 2015).

3.8. Regional correlation

One of the main issues in end-Ordovician studies is to build robust stratigraphic correlations through multiphased glacially-controlled depositional sequences linking ice-proximal to ice-distal settings (Ghienne, 2003, Le Heron et al., 2006; Ghienne et al. 2007), or near-field to far-field settings relative to the ice centers (e.g. high southern vs. intermediate latitudes of Gondwana, or Gondwana vs. Laurentia; Bergström et al., 2006; Melchin et al., 2013; Ghienne et al., 2014). In this section, the regional-scale relationships of the ice-distal Tazekka section with that of Bou Ingarf, which is a representative of the end-Ordovician glacial record in the Anti-Atlas (Loi et al., 2010), are inspected. Potential global correlations are discussed in a following section.

At time, the Bou Ingarf section lay at 500 km to the SSE of the Tazekka sections (Fig. 3.1, A). Owing to Variscan and Alpine tectonics, this distance may have been even larger. However, both areas are representative of depositional settings that should have been closer as far as only facies belt are concerned, the Bou Ingarf section corresponding to an inner shelf setting, the Tazekka section to an outer shelf or basin-floor fan setting (see section 3.2.3); both the related facies belt separated by a less than 500 km distance (100-300km?).

Biostratigraphic results discussed above have demonstrated that the main part of the Tifarouine Fm. relates to the *elongata* Biozone and thus is Hirnantian in age. It is of course not synonymous with the following statement: the main part of the Hirnantian is recorded in the Tifarouine Fm. As explained above, pondering a base of the Hirnantian *elongata* Biozone positioned well below the main glacio-eustatically controlled downward shift of the depositional facies belts in the Anti-Atlas (Bourahrouh et al., 2004; Loi et al., 2010), the *elongata* Biozone most likely has to be revised downward, beneath the sharp contact between the Tehar el Brehl and Tifarouine formations, in strata from which no information is provided by the chitinozoan record. The lower, 'pre-glacial' Hirnantian, assuming it is recorded in the Tazekka Massif, then corresponds to the upper part of the Tehar el Brehl Fm. (Fig. 3.6). This relationship is corroborated by stable isotopic constrains using a correlation with the Prague Basin (see below).

In the absence of a firm timeline originating from the chitinozoan biostratigraphy, we take advantage of a clear sedimentological signature of the glaciation into the Tazekka sections. Considering that the acme of the glaciation is somewhere within the Tf2 toTf3 intervals, which show the more glaciation-impacted depositional conditions —glaciomarine facies in Tf2 (Fig. 3.4, D) and the more energetic and amalgamated turbiditic deposits in Tf3 (Fig. 3.4, E)—, our chitinozoan assemblages 3 to 5 post-date the chitinozoan record of the Bou Ingarf section that only characterizes the 'pre-glacial' Hirnantian time-interval in the Anti-Atlas (Bourahrouh et al., 2004; Loi et al., 2010). In this scheme, most of the Tifarouine Fm. (Tf2 to Tf5) records the glacial maximum and the early deglacial evolution, a time interval corresponding to the third Latest Ordovician Glacial Cycle (LOGC3) *sensu* Ghienne et al. (2014). Assemblage 2 and the Tf1 depositional unit, which post-date the main lithological dislocation, most likely correlate with the regressive sandstone-dominated, but non glaciogenic, Hirnantian depositional sequences preceding the glaciation acme in the Anti-Atlas (LOGC2 in Ghienne et al., 2014). These sequences show a chitinozoan assemblage, which is largely compatible with our Assemblage 2 (Tessitore et al., in prep; cf. Chapter 2). The LOGC 1 of Ghienne et al. (2014), a glacial lowstand occurring in the uppermost Katian with a correlative postglacial transgression expanding in the lowermost Hirnantian, is tentatively correlated with the TB(iii) interval (Fig. 3.6).

A brief discussion of the *oulebsiri* Biozone *sensu* Paris et al. (2000), which follows the *elongata* Biozone in the Hirnantian, seems warranted. In the Tazekka domain, though it has not been identified in this study, the index species first appears at the base of the Tf3 unit (Fig. 3.3; Le Heron et al., 2008), i.e., after the glacial maximum. In the Anti-Atlas, *S. oulebsiri* is recorded below the glaciation maximum (Fig. 3.7, see Chater 2 and Loi et al., 2010). Whether the *oulebsiri* Biozone is a highly useful feature for biostratigraphic studies, even at a regional scale, is thus questioned. We may suggest that *S. oulebsiri* is highly facies-dependent and its occurrences therefore rather time-transgressive. By correlation with the Anti-Atlas, the presence of *S. oulebsiri* is to be expected in Tf2. This would imply that, for the Tazekka case study, the Hirnantian chitinozoan record would almost entirely be confined to the *oulebsiri* Biozone, the preceding *elongata* Biozone characterizing only the upper Tehar el Brehl Fm., lacking a chitinozoan record. Pending the hypothetical recovery of the index species in Tf2, which could validate the *oulebsiri* Biozone, and based on data rather than assumptions, we prefer to use only the *elongata* Biozone when characterizing the Hirnantian (Figs 3.6 & 3.7).

3.9. Correlation outside Morocco

A stratigraphic correlation between the Tazekka Massif and the Prague Basin (Štorch et al., 1993; Fatka and Mergl, 2009) is proposed (Fig. 3.7). The end-Ordovician Prague Basin succession, including the Kraluv Dvur Fm. and the Kosov Fm., share with the Tazekka succession a ‘peri-Gondwana’ palaeogeographic context. Similar as for the Tazekka area, the glacial record in the Prague Basin shows initially diamictite units (Brenchley et al., 1991), though here consisting only in two thin intervals, and then a relatively continuous succession of alternating sandstones and shales. This flysh-type succession of the Prague Basin has been interpreted as deposited in storm-dominated environments (Brenchley and Štorch, 1989;

Štorch, 2006), and thus characterizes an ice-distal outer continental shelf, with shallow conditions during glacial lowstands. Moreover, the Prague Basin record includes a $\delta^{13}C_{org}$ signal (Mitchell et al., 2011; Melchin et al., 2013), a chitinozoan record (Bourahrouh, 2002) and graptolite tipping points with the *extraordinarius* and *persculptus* Biozones identified at the base and the top of the glacially-related succession. Finally, a marker bed known as the Pernik Bed, initially though to be the expression of the Boda Event (Cocks and Fortey, 2004), but recently re-interpreted as the signature of a very latest Katian regressive event (Mergl, 2011), is positioned within the rising limb of the basal $\delta^{13}C_{org}$ signal at the Katian-Hirnantian boundary (Mitchell et al., 2011; Melchin et al., 2013). The Pernik bed was correlated with the ouzregui marker bed of the Bou Ingarf section in the Anti-Atlas (Ghienne et al., 2014). The correlation proposed in Fig. 3.7 considers that:

- the basal isotopic excursion, including the Pernik bed in its rising limb, and overlying shale-dominated intervals in its declined limb, has its counterpart in the upper Tehar el Brehl and lower Tifarouine Fms.
- the *elongata* Biozone started beneath the first, thin, diamictite horizon in Tf 2 unit (Tifarouine Fm.).
- the segment of the Prague Basin section bracketed between the base of the upper — and thicker— diamictite bed and the erosional unconformity and associated coarse-grained beds in the upper part of the Kosov Fm., is linked to the glacial maximum represented by the Tf2 and Tf3 units.
- the overlying strata, post-dating the glacial maximum and grading to post-glacial deposits can be correlated with the Tf4 and Tf5 units; the re-appearance of a shelly *Hirnantia* fauna echoing with recovery patterns identified in Tf5 (see section 3.7) and with a similar fauna in the Anti-Atlas (Sutcliffe et al., 2001).

Such a correlation, which is consistent across the biostratigraphic, sedimentological and stable isotopic records, has some implications. Locally, it corroborates a Katian-Hirnatian boundary positioned in the upper Tehar el Brehl Fm. Our favored correlation is shown in Fig. 3.7. A slightly higher position would be also possible (Fig. 3.6), which is less convincing on isotopic grounds. For the Czech record, our correlation would imply that the Hirnantian time interval preceding the glaciation of the Anti-Atlas, i.e. the upper LOGC 1 & LOGC2 in the Bou Ingarf section, is restricted to the uppermost Kraluv Dvur Fm. and lowermost Kosov Fm. In this case, the thin diamictite bed at the very base of the latter is the counterpart of the relatively thick package of lowstand strata in the Anti-Atlas. This is in agreement with the diamictite interpretation by Brenchley et al. (1991) favoring depositional conditions related to sea-ice processes, thus reflecting a marked cooling rather than shelf englaciation at that time. In addition, the stratigraphic intervals in both the sections show a marked color change in shale deposits —green to red in the Tazekka, grey to brown in the Prague Basin (Brenchley et al., 1991)—, suggesting contemporaneous redox changes, which would feature the regressive segment of LOGC2 in distal settings.

Following the Gondwana (Anti-Atlas)-Laurentia (Ancosti Island) correlation of Ghienne et al. (2014), the main part of the Kosov Fm. would be ascribed to the *persculptus* graptolite chronozone, the latter having been identified before the glaciation maximum in Anticosti Island (Melchin et al. 2013) but also in some rare places of North Gondwana as in the Carnic Alps (Schönlaub et al., 2011). This correlation does not however calibrate precisely the base of the "north Gondwana" *elongata* Biozone against the chronostratigraphic timescale nor against the graptolite biostratigraphy. If the Prague Basin record indicates that the *elongata* Biozone is definitely and entirely included in the Hirnantian, a part of the preceding *merga* Biozone might still characterize the lowermost Hirnantian, pending a future identification of the index species immediately above the Pernik bed. The ouzregui bed of the

Anti-Atlas, representing a transgressive condensed interval, most probably was deposited, in time, immediately after the deposition of uppermost Katian Pernik bed (Fig. 3.7), which essentially reflects the previous regression (Mergl, 2011; Melchin et al., 2013). The regressive strata are also recognized in the Anti-Atlas, forming the regressive record of the first Latest Hirnantian Glacial Cylce (LOGC1, Ghienne et al., 2014, Loi et al., 2010), during which ice-sheet fronts remained remote relative to the Gondwana margin. Given that the uppermost horizons of the Pernik bed are Hirnantian owing to the identification of the *ojuensis-extraordinarius* graptolite Biozone, the transgressive ouzregui bed itself is thought to be positioned in the lowermost Hirnantian. Additionally, the index species *T. elongata* has been recorded from the ouzregui bed in the Bou Ingarf section in the Anti-Atlas, which suggests that this marker bed is comprised in the Hirnantian *elongata* Biozone.

Finally, our correlation shows that short-term but significant $\delta^{13}C_{org}$ shifts occurred during the early deglaciation, as best illustrated by the Tazekka record, but also suggested by the Prague Basin record. These isotopic shifts echo the major isotopic excursions that were identified in the carbonate platform sedimentary records, and which characterize both the organic and carbonate carbon signals of the *persculptus* Biozone (Fan et al., 2009; Melchin et al., 2013). They suggest that the deglaciation —rather than the glaciation—, and then transgressive conditions in far-field, low-palaeolatitude areas, is favorable to the development of major, distinctive isotopic shifts (Ghienne et al., 2014); their precise basin-to-basin temporal correlation waiting for confirmation.

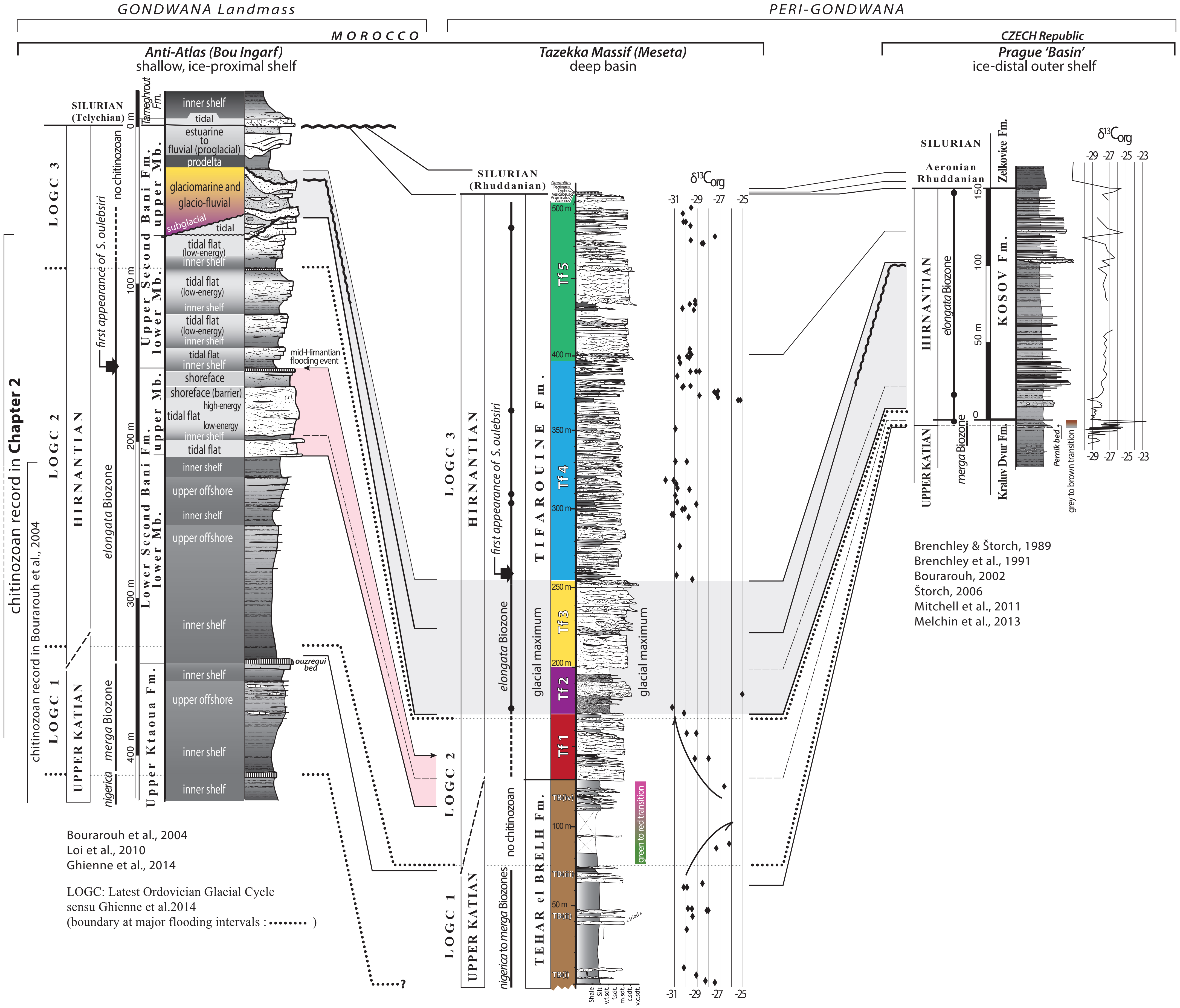

Fig. 3.7 Stratigraphic correlation scheme between the Tazekka Massif and the Anti-Atlas (Morocco) and between the Tazekka and the Prague Basin (North Gondwana).

3.10 Conclusions

In the Tazekka Massif, five chitinozoans assemblages have been identified. The first one corresponds to the pre-glacial environment conditions, the second to the fourth assemblages correspond to the glacial conditions, and the fifth one suggests a recovery assemblage. Two chitinozoan biozones have been properly recognized through the Tazekka succession: *nigerica* (in Tehar el Brehl Fm.) and *elongata* (in Tifarouine Fm.) biozones. The presence of *T. elongata* in the diamictite facies, which are a good glacial marker, highlights continuous biodiversity patterns even during the development of glacial facies. The abundant *Sphaerochitina* genus in the Tazekka Massif in contrast to its near-absence in the substantially shallower Central Anti-Atlas domain, suggests a living environment such as an open-shelf/deep marine environment. Preliminary worldwide correlation through the end-Ordovician Gondwanan margins has been possible thanks to the presence of *T. elongata*, *S. oulebsiri*, and *B. llangrannogensis* in our work, in Wales, and in South China. The carbon isotopes ($\delta^{13}C_{org}$) and related changes in microfossil assemblages can be temporally calibrated against a stratigraphic signal directly impacted by the end-Ordovician glaciation. A total record of the uppermost Katian and Hirnantian is when correlating the chitinozoan assemblages of the Tazekka Massif with the one from Bou Ingarf (Central Anti-Atlas). The Tazekka Massif is fully complementary with Bou Ingarf (a very ice-marginal, pro- to sub-glacial position) and allows the syn-glaciation chitinozoan development to be deciphered at a high resolution.

In the Tazekka the restricted marine environments were really unfavourable to the chitinozoan record in contrast to open-marine glaciomarine deposits (Tf2) or turbidite-dominated systems (TF4 an Tf5). This study permitted to determine a high-resolution record during a time interval that is mainly characterize by superimposed glacial erosion surfaces and an intricate stratigraphic record. Finally, the Tifarouine Fm. appears to be a benchmark for the glaciation acme (LOGC3) and not of the whole end-Ordovician glaciation (LOGC1-3).

Acknowledgements

We greatly thank the financial support of CNRS and the French 'Agence Nationale de Recherche' grant ANR 12-BS06-0014 'SeqStratIce'. We would like to thank help from Laurence Debeuvais for the palynological lab process, and Philippe Recourt for SEM imaging. Petr Storch for the graptolites analyses, identifications, and interpretations.
Matthias Sinnesael thanks the Research Foundation – Flanders (FWO) for the awarded PhD fellowship (FWOTM782). Laboratory technician David Verstraeten (V.U.B.) is thanked for assisting with measuring the organic carbon isotopes.

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Appendix

In this appendix it will be described the graptolite fauna founded in each collected sample from the upper Ousserdoune end-Ordovician section (Fig. 3.8).

Fig. 3.8 Graptolite sampling on the upper Ousserdoune section.

Ten samples from the Tifarouine Formation up to the lower Silurian have been collected and here below the results of each sample, in ascending stratigraphical order:

The first sample (-1) contains *Akidograptus ascensus* (Davies), *Normalograptus* cf. *mirnyensis, Normalograptus crassus* (Štorch and Feist), which suggest an *Akidograptus ascensus* Biozone. The second sample (0) suggests the lower *Parakidograptus acuminatus* Biozone. It contains indeed, *Normalograptus trifilis* (Manck), *Normalograptus* sp., *Neodiplograptus parajanus* (Štorch), *Neodiplograptus lanceolatus* (Štorch and Serpagli). The third sample (1) is still in the lower *Parakidograptus acuminatus* Biozone, but suggests an higher assemblage because it contains *Parakidograptus acuminatus* (Nicholson), *Normalograptus longifilis* (Manck), *Neodiplograptus lanceolatus* (Štorch and Serpagli), *Glyptograptus* sp., and *Cystograptus ancestralis* (Štorch). The sample number (2) indicates probably an identical stratigraphic assignment as the previous sample (1). It contains indeed only *Normalograptus longifilis* (Manck). The fifth sample (3) suggests an hypothetical *Parakidograptus acuminatus* Biozone. In this sample there are not enough information to confirm the biozone, it shows *Normalograptus* cf. *ajjeri* (Legrand), formerly being referred as *N. normalis* (Lapworth) and *Neodiplograptus* sp. The following sample (4) suggests the same biozone as the previous two samples *Parakidograptus acuminatus* Biozone. Actually, it contains *Parakidograptus acuminatus* (Nicholson), *Normalograptus normalis* (Lapworth), *Normalograptus* cf. *angustus* (Perner), and *Cystograptus ancestralis* (Štorch). The sample number (5) did not yield any identifiable graptolite, so no suggestion for its biozone. Reaching the upper part of the collected samples, the subsequent sample (6) shows a different biozone, it is composed by *Cystograptus vesiculosus* (Nicholson), *Dimorphograptus confertus* (Nicholson), and *Normalograptus* sp., and it suggests the upper *Cystograptus vesiculosus* Biozone. The sample (7) is composed by *Normalograptus ?medius, Normalograptus ?normalis, ?Atavograptus atavus* (Jones), and *?Huttagraptus acinaces* (Törnquist). This suggests the ? upper *Cystograptus vesiculosus-Coronograptus cyphus* biozones. The last sample (8) displays another graptolite biozone, we are here in the lower *Demirastrites pectinatus* Biozone, lower Aeronian Stage. Indeed, the sample is composed by *Metaclimacograptus* sp., *Petalolithus ovatoelongatus* (Kurck), *Pseudorthograptus inopinatus* (Bouček), *Rhaphidograptus toernquisti* (Elles and Wood), *Coronograptus gregarious* (Lapworth), *Rastrites longispinus* (Perner) , *Demirastrites pectinatus* (Richter), *Demirastrites* *triangulatus* (Harkness), and *Campograptus* aff. *communis* (Lapworth).

Of the species listed above, only *Normalograptus ajjeri* is widespread in Libya, Tunisia, Algeria, and Mauritania. *Campograptus communis* was found in the Murzuq Basin and *Cystograptus vesiculosus* in the Ghadames Basin. All other species are typical of the so-called peri-Gondwanan Europe and many of them are palaeogeographically more widespread. Additionally, neither much of the *cyphus* Zone nor *triangulatus* Zone has been recorded in the collected samples.

The substantial difference in graptolite faunas of the two current adjacent regions Morocco and the cratonic Africa and the Middle East is caused by a separation of these areas. Postglacial Silurian successions of Morocco remained little known till now, here is presented our preliminary results concerning the early Silurian graptolite fauna. However, additional material would bring more robust, more detailed evidence of this early Silurian biogeographic (and probably palaeogeographic) separation between the two regions.

CHAPTER IV:

CHITINOZOANS FROM THE UPPER ORDOVICIAN HIRNANTIAN STAGE IN THE NEIGHBOURHOOD OF THE STAGE GSSP, WANGJIAWAN, YICHANG, SOUTH CHINA

Preamble

In chapter 4, the chitinozoan assemblages from the Wangjiawan Riverside section, South China, are investigated. This location is immediately adjacent to the Global Boundary Stratotype Section and Point (GSSP) of the base of the Hirnantian Stage (Upper Ordovician Series) in the Wangjiawan North section, but yields fresher rocks that are more likely to preserve palynomorphs. The occurrences of the chitinozoans are precisely calibrated against the graptolite biozonation and the international chronostratigraphy, which are identical to that of the nearby GSSP of the base of the Hirnantian Stage in the Wangjiawan North section. Additionally, chitinozoans index species recorded at global scale permitted preliminary worldwide correlations.

This chapter is written as an article manuscript and submitted to *Review of Palaeobotany and Palynology* and at present ‘Under Review’. The section and figure numbering are kept as the submitted paper and not in line with preceding and following chapters of this thesis.

4. Chitinozoans from the Upper Ordovician Hirnantian Stage in the neighbourhood of the Stage GSSP, Wangjiawan, Yichang, South China

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Abstract

Thirty-three samples from the Wangjiawan Riverside section in the Yichang region (South China) have been processed for palynomorphs, mainly for chitinozoans. The Riverside section is immediately adjacent to the Global Boundary Stratotype Section and Point (GSSP) of the base of the Hirnantian Stage (Upper Ordovician Series), defined in the Wangjiawan North section, and yields fresher rocks more likely to preserve palynomorphs. More than 2000 uppermost Ordovician – lower Silurian specimens have been recovered, but the overall rather poor preservation of the specimens does not permit a routine and accurate systematic analysis and biostratigraphic interpretation. Nevertheless, this study resulted in the exhaustive documentation of the first chitinozoans from the Kuanyinchiao Bed and the Lungmachi

Formation in the Wangjiawan Riverside section. The occurrences of the chitinozoans are precisely calibrated against the graptolite biozonation and the international chronostratigraphy, which are identical to that of the nearby GSSP of the base of the Hirnantian Stage in the Wangjiawan North section, a mere 180 m northward, higher up flank of the valley. The Kuanyinchiao Bed yields a rather abundant and characteristic chitinozoan fauna, but fewer and poorly preserved specimens are collected from the Wufeng and Lungmachi formations. The discovery of *Belonechitina llangrannogensis* and of *Tanuchitina elongata* from the Hirnantian Kuanyinchiao Bed is important in providing an accurate correlation between graptolite-bearing sections and sections that only yield chitinozoans. *B. llangrannogensis* and *T. elongata* are characteristic for the Hirnantian Stage, and have also been found in Avalonia (Welsh Basin) and along the Gondwana margin (North and South Morocco, Algeria, Libya, etc.) in Upper Ordovician strata.

Key words

Chitinozoan, biostratigraphy, Hirnantian GSSP, South China, Gondwana, Avalonia

4.1 Introduction

The term ‘Hirnantian’ was first introduced by Bancroft (1933) as a regional stage name for the highest rocks in the Ordovician System at Bala in North Wales (UK) and was later adopted as the highest global stage of the Upper Ordovician Series (Chen et al., 2006). The top of the Hirnantian Stage corresponds to the base of the Silurian System. This stage has a very short duration, less than 2 Myrs (Cohen et al., 2013), but it records one of the largest global extinctions in Earth history, and a major glaciation. Physical sedimentary and stratigraphic evidence for the Hirnantian glaciation is widespread along the margins of Gondwana (Deynoux et al., 1985; Ghienne, 2003; Le Heron et al., 2005, 2010; Davies et al.

2009, 2016; Deschamps et al., 2013; Ghienne et al. 2014; Benedetto et al. 2015; Girard et al., 2015), and has served to ground-truth numerical ice-sheet models (Pohl et al., 2016).

As defined by Chen et al. (2006), the base of the Hirnantian Stage (in South China) is coincident with the First Appearance Datum (FAD) of the graptolite *Metabolograptus extraordinarius* (Sobolevskaya, 1974). This species, originally within the genus *Normalograptus* was re-assigned to the genus *Metabolograptus* by Melchin et al. (2011), as was *Normalograptus persculptus*. Accordingly, the Hirnantian Stage consists of two graptolite zones: the (lower) *Metabolograptus extraordinarius* Biozone and the (upper) *Metabolograptus persculptus* Biozone (Chen et al., 2006).

During the Late Ordovician to early Silurian, the South China palaeoplate was situated at low palaeolatitudes, and it was characterised by a shallow sea environment (Stampfli and Borel, 2001; Chen et al., 2004; Cocks and Torsvik, 2004, 2013; Stampfli et al., 2011; Torsvik and Cocks, 2013). The Wangjiawan study area (Fig. 1) is situated on the Yangtze platform in South China. The village of Wangjiawan, located 42 km north of Yichang city, exposes several sections through the Upper Ordovician and lowermost Silurian strata. In these strata two formations have been identified, the Wufeng and Lungmachi formations, which are composed mainly of black shales and cherts, and are separated by a distinctive limestone horizon, the Kuanyinchiao Bed (HF, Fig. 1,C, a) that commonly yields abundant and diverse elements of the *Hirnantia* shelly fauna (Rong et al., 2002). The succession has been sampled from the Wufeng Formation across the Kuanyinchiao Bed (HF) and up into the Lungmachi Formation (Fig. 1, C, a).

The Wangjiawan North section (Fig. 1, C, b) received international attention, when it was first proposed as candidate for the Global Boundary Stratotype Section and Point (GSSP) of the base of the Hirnantian Stage, defined at the FAD of the graptolite *Metabolograptus extraordinarius* (Chen et al., 2006). Both the Wangjiawan South and North sections are roadcut sections that are characterised by weathered shales. Our studied section, the Wangjiawan Riverside section, is c. 180 m to the southeast along strike from the Wangjiawan North section (Fig. 1, C, a), in an incised valley where the rocks are less weathered than in the GSSP and are more suitable for palynological and geochemical analysis (Fan et al., 2009).

The biostratigraphy of the Upper Ordovician at Wangjiawan was mainly based on graptolites because they constitute abundant and diverse faunas in the Wufeng and Lungmachi formations, which can be used in global correlations. The biozonation through these lithostratigraphic units was originally erected by Mu et al. (1984, 1993), Wang et al. (1987), and revised by Chen et al. (2000, 2006). The presence of the *Hirnantia* fauna in the Kuanyinchiao Bed provides a means of correlation into non-graptolitic facies, although the presence of the shelly fauna is limited to a single, 27 cm thick, limestone bed at Wangjianwan.

Graptolites are not the only instrument to provide a detailed biozonation of the Upper Ordovician. Chitinozoan biostratigraphy can be an equally robust tool. The presence of these palynomorphs in the Wangjianwan sections was first demonstrated by Vandenbroucke et al. (2005), which was based on 15 samples from the Wangjiawan Riverside section and five from the weathered outcrop at Wangjiawan South. However, the stratigraphic distribution of the chitinozoans in these strata remained to be studied in detail.

Here we present a systematic study of the biostratigraphic potential of chitinozoans in the freshly exposed Hirnantian black shales and limestone bed of the Wangjiawan Riverside section. We did not consider the Wangjiawan North section (i.e., the GSSP) because the shales there are too weathered to yield any chitinozoans. We intend to test if we can use these chitinozoans to correlate into key Hirnantian sections that generally lack graptolites, such as those of the near-field western Gondwana margin in Morocco (Paris et al., 2000, 2015; Ghienne et al., 2007; Le Heron et al., 2007; Loi et al., 2010). These sections display a highly resolved sequence stratigraphic record of the Hirnantian glaciations events (Ghienne et al., 2014), as well as a detailed chitinozoan biostratigraphy (Oulebsir and Paris, 1995; Bourahrouh et al., 2004; Vandenbroucke et al., 2010, 2014; Paris et al., 2015), but it remains difficult to link the Moroccan stratigraphy accurately into the global chronostratigraphy because of the lack of graptolite control. Additional tools that allow us to correlate those sections with the GSSP will help solve this problem. Our results will permit a preliminary correlation between the northern (South China) and western (Morocco) Gondwana margins and with Avalonia (Wales).

4.2 Material and Methods

A total of thirty-three samples from the Wangjiawan Riverside section were collected from the black shales and the intervening limestone horizon. The samples originate from a condensed section, which is about 3 metres thick. Fifteen of our samples were collected from the Wufeng Formation, four from the Kuanyinchiao Bed, and fourteen from the Lungmachi Formation.

The palynological analyses were carried out at Ghent University (Belgium) and the University of Lille (France). We used 40g of rock for the black shales, twice 100g for two limestone samples (TVDB 07-026 and TVDB 07-027), and 100g for the last best limestone sample (WRS 2.28-2.34) of the Kuanyinchiao Bed. The analytical protocol involves crushing the rock samples into 0.5 cm pieces followed by a first acid treatment with 38% HCl over 24h. The residue was then washed with demineralized water, and subject to a second acid treatment with c. 200 ml 40-45% HF, while being agitated during 12h to 24h (Lille) or heated to 80°C (Ghent). Afterwards, the residues were treated again with warm 38% HCl to remove any newly formed F-compounds. Finally, the samples were neutralized and filtered at 51 or 53 μm. The residues on the filters were handpicked using a binocular microscope at 32-63 times magnification, and then studied with a FEI Quanta 200 and a LEO 435VP Scanning Electron Microscope (SEM).

4.3 Results

The Wangjiawan Riverside section yielded more than 2000 chitinozoan specimens, identified when possible. The results are summarised in Table 1. The poor preservation (broken specimens, undeterminable morphology, ornamentation, etc.) of a large percentage of the chitinozoans explains the doubtful identification of many specimens, often limited to the genus level. The samples dissolved from the black shales contained a large amount of amorphous organic matter, graptolite fragments, and fragmented specimens of chitinozoans. Stratigraphically interesting material was recovered in three samples of the Kuanyinchiao Bed (samples TVDB 07-027, WRS 2.28-2.34, and TVDB 07-026). In the following section, we list the palynological results of each stratigraphic interval.

4.3.1 Wufeng Formation

The fifteen samples of the Wufeng Formation (between 1.53m and 0.55m below the Ordovician-Silurian boundary, see Table 1) contain 508 chitinozoans. This relatively low amount of microfossils, together with the fact that most of the chitinozoans are flattened (2D) and poorly preserved, complicates an exhaustive identification of the assemblages. The few identifiable microfossils include *Desmochitina minor, Desmochitina typica, Belonechitina* sp., *Cyathochitina campanulaeformis*, and *Rhabdochitina allantoides* (Plate I, 1-5).

4.3.2 Kuanyinchiao Bed

The Kuanyinchiao Bed is only 27cm thick at the Wangjiawan Riverside section. The four samples from the limestone horizon situated between 0.55m and 0.28m below the

Ordovician-Silurian boundary, yielded a large number of chitinozoans, i.e., 747 specimens. These chitinozoans are better preserved than the ones from the underlying Wufeng Formation. Sample TVDB 07-027 yielded the largest assemblage of the entire section and contains the following genera and species: *Desmochitina minor, Desmochitina typica, Cyathochitina campanulaeformis, Rhabdochitina* sp., *Conochitina* sp., *Tanuchitina* sp., *Tanuchitina elongata, Belonechitina* sp., *Belonechitina llangrannogensis* and *Lagenochitina* sp. (Plate I, 6-11).

4.3.3 Lungmachi Formation

In the upper part of the section, fourteen samples have been collected. The lowest four are from the uppermost Ordovician (from 0.28m below the Ordovician-Silurian boundary to the top of the system); whereas the other 10 are from 0 to 0.72m above the Ordovician-Silurian boundary. They yielded a total of 899 chitinozoans, but most of them can only be doubtfully identified. The identified specimens mainly belong to two species: *Cyathochitina campanulaeformis* and *Sphaerochitina* sp. (Plate I, 12-13), with a specific identification for only two specimens of *Rhabdochitina* sp. (Table 1).

4.4 Discussion and Correlation

The chitinozoans from the Wufeng and Lungmachi formations at Wangjiawan area were first reported by Vandenbroucke et al. (2005, 2007), but their material only supported the questionable recognition of the *Ordochitina nevadensis* or *Nevadachitina vininica* chitinozoan biozones from the middle part of the Wufeng Formation. In the present study, we discovered a few specimens that are of importance for correlation across palaeolatitudes along the Gondwanan margin, and between Gondwana and Avalonia.

In the Wufeng Formation one of the relevant species is *Rhabdochitina allantoides*, first described by Qian and Geng (1989) in the same formation, where it is present from the Katian to the lower Hirnantian. The sample has been collected at the base of the *extraordinarius* Zone, and the presence of *Rhabdochitina allantoides* is in agreement with its lower Hirnantian age.

Further up section the argillaceous limestone bed of the Kuanyinchiao Bed yields two species of interest, i.e., *Belonechitina llangrannogensis* and *Tanuchitina elongata*, both characterizing a biozone of the Hirnantian Stage at different palaeolatitudes. *Belonechitina llangrannogensis*, first described by Challands et al. (2014) in the Welsh Basin (Yr Allt Formation, Traeth Yr Yscland), gives its name to a local Hirnantian biozone in Avalonia at intermediate palaeolatitudes. This biozone is located below the base of the *persculptus* graptolite Zone, i.e. the lower part of the Hirnantian Stage (Challands et al., 2014). The discovery of *Belonechitina llangrannogensis* in the Wangjiawan Riverside section and in Morocco marks for the first time the larger distribution of this species. This means that the species is not limited to a single area, but it can be present worldwide. The *Tanuchitina elongata* Biozone typifies the Hirnantian of the western Gondwana margin, at high palaeolatitudes (e.g., Paris, 1990; Bourahrouh et al., 2004, and our own studies in the Central Anti-Atlas of South Morocco, see below). The presence of *Belonechitina llangrannogensis* and *Tanuchitina elongata* in the Kuanyinchiao Bed (Hirnantian) is therefore useful to correlate the strata at Wangjiawan to those in Avalonia (Welsh Basin) and across the Gondwanan margin (Fig. 2). In addition, we can report that we have recently found *Belonechitina llangrannogensis* and *Tanuchitina elongata* together in the Tazekka region (North Morocco; Tessitore et al., in preparation), suggesting the presence of the same stratigraphic interval in that area.

In the Central Anti-Atlas, *Tanuchitina elongata* is considered an index species for the Hirnantian. However, the chronostratigraphic calibration of this biozone is based on the fairly abundant brachiopod fauna (*Hirnantia sagittifera*, *Hirnantia* sp.1 and 2) from the Lower and Upper Second Bani Formation (Paris, 1990) and the calibration of the base of the biozone is based on the trilobites from the Ouzregui Bed defined in the Bou Ingarf section that are suggestive of the Hirnantian Stage (Bourarouh et al., 2004; Loi et al., 2010). Importantly, its calibration against the graptolite biostratigraphy that replaced the shelly fauna as the formal marker fossils in the Upper Ordovician remains to be established. Owing to the discovery of the Chinese specimens of *Tanuchitina elongata* in the GSSP of the Hirnantian, this index species is now more precisely calibrated against the chronostratigraphy and the graptolite biostratigraphy: it occurs in the lower part of the Kuanyinchiao Bed, which probably correlates with the upper part of the *extraordinarius* Biozone in the Hirnantian GSSP (Fan and Chen, 2007, using graphic correlation). In addition, the discovery of *Belonechitina llangrannogensis* (defined in the Hirnantian of the Welsh Basin; Fortey et al., 1995; Challands et al., 2014) in the Wangjiawan Riverside section and in the Tazekka area in northern Morocco (lower part of the Tifarouine Fm. of Le Heron et al. 2007, 2008; Tessitore et al., in preparation) allows a correlation between South China, Morocco, and the Welsh Basin during an overall glacial period. Given the issues involved in correlating between low and high palaeolatitudes in a glacial world (Vandenbroucke et al. 2010; Ghienne et al., 2014;), this is an important advancement.

Further up section, the Ordovician-Silurian boundary is located near the base of the Lungmachi Formation. This boundary is generally distinct by a chitinozoan fauna of reduced diversity, and a decreased number of genera. The fauna here is reduced to specimens of *Cyathochitina campanulaeformis* and *Sphaerochitina* sp. (Plate I, 12-13). Worldwide, the lower Silurian is characterised by a reduced fauna compared to the Upper Ordovician. The pattern of dominance of the two genera cited above (*Cyathochitina* and *Sphaerochitina*) is typical for this interval, and is not only observed in South China, but also in Western Gondwana and Avalonia (Grahn, 2006; Achab and Paris, 2007; Vandenbroucke et al., 2008; and references therein).

Our results complement the scarce data from other regions with documented associations of Hirnantian chitinozoans and graptolites, such as in the Prague Basin (Brenchley and Storch, 1989), the Algerian Sahara (Ghienne et al. 2007), and the French Massif Armoricain (Paris and Robardet 1990, 1994), i.e., areas that also have Hirnantian glacial deposits that help place the fossils finds within a stratigraphic framework. For instance, the *extraordinarious* Zone is known from syn-glacial deposits (e.g. 10 m of shales with *Ojsuensis* between two glacial floors in Niger: Legrand, 2003; Denis et al., 2007; the *Ojsuensis* bed in Sardinia), but the *llangrannogensis* Biozone is probably below the glacial maximum (e.g., in lower part of the Tifarouine Fm. in the Tazekka Massif, North Morocco).

In summary, the added value of the chitinozoans documented here from the Wangjiawan Riverside section is that for the first time occurrences of certain key Hirnantian chitinozoans are perfectly calibrated against the revised international chronostratigraphy for the Hirnantian. Remarkably, some of the species recovered are index species that also occur in other places around the globe (Welsh basin, Morocco). Our discoveries enable us to improve the correlations of those Hirnantian sections that lack the classical biostratigraphic tools (i.e., graptolites, conodonts, etc.), but that do have chitinozoans, such as many of the near field sections in North Africa.

4.5 Conclusions

The Wangjiawan Riverside section, immediately adjacent to the GSSP of the base of the Hirnantian Stage in the Wangjiawan North section, yielded poorly preserved chitinozoans in the Wufeng and Lungmachi formations. Specimens from the Hirnantian Kuanyinchiao Bed are better preserved and show affinities with the chitinozoans from Morocco (Central Anti-Atlas and Tazekka) and the Welsh Basin.

The discovery of the recently described species *Belonechitina llangrannogensis* (Challands et al., 2014) and of Gondwanan index species *Tanuchitina elongata* in the Kuanyinchiao Bed supports a precise correlation with sections in Morocco and the Welsh Basin, which lack or have restricted biostratigraphic graptolite control. Crucially, this discovery confirms a Hirnantian age for the *Tanuchitina elongata* Biozone, which was previously poorly calibrated against the graptolite biostratigraphy and international chronostratigraphy.

Acknowledgements

We acknowledge the financial support from the CNRS and the 'Agence Nationale de Recherche' grant ANR 12-BS06-0014 'SeqStrat-Ice'. Junxuan Fan thanks the NSFC grant U1562213. We would like to thank Laurence Debeauvais for help with the palynological lab analyses, and Philippe Recourt for SEM imaging. This is a contribution to the International Geoscience projects (IGCP) n° 591 and 653.

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Table 1

Chitinozoan results from the Wangjiawan River Section.

Chronostratigraphy			Graptolite Biozone	Chitinozoan Biozone	Lithostratigraphy	Samples	*D. minor*	*D. typica*	*C.campanulaeformis*	*Lagenochitina* sp.	*Spaherochitina* sp.	*Rhabdochitina* sp.	*R. allantoides*	*Tanuchitina* sp.	*T. elongata*	*Belonechitina* sp.	*B. llangrannogensis*	*Conochitina* sp.	Chitinozoan indet.	Total Chitinozoan
SILURIAN	Llandovery	Rhudanian	*acuminatus*		Lungmachi Formation	WRS 3.50-3.55			1										83	84
						WRS 3.43-3.50			18		22								115	155
						WRS 3.35-3.43														0
						WRS 3.30-3.35			2										40	42
						WRS 3.22-3.30			3										59	62
						WRS 3.13-3.22			2										4	6
						WRS 3.07-3.13														0
			ascensus			WRS 2.99-3.07													51	51
						WRS 2.88-2.99													78	78
						WRS 2.83-2.88													54	54
ORDOVICIAN	Upper Ordovician	Hirnantian	*persculptus*	*elongata*		WRS 2.75-2.83			23			2							114	139
						WRS 2.70-2.75			6										90	96
						WRS 2.62-2.70													73	73
						WRS 2.55-2.62													59	59
			HF		Kuanyinchiao Bed	WRS 2.34-2.55														0
						TVDB 07-026						3							53	56
						WRS 2.28-2.34	1		5	1		5			4	7			128	151
						TVDB 07-027		1	27			81		36	9	46	14	4	322	540
			extraordinarius		Wufeng Formation	WRS 2.20-2.28														0
						WRS 2.15-2.20													38	38
				merga?		WRS 2.06-2.15			3				4						47	54
						WRS 1.98-2.06														0
						WRS 1.89-1.98													29	29
		Katian	*mirus* subbiozone			WRS 1.82-1.89														0
						WRS 1.75-1.82														0
						WRS 1.69-1.75										5			71	76
			typicus subbiozone	*O. nevadensis? or N. vininica?*		WRS 1.65-1.69													60	60
						WRS 1.605-1.65													51	51
						WRS 1.535-1.605	3	1											71	75
						WRS 1.49-1.535													30	30
						WRS 1.44-1.49										1			28	29
						WRS 1.38-1.44													20	20
						WRS 1.30-.1.38													46	46

Note: The samples with prefix of WRS represent the continuous sampling by Junxuan Fan and Ping'an Peng in 2005. The samples with prefix of TVDB represent additional samples of the Kuanyinchiao Bed by Thijs Vandenbroucke later in 2007.

Figures

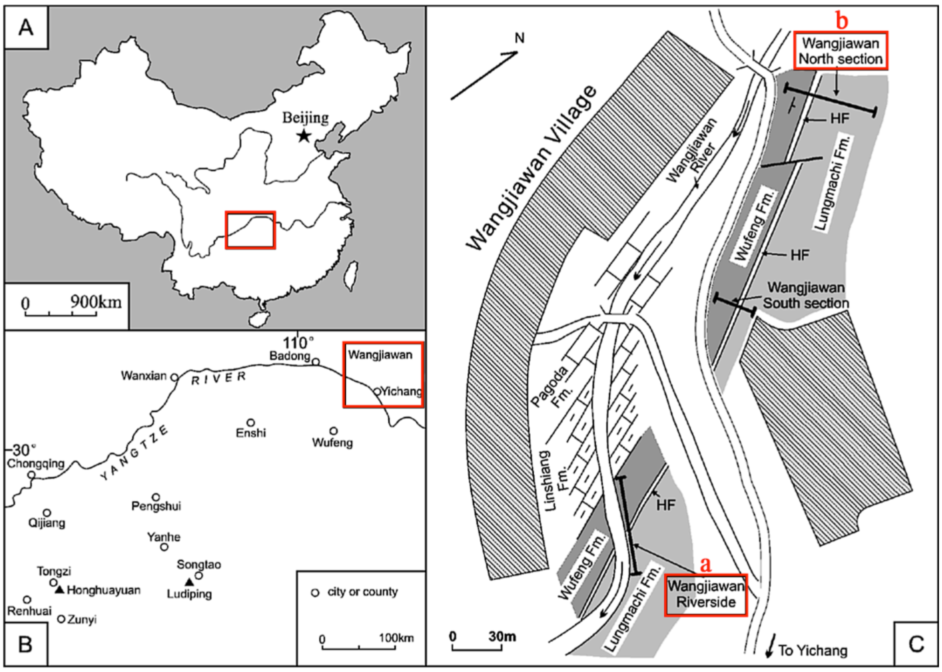

Fig. 1. Map of the study area, Wangjiawan, Yichang, South China. A) Geographic location of the Yichang region; B) Location of Wangjiawan sections; C) Geological map of the Wangjiawan River Section. HF corresponds to the Kuanyinchiao Bed (*Hirnantia* Fauna). (Modified from Chen et al., 2006)

Chronostratigraphy			Graptolite Biozone	Northern Gondwana	Western Gondwana	Avalonia
				South China (Vandenbroucke et al. (2005) and this study)	Morocco (Paris 1990)	Welsh Basin (Vandenbroucke (2008a), Vandenbroucke et al. (2008b), and Challands et al. (2014))
SILURIAN	Llandovery	Rhudanian	*acuminatus*			
			ascensus		*fragilis*	
ORDOVICIAN	Upper Ordovician	Hirnantian	*persculptus*	*elongata*	*elongata*	*cf. taugourdeaui*
			HF			*llangrannogensis*
			extraordinarius	*merga?*	*merga*	
		Katian	*mirus* subbiozo			*cf. gamachiana* *umbilicata*
			typicus subbiozone	*O. nevadensis or N. vininica zones?*	*nigerica*	*fossensis* ?

Fig. 2. Correlation chart of Ordovician-Silurian chitinozoan biozones in Northern Gondwana, Western Gondwana, and Avalonia. HF corresponds to the Hirnantian macrofauna, corresponding to the Kuanyinchiao Bed.

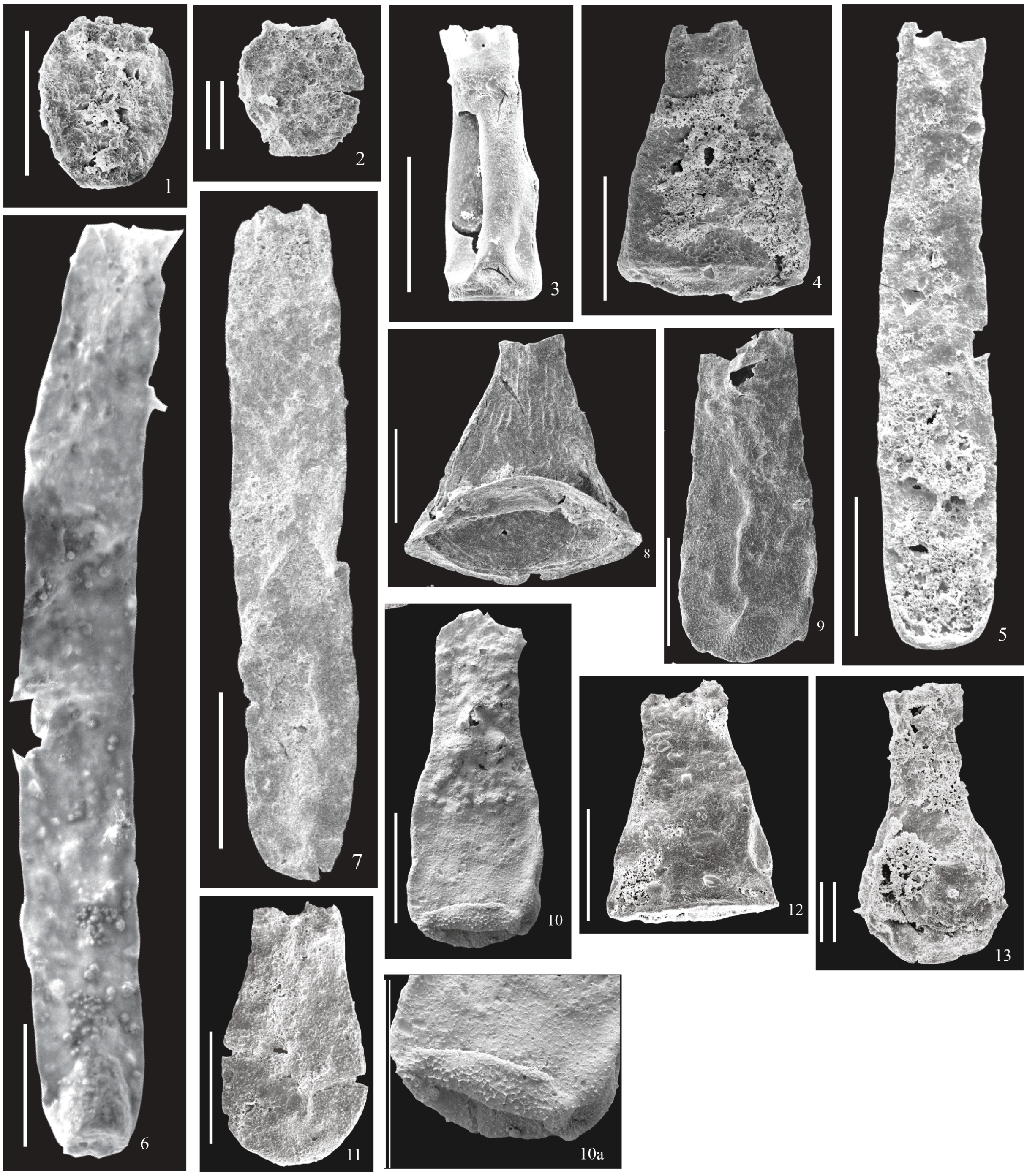

Plate I. SEM pictures of selected chitinozoans from the Wangjiawan Riverside Section. The scale bar represents 100µm, the double scale bar represents 50µm. Wufeng Formation, 1-5: 1. *Desmochitina typica* (WRS 1.535-1.605)*,* 2. *Desmochitina minor* (WRS 1.535-1.605)*,* 3. *Belonechitina* sp. (WRS 1.69-1.75)*,* 4. *Cyathochitina campanulaeformis* (WRS 2.06-2.5)*,* 5. *Rhabdochitina allantoides* (WRS 2.06-2.5); Kuanyinchiao Bed, 6-11: 6. *Tanuchitina elongata* (TVDB 07-027)*,* 7. *Rhabdochitina* sp. (TVDB 07-027)*,* 8. *Cyathochitina campanulaeformis*

(TVDB 07-027)*,* 9. *Belonechitina* sp. (TVDB 07-027), 10-10a. *Belonechitina llangrannogensis* (TVDB 07-027)*,*11. *Lagenochitina* sp. (WRS 2.28-2.34); Lungmachi Formation 12-13: 12. *Cyathochitina campanulaeformis* (WRS 3.43-3.5)*,*13. *Sphaerochitina* sp. (WRS 3.43-3.5).

CHAPTER V:

CONCLUSIONS AND PERSPECTIVES

The extensive work on the chitinozoans of the end-Ordovician glaciation in key areas like the Central Anti-Atlas, the Tazekka Massif (South and North Morocco) and the Wangjiawan Riverside section (South China) permitted a better understanding of the evolution of the Gondwanan ice-sheet through space and time.

Central Anti-Atlas. The study in the Central and Eastern Anti-Atlas, in South Morocco, revealed that the proximal ice-sheet area of the basin (its centre) permitted to identify mainly three chitinozoan biozones corresponding to the upper Katian and the Hirnantian (*nigerica*, *merga*, *elongata* biozones). In contrast, the western margin of the basin lacks in palynomorphs and only one single Hirnantian biozone has been recorded. The incisions in the eastern part of the basin and the easternmost limestones of Erfoud revealed a reworked fauna in the Katian and a Hirnantian biozone (*elongata*) in the upper part of the Erfoud succession. These results enabled to more extensively correlated strata across the entire basin. Moreover, we have been able to identify the Katian-Hirnantian boundary in centre of the basin, within the Upper Ktaoua and lowermost Lower 2nd Bani formations, but doubts remain as to its exact position (few decimetres below the ouzregui bed?).

Tazekka Massif. In the Tazekka Massif, five chitinozoans assemblages have been identified, from strata representing pre-glacial to glacial and post-glacial environmental conditions. Two chitinozoan biozones have been properly recognized through the Tazekka succession: the *nigerica* (in Tehar el Brehl Fm.) and *elongata* (in Tifarouine Fm.) biozones. The presence of *T. elongata* in the diamictite facies, which are a good glacial marker, highlights continuous biodiversity patterns even during the development of glacial facies. Indeed, in those facies is rare to find a well-preserved microfauna, which is normally preserved in other lithologies such as shales and mudstones. Our biostratigraphic and chemostratigraphic studies in the Tazekka Massif suggest an open-shelf/deep marine environment. Preliminary worldwide correlation can be suggested, based on our work, using the presence of *T. elongata*, *S. oulebsiri*, and *B. llangrannogensis* in the uppermost Ordovician of the Gondwanan margins, in Wales, and in South China. The Tazekka Massif is fully complementary to Bou Ingarf (a very ice-marginal, pro- to sub-glacial position) and allows the syn-glaciation chitinozoan development to be deciphered at a high resolution. This study permitted to develop a high-resolution record for a stratigraphic interval that is mainly characterized by an intricate stratigraphic record and by rocks displaying superimposed glacial erosion surfaces. Finally, the Tifarouine Fm. appears to be a benchmark for the glacial acme (LOGC3) and not of the whole end-Ordovician glaciation (LOGC1-3).

South China. The chitinozoans from the Wangjiawan Riverside section, that is immediately adjacent to the GSSP of the base of the Hirnantian Stage in the Wangjiawan North section, permitted to observe several affinities with the chitinozoans from Morocco (Central Anti-Atlas and Tazekka) and the Welsh Basin. A precise correlation with sections in Morocco and the Welsh Basin, which lack or have restricted biostratigraphic graptolite control has been possible thanks to index species that are distributed worldwide (*B. llangrannogensis* and *T. elongata*). This study partially confirmed the Hirnantian age of the *T. elongata* chitinozoan, which was formerly poorly calibrated against the graptolite biostratigraphy and international chronostratigraphy.

To this PhD work will be added other studies such as the Hirnantian macrofauna in the Central Anti-Atlas to settle if a signature of the first Hirnantian extinction event can be fairly evidenced in the near field. Additionally, a more rigourous stratigraphical analysis using CONOP, will help to improve our stratigraphic resolution by using the full assemblage of microfossils instead of only the index chitinozoans (and their biozones), and as such, will help us to understand better the evolution of chitinozoans through space and time during the end-Ordovician glaciation. These further two projects have been already started. The study on the macrofauna (South Morocco) to evaluate if macro-faunal turnovers relate to other specific phases of the many glacial cycles, yield as first results that the Ordovician fauna in the Anti-Atlas is quite diverse and it is composed mostly by graptolites, trilobites, brachiopods, echinoderms, molluscs, ostracods, cephalopods, bryozoans. The graptolites are generally abundant in the Lower Ordovician (from Tremadocian to Llanvirn), but become increasingly rare higher in the stratigraphy. On the other hand, trilobites and brachiopods are abundant in the entire Ordovician succession. The echinoderms are abundant in shales facies and mainly in sandstones; here some tens of families are represented. Bivalves and gastropods have been recorded from Middle to Upper Ordovician and they show tens of genera or families. The gastropods have not been well studied yet, mainly because of their rare occurrences in the Ordovician successions. Cephalopods are extremely abundant and they are mainly represented by Nautiloids ortocones specimens. The same abundance is recorded for the bryozoans, but it is concentrate mostly in the Upper Ordovician as well in the Llandeilo. Finally actritarchs and chitinozoans are described in the whole Ordovician stratigraphic succession. Moreover, we report a decrease in faunal abundance and biodiversity, moving from Southwest towards Northeast, and through time, from the first glacial cycle towards the glacial maximum. To these data, we will be added the new information from this dissertation (see chapter 2 and 3) and at the end it will be possible to test the paradigm of a major macrofaunal crisis during the end-Ordovician glaciation, and how it sits in the revised sequence stratigraphic framework.

A second study that will result in a publication is the analysis of the entire dataset of chitinozoans recorded from the Upper Ordovician from the glaciated margin using a numerical stratigraphical approach and the software package CONOP. This will enable us to decipher full temporal evolution of the palynomorphs. The purpose of CONOP is to eliminate any environmental bias in a stratigraphic dataset and to give us a sequence of idealized FADs and LADs to be used in a virtual biochronological way.

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