The Campanian-Maastrichtian Boundary
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CHAPTER F3

The Campanian-Maastrichtian boundary: definition at Tercis (Landes, SW France) principle, procedure, and proposal

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Sommaire

Les conventions dont les géologues ont besoin pour parler un langage commun sont établies dans le cadre de Commissions de l'Union Internationale des Sciences Géologiques. Les unités du calendrier de l'histoire du globe sont conventionnelles; leur établissement est sous la responsabilité de la Commission Internationale de Stratigraphie. Cette dernière a établi des sous-commissions chargées chacune d'un Système entre le Cambrien et le Néogène. C'est la Sous-commission de stratigraphie du Crétacé qui a institué le Groupe de Travail Maastrichtien, sous l'égide duquel le présent travail a été réalisé.

Ce chapitre résume la convention proposée en conclusion des travaux du Groupe de Travail pour définir la limite Campanien-Maastrichtien. Cette limite répond au concept de Point Stratotypique Global (PSG). Le PSG est un point dans une section qui concrétise par convention une limite entre deux unités chonostratigraphiques, soit, dans le cas présent, entre les deux derniers Étages du Crétacé. Le contenu de ces Étages est représenté par les dépôts accumulés dans l'intervalle de temps passé entre les moments de dépôt correspondant aux PSG qui les encadrent. Ce contenu est historiquement défini par les stratotypes historiques, lesquels ont donné le nom aux Étages qui sont le plus souvent incomplets, imprécis, voire incompatibles au niveau des limites communes. C'est la raison pour laquelle le concept de PSG a été institué car il résout les problèmes pouvant survenir aux limites et conduit à établir un calendrier précis, continu et d'application globale.

Des recommandations de principe ont été formulées afin que l'établissement des PSG soit réalisé de façon homogène et scientifiquement justifiée malgré leur caractère conventionnel. On peut citer 1- une caractérisation par des outils stratigraphiques diversifiés; 2- une définition strictement liée à un point dans une section (une convention) et non à un événement (une interprétation); 3- un choix basé sur des raisons clairement fondées dont la nature est très libéralement laissée à la discrétion des experts.

Le résultat de ces travaux ne devient convention qu'à la suite de votes au sein du Groupe de Travail, puis de la Sous-commission, puis de la Commission qui soumet alors la proposition à la ratification du Conseil de l'Union Internationale. Cette procédure a été suivie par le Groupe de Travail dont il faut souligner que la tâche principale est avant tout de découvrir puis de caractériser une section qui pourra servir de référence, l'aspect administratif n'étant là que pour tirer parti des résultats.

La stratégie suivie pour localiser le PSG a pris en compte la variété des usages antérieurs qui, selon la nature de l'outil stratigraphique mis en jeu et le domaine paléogéographique, privilégiait des limites d'âge très différent que l'on situe aujourd'hui entre 74,5 Ma (événement guide: extinction de *Radotruncana calcarata*) et 70,0 à 70,5 Ma (événement guide: extinction de *Aspidolithus parcus*

constrictus). Un niveau médian a été favorisé dont l'événement guide (et non l'événement marqueur unique) est l'émergence de *Pachydiscus neubergicus*. La rareté de cette espèce, son absence fréquente des niveaux basaux qui devraient la renfermer, le bon nombre d'événements concentrés autour de cet événement guide à Tercis ont conduit le Groupe de Travail à adopter une solution originale pour localiser précisément le niveau limite, avec un maximum de potentiel de corrélation et un minimum d'incertitude. Il s'agit de combiner une série d'événements traduisant une accélération de l'évolution biologique apparente dont fait partie l'événement guide préféré. Le choix de cette solution permet, notamment, d'affirmer résolument le caractère conventionnel de la limite formellement indépendante d'une interprétation de phénomène. Cette affirmation est moins évidente lorsqu'une limite est dite "définie par l'événement biostratigraphique unique X". Cette formulation est souvent proposée ou citée et est incorrecte par rapport aux principes du PSG (un point dans une coupe et nulle autre chose). Elle est, en outre, incompatible avec la réalité biostratigraphique car l'instant représenté par la limite doit être unique et instantané alors que la place d'un horizon biostratigraphique est soumis aux aléas de multiples conditions de gisement, de récolte et de détermination à l'échelle de la grande précision requise pour une stratigraphie à haute résolution qui tente de distinguer des instants distincts de 10 à 20 ka.

Douze bio-horizons constituent les événements clé (figure 1 et tableau 1). Ils ont été choisis autour du repère guide préféré pour représenter une variété de groupes fossiles, une proportion équilibrée de macro- et de microfossiles, des fossiles raisonnablement représentés à Tercis, des fossiles identifiés sans ambiguïté, des fossiles connus dans un large domaine paléogéographique et environnemental.

La localisation du PSG résultant de la combinaison arithmétique des cotes de ces douze signaux est la cote 115,2. D'autres combinaisons, une sélection plus ample ou plus limitée ne modifient pas ce niveau de plus de quelques décimètres qui représentent une différence de moment de dépôt de l'ordre de ±20 ka. Cette marge est négligeable si l'on se remémore que les différents niveaux usités par le passé pour situer la limite étaient distincts de plusieurs Ma. Le niveau conventionnel à 115,2 est entièrement compatible avec l'événement guide préféré situé quelques décimètres au-dessus d'après les récoltes actuelles. La cote 115,2 affleure en quatre endroits du site géologique de Tercis; le mieux à même d'abriter le PSG est le palier IV qui expose depuis longtemps une succession continue.

Le principe de la définition conventionnelle a été adopté en Janvier 1996 par une majorité supérieure à 60% des membres du Groupe de Travail. La Sous-commission a voté ensuite la proposition en Juin 2000. La Commission doit se prononcer prochainement. La limite Campanien-Maastrichtien serait donc fixée dans la succession de Tercis les Bains en un point situé à la cote 115,2 sur le palier IV. Un repère fixe sera établi après la ratification de cette proposition par l'Union Internationale à la fin du processus d'adoption.

La question de la subdivision de l'Étage Maastrichtien était aussi à l'ordre du jour des travaux du Groupe de Travail. Aucun niveau n'est apparu déterminant pour situer cette limite d'autant que, pour le moment, cette portion de la succession reste à dégager sur le site de Tercis qui n'a pu livrer d'information utile. Par contre, des suggestions ont été possibles pour le Campanien qu'il semblerait justifié de subdiviser en trois sous-Étages d'après sa durée. Le Campanien supérieur pourrait débuter à un niveau proche de l'émergence contemporaine de *Radotruncana calcarata* (foraminifère très répandu et très reconnaissable) et du nannofossile calcaire *Quadrum trifidum*. La section de Tercis aiderait à caractériser une corrélation entre ce plancton et la macrofaune, notamment les ammonites.

1. Introduction

This chapter partly sums up previous reports (Odin, compiler, 1996b; 1999) on the Campanian-Maastrichtian boundary definition at Tercis and takes recent progress into account.

In the field of geology, conventions are established under the aegis of the International Union of Geological Sciences (IUGS). This union has set up

a series of Commissions, the largest of which is the International Commission on Stratigraphy which is in charge of problems related to stratigraphy. A major question dealt with by this Commission is the geological calendar. Eleven Subcommissions have been set up: one for each System (Cambrian to Neogene). Within each System, each stage (the fundamental chronostratigraphical unit of the geological calendar) is investigated by a Working Group which is designated to make proposals for the definition of a conventional unit. The Maastrichtian Working Group (MWG) has been established with a view to submitting a proposal for the Campanian-Maastrichtian stage boundary to the Subcommission on Cretaceous Stratigraphy.

Neither in Champagne charentaise, nor in the Maastrichtian type area, is the stratigraphical record complete, so that it had been known since the MWG began its work that another section had to be considered in another area for the definition of the Campanian-Maastrichtian stage boundary. The previous two chapters conclude that the section at Tercis is rich in diversified information and is thus suitable for correlation with a variety of depositional basins all over the world.

This last chapter summarises the formal conclusions reached for the definition of the boundary in agreement with the procedure recommended by the Commission on Stratigraphy. The procedure began following the 1995 meeting in Brussels where informal discussions occurred on the suitability of several successions. The postal ballot taken in the following months led to designate the Tercis succession as the most favourable one and to determine the procedure suitable for the selection of the appropriate level, given the data available at the time (January 1996). The following four years were spent improving the knowledge on the succession, thus allowing to submit a formal proposal of definition to the Subcommission in September 1999. Additional information has been gathered for the last ten months and the final proposal has been improved accordingly.

The question of auxiliary sections is shortly recalled; these sections are of interest for practical use in domains where tools poorly represented in the type section are necessary. Finally, the subdivision of the bracketing stages is briefly examined.

2. Some principles

2.1. The geological calendar

The geological calendar, which is composed of intervals of time, is divided according to events recorded in the deposits. These deposits are subdivided into bodies of rock which constitute the fundamental stratigraphic units called stages. Conventional definitions of these stages are agreed by the appropriate body of the International Commission on Stratigraphy (ICS). Basically, a global Stage is defined between two boundaries, each located at a point in a section: the Global Standard-stratotype Section and Point (GSSP). The guidelines of the International Commission of Stratigraphy for establishing GSSP (Cowie et al., 1986; Remane et al., 1996) are well suited for the major portion of the Phanerozoic Aeon. The corresponding stage-based stratigraphy is valid for Cambrian to Neogene formations (Odin, 1994). The Cretaceous System is fully relevant for the stage-based stratigraphy.

The main content of a stage is usually defined by the historical stratotype. But the historical stages commonly do not record the geological history at their lower and upper boundaries or do it very poorly. This is definitely the case for the boundary between the Campanian and the Maastrichtian stages (chap. F2). In fact, the depositional gaps at the top and bottom of historical stages were often a major factor allowing to distinguish these stages. The resulting calendar was essentially a succession of portions of time: pages of the geological history were only written in their middle while their top and bottom parts were blank. The GSSP concept thus derived from a need for scientific improvement and the building of a continuous succession of units on which a calendar is based, allowing the description of a (more) continuous history.

A corollary of the GSSP concept is that the corresponding stratigraphy is unique for the whole Earth, which is an ambitious decision aiming at a unique language. However, this modern view of global chronostratigraphy must be understood as consistent with possible parallel regional (essentially lithological) chronostratigraphy of major practical interest both for geological mapping and economic applications.

2.2. *Guidelines*

Guidelines were laid down in order to define GSSPs (Cowie et al., 1986; Odin, 1992b; Remane et al., 1996). First, the characterisation of the point and the bracketing section must be diversified. However, this is not always fully achieved. Indeed, what generally happens is that leading experts decide that one criterion (generally based on a single taxon) is a key one for locating the boundary; this criterion is then studied in detail while other experts find little interest in contributing to the work on other fossil groups or other stratigraphical approaches on which the definition will not directly depend. As a result, many GSSP proposals considered only one or two fossil groups (Chlupac & Oliver, 1989; Cocks, 1985; Flajs & Feist, 1988; Holland, 1985; Klapper et al., 1987; Ziegler & Klapper,1985).

Second, the conventional definition of a boundary should be a point located in a succession. It is not a horizon, it is not an event nor any sort of abstract concept concluded from the study of the succession. This means that commonly used expressions such as "the taxon A has been proposed as defining the base of the Stage" or "the stage boundary is located at the first occurrence of taxon A" (or any other kind of event) are incorrect. In a nutshell, the stage boundary is distinct from a biostratigraphical (or any other) concept. Thus, the best way to guarantee the distinction between the convention and interpretative knowledge is to disconnect the GSSP from a particular event.

A third rule is that the main problem to solve is a correlative one. In this respect, the "type-sections must provide significant biostratigraphic data of high quality" (Remane et al., 1996) in addition to physical, chemical or geochronological information when available.

Finally, there is a need for "clear and succinct reasons for the choice of the GSSP in both stratigraphic level and geographic location" (Cowie et al., 1986). The authors of the different versions of the guidelines have always insisted on giving the Working Groups a full liberty concerning the reasons for their choices. It is to be noticed that there is no constraint on the nature of the correlative event to be selected as the guide for locating the boundary. This means that the definition may be independent of a particular guide event, provided that the correlation potential is considered better when using another "reason"; disconnecting the GSSP from an event is thus statutorily valid. A contingency considered by the authors of the guidelines is that a criterion (an event) can be used to guide the definition but it is not absolutely necessary to locate a point in concurrence with a guide-event.

The liberality of the Commission and its guidelines for agreement of a GSSP can be illustrated with the Eocene-Oligocene boundary definition. Data on the proposed GSSP were originally gathered by a Working Group of the International Geological Correlation Program (Project 196) (Odin, 1986; Odin & Montanari, 1989). Following this convincing work, the information was submitted to the Subcommission on Palaeogene Stratigraphy and the LO of hantkeninids was selected as the guide-event for locating the GSSP in the succession at Massignano (Italy, Odin & Montanari, 1988). This criterion was in disagreement with the IUGS recommendation that a FO is preferable to a LO as a key bio-horizon (Remane et al., 1996) to define the base of a stage because the thus defined stage is then founded on an absence which can be due to several causes different from the normal course of evolution. However, the Commission accepted the proposal.

Another example is the GSSP for the Cretaceous/Palaeogene boundary at the top of the Maastrichtian stage. A lithological criterion was suggested there by the Working Group in contradiction with the rules proposed in the guidelines, which recommend that a boundary should be located in a lithologically continuous succession. That GSSP was also favourably received.

In summary, it is sufficient to propose a GSSP which has a good correlation potential to the ICS.

2.3. *Procedure*

The main problem to be solved when establishing a new GSSP is to discover a new section or a new content in an already known section; in summary, to discover data rather than solve an administrative problem. This is the reason why the procedure for

establishing a new GSSP begins with the setting up of a Working Group which is distinct from the Subcommission and whose members are given complete freedom of action. When a sufficient amount of knowledge is reached on an appropriate succession, the Working Group (WG) organises a postal ballot on such a final and simple question as: "do you agree on that point in that section?" The statutes of the ICS require that a 60% majority of the voting members be reached for a proposal to be accepted and submitted to the next step of agreement.

When the WG has reached that majority, the proposal is transmitted to the Subcommission which is supposed to examine the acceptability of the proposal. Members of the Subcommissions are not necessarily experts who know the particular problem but they are able to see the proposal from a more general point of view.

When the Subcommission (Subcommission on Cretaceous Stratigraphy in the case of the Campanian-Maastrichtian boundary) has given a favourable answer to the postal ballot resulting in a majority of 60%, the proposal is transmitted to the Commission of Stratigraphy. Its role is to decide whether the proposal is in accordance with the guidelines and statutes or not; its scientific basis is also examined again.

The positive answer to the postal ballot by the Commission members (60% majority) leads the chairman of the Commission to transmit the new GSSP to the IUGS for ratification.

3. Practice

3.1. Brief historical account

The justification of the proposal and subsequent postal ballots is considered below. The Maastrichtian Working Group was established in 1993 on request of the board of the Subcommission on Cretaceous stratigraphy. The undersigned compiler was designated following his proposal that the succession at Tercis should be considered, on account of the preliminary work published that same year by Hancock et al. (1993) and the favourable situation for additional study. The membership of the WG was assigned to efficient contributors to the action of the WG; all of them were considered voting members at the time of ballot.

Between 1993 and the Cretaceous symposium at Brussels in 1995 a first set of studies had been undertaken to confirm the suitability of the Tercis section with regard to sedimentological continuity, amenability of diversified stratigraphic tools including a variety of biostratigraphical scales, absence of other candidate sections . . . and possibility for preservation. Both macro- and microfossils were shown to be present and significant. In addition, potential developments of knowledge still remained widely open. The discussion organised during the 1995 symposium showed that the major part of the community was favourable to the section. The following accumulation of new results led to establish the proposal based on guidance for locating the boundary interval near the FO of *P. neubergicus* in preference to other positions used in the past and location of the precise boundary level in agreement with a combination of criteria bracketing the guide-event.

3.2. Choice of the strategy

Identification of the taxon *P. neubergicus* used to delineate the guide-event does not seem to be a fundamental problem for some experts. However, intermediate forms are present and the intuitive factor can thus play a role in identification. The boundary level could thus depend on an uncertain divide drawn between "typical" and "less typical" specimens all collected far from (in deposits several Ma older than) the holotype specimen of Austria which can thus have no perfectly similar equivalent at an earlier time.

The guide fossil is an ammonite which is rare at Tercis and elsewhere. In this situation, the absolute precision of the signal in the quarry at Tercis is necessarily poor. Founding a boundary on this signal is thus partly submitted to the good fortune of the collector.

The total range of the guide fossil covers a large portion of the Maastrichtian. Therefore, there is a potential diachronism of the FO of this taxon.

Examples of FO of *P. neubergicus* at levels younger than the Campanian-Maastrichtian boundary, though commonly within a lower portion of the stage, are numerous (Kennedy & Summesberger, 1986; 1987; Jagt & Felder, 1999). It has been emphasised above that, although ***locally*** contemporaneous, the signal provided by the guide fossil and the limit are distinct concepts. However, founding a boundary on a guide which is known to have a significant potential of diachronism is not satisfactory.

On account of this problem, the chronological meaning of the FO of *P. neubergicus* at Tercis could be questioned. Nevertheless, two reasons support the interest of the bio-signal. First, the morphological transition observed at Tercis between *P. perfidus* and *P. neubergicus* at the base of the local range of the latter (interval 115.2–117.5, see appendix 2 in chap. D4g), if accepted, suggests that *P. neubergicus* actually appears at that moment as the descendant of *P. perfidus*. The second reason is the relationship between the guide-event and contemporaneous bio-signals. Contemporaneity of several bio-signals is a good way for documenting a chronological significance (Guex, 1987). The best proof must come from a subcontemporaneous LO of a Campanian taxa which would thus confirm that the local FO of the Maastrichtian *P. neubergicus* is located near the base of its range. Among others, the short interval between the LO of *N. hyatti* and the FO of *P. neubergicus* is a good argument.

A major reason for preferring an improved approach is the excellence of the succession at Tercis as a multiple biostratigraphical reference. In addition, the best guide for locating a boundary is the one that brings the highest correlation potential. The point with the highest biostratigraphical correlation potential is the one located where the highest rate of evolutionary change can be demonstrated. An easy way to estimate the highest rate of evolutionary change is to draw a histogram of all the known biostratigraphical changes (Odin, 1996a). This is the principle used in the combined criterion which has been preferred by the Maastrichtian Working Group. As soon as 1995, the accumulated data showed that a number of biostratigraphic features bracketed the criterion used for guidance (see table 2 in chap. F1). These bio-horizons, which bracket the local FO of *P. neubergicus*, mutually reinforce themselves as correlative and chronologically significant tools.

Therefore, a combined criterion has been preferred, allowing a precise and efficient selection of the conventional level where to put the GSSP. This approach is consistent with the rules recalled above. An expert of the Working Group worried that a level unconnected with an event might lead to some confusion as for locating the boundary elsewhere. Such concern is not justified because the boundary IS connected to an event; moreover, it is connected to several events and is thus more richly defined than it would be by a single event. Confusion would result from the fact that the boundary is not only connected to the preferred guide-event; again this is in contradiction with the principle accepted here: the used criteria were selected because they bracket the FO of *P. neubergicus* and thus depend on that particular feature. Finally, some geologists could believe that confusion might result from several of the used criteria showing contradictory information when present together in another outcrop. In that case, the superiority of the combination is obvious because it evidences possible diachronism in bio-horizons. That is why the biostratigraphical analysis of a section must include a critical examination of different bio-horizons and not a direct uncritical application of a single piece of information. Confusion will arise the other way, when potentially diachronous stage boundaries tend to be used while linked to a criterion which is diachronous in essence at least on a high resolution scale. In the present view, the documented, apparently contradictory information will be a measure of the stratigraphical uncertainty in the location of the boundary, a question which is difficult to quantify when a single(or few) biostratigraphical criterion(a) is(are) present in the reference section.

3.3. Selection of significant bio-horizons

Table 1 lists twelve bio-horizons which have been selected at the end of the cooperative study. In addition to the criterion used for guidance, this list partly considered the need to include: i- a variety of

Table 1. The twelve bio-horizons selected to locate the level of the GSSP. Approximate distance in metres and the corresponding duration of deposition between the boundary level and the bio-horizon are given to the left.

Fossil group	Biohorizon	level	≠ (≈m)	≠ ka
Ammonites				
1-	FO *Pachydiscus neubergicus*	≤ 116.1	+0.9	≈35
2-	LO *Nostoceras hyatti* and allied forms (N. sp 2)	≥ 114.1	-1.1	≈45
3-	FO *Diplomoceras cylindraceum*	≤ 111 ±3	-4.2	≈165
Inoceramids				
4-	FO genus *Trochoceramus*	≤ 97.7	-17.5	≈700
Dinoflagellate				
5-	LO *Corradinisphaeridium horridum*	112.4 ±2.4	-2.8	≈110
6-	LO *Raetiaedinium truncigerum* (≈*R. evittigratium*)	118.6 ±3.8	+3.4	≈135
7-	LOs *Samlandia mayii* & *S. carnarvonensis*	> 122.4	+7.3	≈300
Calcareous nannofossils				
8-	LO *Quadrum trifidum*	134.2 ±2.7	+19	≈750
Planktonic foraminifera				
9-	FO *Contusotruncana contusa*	116.5 ±0.3	+1.3	≈50
10-	FO *Rugoglobigerina scotti*	116.2 ±0.5	+1.0	≈40
Benthic foraminifera				
11-	FO *Bolivinoides* 5 lobes > 4 on last chamber	107.4 ±7.4	-7.8	≈310
12-	LO *Gavelinella clementiana*	115.5 ±0.7	+0.3	≈12

fossil groups; ii- an equilibrated proportion of micro- and macrofossils; iii- fossils acceptably documented at Tercis (a large enough number of identified specimens); iv- fossils whose identification neither presents repulsive difficulty nor depends on unclarified taxonomic definition; v- fossils able to document a wide palaeogeographical area and diversified environments. The list has been modified in the course of the study because new specimens have constantly accumulated and because the relative importance of the different bio-horizons has been influenced by subsequent discussion with WG and Subcommission members.

Comments on the twelve bio-horizons are given below after information available in this monograph.

Among ammonites, criterion 1 is the FO of *Pachydiscus neubergicus*. This bio-signal is the guide for locating the GSSP and the result of the present combination must be found in the vicinity of this FO. Different portions of the collection of the WG were submitted to different experts: the oldest specimens of each of these portions were found between 116.1 and 118 (see chapters in part D4). It is assumed that all experts will agree on the identification of the lowest specimen and the FO is thus at or below level 116.1. The occurrence of intermediate forms (between levels 115.2 and 117.5; table 3 in D4g) must be considered in the light of the possible extension of identification (open rectangle in figure 1).

The LO of *Nostoceras hyatti* is criterion 2. Although it is not easy to distinguish from nearby forms, *N. hyatti* is a key Campanian fossil to check the validity of the former criterion. Combining this LO with the above FO is the best way to determine a chronological instant, whether there is a co-occurrence or not. The actual co-occurrence is probably rare and short (North Spain, Küchler et al. this volume, chap. E3). At Tercis the LO is located at level 114.1 or above according to a specimen identified by W. A. Cobban and P. Ward. T. Küchler prefers to identify it as *N.* sp. 2 though he agrees that the latter is morphologically close to the species identified by his colleagues.

Criterion 3: the FO of *Diplomoceras cylindraceum* is a Campanian signal which is located at level 111 ± 3 or below. The double arrow in figure 1 shows the uncertainty on the find level of several specimens found loose in Spring 2000. This criterion can be used in the field, even on small crushed pieces thanks to the ease of identification of this heteromorph. In addition, the palaeogeographical distribution is exceptionally wide for a macrofossil in general and an ammonite in partic-

ular. Criteria 2 and 3 delineate a short co-occurrence which is a way to reliably date the uppermost Campanian interval using macrofossils.

The original selection also considered the species *Hoploscaphites constrictus*; it has finally been removed because i- no typical well preserved specimen has been collected at Tercis near the boundary, ii- confusion with the species *H. pumilus* may have occurred in the past, iii- other contemporaneous outcrops display either poor specimens of the taxon or none and iv- most commonly the taxon first occurs at a younger level than the stage boundary defined in this volume.

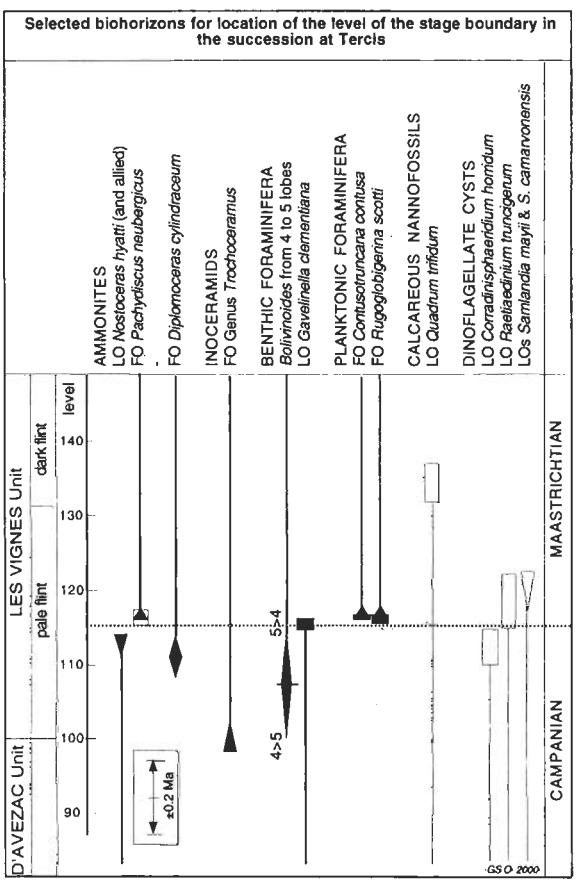

Fig. 1. Criteria selected to calculate the level of the Campanian-Maastrichtian boundary GSSP. The arithmetic mean of the mean levels of the 12 criteria is 115.2: the conventional level for locating the GSSP on floor 4 of the quarry at Tercis. Deletion of the two extreme criteria (calcareous nannofossils and inoceramids), selection of other criteria or deletion of some criteria in this group would not modify this mean value by more than a few dm (improved from original proposal: Odin, 1996b, following more recent information).

A single other macrofossil has been selected for criterion 4: the inoceramid genus *Trochoceramus*, the FO of which is accepted at level 97.7 or below. As this fossil is fairly common, it can be easily identified in the field.

Three bio-horizons have been selected for the best macrofossil group (ammonites); thus, three bio-horizons have also been selected in the most promising microfossil group of dinoflagellates. Criteria 5, 6 and 7 are: the LO of *Corradinisphaeridium horridum* (interval 112.4 ± 2.4), which is well located for an easy-to-identify and beautiful taxon; the LO of *Raetiaedinium truncigerum* (interval 118.6 ± 3.8), which is based on a taxon differently named by different authors but identified by several of them; the contemporaneous LOs of *Samlandia mayii* and *S. carnarvonensis* at level 122.4 or above, which has also been identified at about the same level by different experts. The open boxes for criteria 5 and 6 in figure 1 show the interval between the last sample bearing the fossil and the first sample without.

The calcareous nannofossils do not deliver bio-horizons in the immediate vicinity of the boundary but one of the nearest ones has been selected as criterion 8. The LO of *Quadrum trifidum* has been consistently identified by four experts in the interval 134.2 ± 2.7. This consistency as well as the ease of identification suggest that this Maastrichtian bio-horizon has a rich correlation potential. This is not the case of the LO of *Q. gothicum* (129.1 ± 2.4?) which is nearer the stage boundary but has proved to be inconsistently located by different experts at Tercis.

Two bio-horizons have been selected among the planktonic foraminifera, a widely used tool for biostratigraphical dating of the low palaeolatitude outcrops. Criterion 9 is the FO of *Contusotruncana contusa* in the interval 116.5 ± 0.3 (sampling interval) at Tercis. Compared to some other successions, *Ct. contusa* appears at an apparently older level. For example, in the succession of the Bottaccione (Apennines, chap. E4) this bio-horizon is located at metre 342 and is contemporaneous with the FO of *Racemiguembelina fructicosa*; this is 22 m above metre 320 where we correlate the stage boundary

and this represents more than 2 Ma of deposition. In that particular case, the succession in the Apennines does not record the inception of the taxon. A difference in taxonomy could be another interpretation of the difference.

Criterion 10 is the FO of *Rugoglobigerina scotti* identified by J.-A. Arz in the interval 116.2 ± 0.5. Some discussion arose about that bio-horizon when it was submitted to postal ballots. In particular, it was suggested that the two pictures in Arz & Molina (plate II in chap. C5b) used for illustration of the proposal do not represent typical forms. This is agreed by J.-A. Arz (personal communication, June–2000) who i- suggests calling the specimen *Rg.* cf. *scotti* in the particular case, ii- underlines that some of the oldest specimens of a taxon may not be in entire conformity with the younger holotype of the taxon, and iii- points out that although more typical specimens were present in the same sample, they could not profitably be pictured due to poor preservation.

In addition, M. Caron (pers. comm. VI–2000) remarked that the FOs of *Ct. contusa* and *Rg. scotti* are also contemporaneous in Tunisia, which supports the contemporaneity established independently by different experts at Tercis; however, the two signals are younger than the locally assumed stage boundary of Tunisia. Li & Keller (1998) reported subcontemporaneous FOs of *Ct. contusa*, *Rg. scotti* (39.8 to 41.6 metres below the Cretaceous-Palaeogene boundary) slightly younger than the FO of *Gansserina gansseri* (48.8 m below the same boundary) all significantly older than the FOs of *Abathomphalus mayaroensis* and *Racemiguembelina fructicosa* (21.0 and 22.5 m below the same boundary respectively) which are sometimes taken as markers for the beginning of the upper Maastrichtian.

It was also important to consider benthic foraminifera, a key fossil group useful for general correlation, especially toward the Boreal Domain. Criterion 11 is the LO of *Gavelinella clementiana* located in the interval 115.5 ± 0.7 at Tercis. The taxon is a good upper Campanian microfossil which is not rare in platform deposits (Robaszynski & Christensen, 1989).

Criterion 12 is based on the morphological evolution of the genus *Bolivinoides*, an easy-to-identify genus, for which a preliminary statistic study has documented again the progressive increase with time in the number of "pustules" on the last chamber. At Tercis, there is a change from dominant 4 pustule-bearing specimens in the oldest deposits to dominant 5 pustule-bearing ones above the interval 107.4 ± 7.4. This evolutionary lineage is a statistic estimate and does not imply that 5 pustule-forms are absent below or 4 pustule-ones absent above. This statistic criterion probably corresponds to a real chronological and reproducible event.

A last criterion: the FO of *Coleites reticulosus* (109.7 ± 0.5) could have been included in the set of criteria but benthic foraminifera have not been fully studied at Tercis yet and taking this last criterion into account would have given too much weight to this fossil group.

3.4. Location of the GSSP

The combination of the twelve criteria mentioned above has been made in the most simple way, an arithmetic mean of the presently accepted levels. More sophisticated calculations considering uncertainties in the location of bio-horizons for example lead to fairly similar results; besides, that conventional exercise confers a conventional dimension to a question where rigour does not fit (we are proposing a "mean" between objects of different nature).

The arithmetic mean of the twelve levels is 115.2. This level is exposed in four different places in the geological site at Tercis (platform III, platform IV, platform V, and E section). The best outcrop (less disturbed by tectonics or quarrying) is located on platform IV. In addition, this platform has been exposed longest and sampling macrofossils is difficult there and it will be easier to protect it from the action of fossil amateurs. Therefore, the golden nail for the Campanian-Maastrichtian boundary will be hammered at level 115.2 in the deposits exposed on platform IV of the succession at Tercis when the IUGS has ratified the proposal.

The 115.2 level is consistent with the information provided by the guide-event. It is also consistent with the opinion induced from the

simple observation of table 2 in chap. F1 where several bio-horizons are listed between levels 111 and 119 (or 115 ± 4), the interval where biological evolution apparently accelerates. The obtained mean is located in the middle of that easy-to-observe feature.

One might question the addition of the two extreme bio-horizons given by inoceramids and nannofossils; however, the arithmetic mean of the remaining 10 criteria (at 115.0) is not different. Another possibility would be to delete also the imprecise *Bolivinoides* bio-horizon; the remaining nine criteria would give a mean of 115.9. Finally, the mean of the 13 criteria quoted in table 2 of chapter F1 is 115.5. In summary, the different ways to apply the principle of multiple criteria for selection of the precise level where to locate the GSSP lead to results which are reproduced with a precision which represents no more than ± 20 ka at Tercis; this is the field of high resolution stratigraphy. During the different steps of the collection of fossils, the oldest find of *P. neubergicus* has been submitted to a wider variation (± 1 to 2 metres). The strategy of combining criteria thus leads to a result which is not influenced by the arbitrary selection of a criterion.

3.5. The Working Group ballot

A formal proposal for selection of the site at Tercis was made in 1995 together with a recommendation for locating the level (circular 4 of the Maastrichtian Working Group, IX–1995). The results of the postal ballot by the Maastrichtian Working Group were reported in Circular 5 of the Maastrichtian Working Group and by Odin (1996a). The postal ballot for which WG members were able to choose between yes, no, or abstain led 1- to a preference for the first occurrence of *Pachydiscus neubergicus* as the guide-event for approaching the level (86.5% majority, yes or no return) with 2.7% no and 10.8% abstain, 2- to a preference for a combined criterion including several key marker horizons for definition of the precise level and point (62.2% majority, yes or no return; 24.3% no and 13.5% abstain), 3- to a recommendation of the section at Tercis with a majority of 94.6% (yes or no return) with 5.4% abstain. Detail of the ballot is given in appendix 1 to this chapter.

3.6. Auxiliary sections

Neither discussion nor vote have been undertaken for the appointment of official auxiliary sections; no candidate has been proposed by any expert. The statute of the two sections in the Apennines (Bottaccione Gorge) and at Kronsmoor (Germany) discussed in the previous chapter is therefore strictly similar to that of any other succession outcropping in the world.

The exact position of the newly defined stage boundary in these two sections has been suggested in the light of the data presently available. They could be changed or made more precise in the future if new data and more reliable correlation can be obtained between the definitely located point at Tercis and the other successions.

4. Subdivision of the Campanian and the Maastrichtian stages

4.1. Principle

The Maastrichtian Working Group was supposed to examine the question of the subdivision of the stage into substages. The task is somehow contradictory with the principle that the stage is the fundamental (and thus smallest) chronostratigraphic unit of the geological time scale for which a global definition and convention are required. From a practical point of view, "global" substages could be desirable if their recognition was possible all over the world or, at least, on a large portion of the Earth.

The limit in the recognition of stages on a global palaeogeographic scale was discussed by Odin & Odin (1990). It is linked to the primary dating tool (biostratigraphy in the stage-founded stratigraphy). This tool is similarly precise during the major portion of the Phanerozoic (Silurian to Neogene) with units (biozones), the mean duration of which is between 0.5 and 1.5 Ma (for example see Westermann, 1984; House, 1985). The resolution of a stage is historically connected to the resolution of the biostratigraphical tool and thus, the duration of the biozones. Therefore, a stage shorter than 2 to 3 Ma will be difficult to identify, not reproducible on a global scale, and superfluous.

This practical principle is evidenced by the remarkably constant mean duration of historical

stages established by the pioneer stratigraphers in the Cambrian to Neogene Systems: between 3 and 8 Ma (Odin & Odin, 1990). Shorter than 4 to 5 Ma, they are not easy to recognise; longer, they can be subdivided. The wish for stage subdivision depends on this observation.

4.2. Subdivision of the Maastrichtian stage

The approximate duration of the Maastrichtian stage (7 Ma, Odin, 1994 and this volume) suggests that it could be subdivided into subunits recognisable on a large portion of the Earth. The solution to this problem needs i- the availability of clear cuts; ii- a consensus on one cut, and iii- a continuous succession for documentation of the limit.

The most commonly quoted cut in the oceanic domain seems to be the FO of the planktonic foraminifera *Abathomphalus mayaroensis*. In the succession of the Bottaccione, the homonym range zone covers about half of the thickness of the Maastrichtian beds and the subdivision would appear appropriate with the FO of a calcareous nannofossil (*Lithraphidites quadratus*) slightly younger than the latter bio-horizon.

However, there are problems with the foraminiferal guide fossil which is rare or absent in tropical areas and in comparatively shallow deposits (Odin, Desreumaux et al., chap E5b). As a result, the taxon first occurs sooner in high latitude deposits (Masters, 1984; Keller, 1988; Canudo et al., 1991; Olsson and Liu, 1993) than in tropical areas and is thus a poor guide fossil for precise correlation. The subdivision of the Maastrichtian into two formal global substages is not practicable at present.

4.3. Subdivision of the Campanian stage

This question is not under the responsibility of the WG. However, the information gathered in this volume may help to profitably discuss the question. According to the numerical time scale the Campanian stage is 11 Ma long between boundaries at 83 and 72 Ma (Odin, 1994); a formal subdivision of that stage seems practicable, either into two or three substages.

Regional subdivision into two (lower and upper) substages is in use in the Boreal Domain. The German boundary can be located at the ammonite contemporaneous LO of *Scaphites hippocrepis* III and FO of the genus *Hoplitoplacenticeras* and sub correlative gracilis/senior conica/senior macrofossil zone boundary. If the magnetostratigraphic interpretation of Lewy & Odin (chap. B2d) is correct, that boundary would fall near the base of magnetozone 33N, which can be dated at 79.5 or 81.0 Ma. In terms of duration, this subdivision is not appropriate between a too thin lower Campanian and a thick upper Campanian. The boundary quoted above would be more appropriate between a lower and a middle Campanian substage mostly defined in ammonite-bearing deposits.

In terms of ammonites, the middle Campanian/upper Campanian boundary could be located at or between the subcontemporaneous LO of the genus *Hoplitoplacenticeras* and the FO of *Bostrychoceras polyplocum*. This level would fall in the lower portion of the d'Avezac unit at Tercis with an estimated age of 76–77 Ma. However, in agreement with the high interest of the foraminifera *Rd. calcarata*, a boundary located at a level related to this guide fossil would be most suitable. The FO of the taxon would probably be the best guide-event since its age is estimated at about 75.5 Ma leaving a 3.5 Ma-long upper Campanian deposition above (figure 2 in chap. F1). In addition, the FO of the calcareous nannofossil *Quadrum trifidum* is subcontemporaneous with this level and the resulting pair of bio-horizons would have a superior value for correlation in oceanic basins. The succession at Tercis could provide this proposed boundary level with useful relationships between macro- and microfossils.

5. Conclusion

The major aim of the Maastrichtian Working Group has been achieved with reasonable success following seven years (1993–1999) of work, thanks to the contributions of more than 60 experts. The GSSP for the Campanian-Maastrichtian boundary has been formally proposed at level 115.2 on platform IV of the geological site at Tercis.

This level is consistent with the criterion for guidance favoured by the majority of the WG members as it is near the presently known FO of the ammonite *P. neubergicus*. The exact location of the FO in the quarry cannot be known for sure partly due to the rarity of the guide fossil, and it could remain unknown for long. However, the procedure preferred for a precise location of the level overcame that problem by combining a series of twelve bio-horizons. These bio-horizons selected in a wide spectrum of fossil groups and environmental conditions will allow easy correlation within a wide palaeogeographic domain. This procedure appears superior to the one in which a single criterion is raised to the rank of a mythic event that few, if any, fossils (especially macrofossils) can actually take on with demonstrable justification at the Campanian-Maastrichtian boundary.

The selected procedure has been preferred for this reason as well as for the fact that the resulting preferred level remains insignificantly modified either when removing one or several of the selected bio-horizons or when a new fossil is discovered, which has happened in the past few years. The newly created procedure is also consistent with the guidelines established by the International Commission on Stratigraphy. It has the advantage of taking into account the wide amount of knowledge established on the rich succession outcropping at Tercis. It also makes the chronostratigraphic concept conventionally defined here definitely distinct from each individual stratigraphic information. By this means, erroneous interpretation of the boundary will be avoided. This confusion occurs when the location of the boundary primarily depends on a single mythic event which has a diachronous potential.

To some supporters of a boundary exactly located at a locally observed event, a difficulty may arise when two or more of the selected criteria are located at significantly different levels in the section to be correlated with. In that case, it is the philosophy of the present work that the difficulty is the reflection of actual problems in stratigraphical correlation which could be (and are often) concealed (underestimated) when a single criterion is used for establishing a boundary. Dependence on several criteria in the definition has thus a superior power by evidencing problems of location related to the stratigraphical record.

The GSSP at Tercis was agreed by a majority of the WG members in early 1996. After gathering additional information, that proposal was submitted to the Subcommission on Stratigraphy in September 1999. The subcommission agreed (13 yes, 2 abstain, 3 no) with a statutory majority on the GSSP established during this study at Tercis (personal communication, P. Rawson June 2000).

6. Appendix: The postal ballot of the Maastrichtian Working Group (January 1996)

During the meeting in Brussels (September 1995), the question of the designation of a Global Standard-stratotype Section and Point (GSSP) for the Campanian-Maastrichtian boundary was discussed. The succession at Tercis was proposed as a candidate (Odin, 1995; Odin, compiler, 1996b). The generally favourable support led to prepare a proposal which was submitted to the Maastrichtian Working Group. The result of the postal ballot organised among the members of the WG (Circular 4 of the WG, October 15th, 1995) is presented here. The formal vote had the aims i- to choose the procedure for selecting the horizon, namely according to a single criterion or to a combination of criteria, ii- to choose the criterion for locating the boundary interval, and iii- to choose the most favourable site where to locate the boundary stratotype.

Circular 4 was sent to 37 people considered to be voting members of the "Maastrichtian WG" as a result of their (or promise of) contribution to the definition of the stage boundary.

Those members were Antonescu E., Arz J.-A, *Atabekian A., Bengtson P.*, Bilotte M., *Bonnemaison M.*, Buffetaut E., Cahuzac B., Caron M., Christensen W. K., Cobban W. A, *Dhondt A.V.*, Gallemi J., Gardin S., Gaspard D., Hancock J. M., Ion I., Jagt J. W. M., *Kauffman E.*, Kennedy W. J, Lamolda M. A., *Lopez G., Magné J., Martinez*, Melinte M., Molina E., Monechi S., Néraudeau D., Neumann M., Odin G. S., *Orr W., Pons J. M.*, Robaszynski F., von Salis Perch Nielsen K., *Turpin L.*, Ward P. D., Wilson G. J.

Table 2. Procedure for selection of the level (yes: combined criteria; no: single criterion). return: number of returned ballots; o: no return (assumed to represent a yes vote); nd: no vote for that particular question; abst.: abstain.

return	o	yes	no	nd	abst.	total (yes + o)	-> %
26	11	12	9	3	2	23	-> 62 %

26 people returned the ballot (no answer from italicised names), the last answer came on January 15th, 1996. The remaining 11 people ("o" in tables) are supposed to have delivered a "yes vote" to all questions following the rules of the International Commission on Stratigraphy valid in 1995 (Cowie et al., 1986, p. 3) and recalled in circular 4.

vote A- Principle for selection of the Global Standard-stratotype Point

Members were requested to express their opinion on the principle for selection of the level: either a level resulting from the arithmetic combination of several potentially correlative bio-horizons as illustrated in the circular (vote yes) or a single so called "primary marker" (vote no). The possible correlative bio-horizons suggested at that time for calculation of the arithmetic mean included ammonites (LOs of *Nostoceras hyatti*, *Hoploscaphites pumilus* and *Pseudokossmaticeras tercense*, FOs of *Pachydiscus neubergicus* and *Hoploscaphites constrictus*), calcareous nannofossils (LOs of *Nannoconus*, *Quadrum trifidum*, *Aspidolithus parcus constrictus*, FOs of *Quadrum trifidum* and large *Arkhangelskiella cymbiformis*); Dinoflagellate cysts (LO of *Subtilisphaera pontis-mariae*, and FOs of *Manumiella cretacea*, *Isabellidinium acuminatum*, *Manumiella raijae*, *Alterbidinium minus*); Pollen (FO of *Pseudoconvexipollis*); benthic foraminifera (LO of *Bolivinoides decoratus* and FO of *Coleites reticulosus*); planktonic foraminifera (LO of *Radotruncana calcarata*). The information gathered later allowed to select a series of criteria closer to the ammonite guide-event and better documented.

Following the rules valid at that time, the non-votes (three votes "nd" in table 2) should have been considered positive votes. Slightly more than 60% (the percentage required for a statutory valid majority) chose to select the boundary level according to a combination of bio-horizons.

vote B- Primary markers

Voting members were invited to propose the names of the primary signals they considered important (ballot B1). Each member was entitled to propose

Table 3. Preferred key marker(s) useful for location of the stage boundary interval.
B1: one or several criteria could be proposed by each voting member; B2: single preferred criterion; B3; ballot for (yes) or against (no) the criterion preferred by the majority of members in B2 (FO of *P. neubergicus*).

Ballot	Detail							Total
B1	FO *Pachydiscus neubergicus* alone: 11 + Pn & others: 8							19
	FO *Belemnella lanceolata* and others:							7
	magnetic reversal and others:							7
	LO *Aspidolithus parcus constrictus* and others							5
	FO *Gansserina gansseri* alone: 2; Gg and others: 1							3
B2	FO *Pachydiscus neubergicus*:							20
	LO *Aspidolithus parcus constrictus*:							2
	FO *Belemnella lanceolata*:							1
B3	return	o	yes	no	nd	abst.	yes + o	
	26	11	21	1	1	3	32 -> 86 % for P. neub.	

Table 4. Ballot for (yes) or against (no) the succession at Tercis as the Global stratotype section (the single candidate where the preferred criterion was present).

return	o	yes	no	abst.	total yes + o	
26	11	24	0	2	35	-> 95 %

one or several names. The second ballot was aimed at the designation of the preferred signal (guide-event); a single one was allowed per ballot (ballot B2). Then a ballot was taken for or against the preferred signal confirmed by the WG: FO of *P. neubergicus* (ballot B3). Among the significantly different levels where to locate the boundary, the interval of first occurrence of *P. neubergicus* was widely preferred. The last occurrence of *Radotruncana calcarata* (Odin, compiler, 1996b) was not supported by any Working Group member: the ballots received unanimously considered that this level was too low in the succession.

vote C- Site for the Global Standard-stratotype Section

As the resulting decision, members were invited to vote for or against the Tercis quarry as the site where to define the Campanian-Maastrichtian boundary. This section was proposed mostly because it was the single one where the ammonite *P. neubergicus* was quoted among the already studied outcrops known to bracket the stage boundary. The majority of the voting members consistently delivered a yes vote for the Tercis quarry. Therefore, the Tercis quarry was recommended for locating the GSSP of the Campanian-Maastrichtian Boundary. This majority encouraged to gather additional information on this succession. The aim was to precisely document a series of criteria bracketing the FO of *P. neubergicus* for a better documented application of the procedure of selection of the precise level.

(Compiled: June 2000; revised: July 2000)

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Note added in proofs

The postal ballot of the International Commission on Statigraphy occurred at the end of year 2000. The GSSP for the Campanian-Maastrichtian boundary defined at Tercis has obtained 76% of yes.