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The new chronostratigraphic classification of the Ordovician System and its relations to major regional series and stages and to $\delta^{13}C$ chemostratigraphy

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The extensive work carried out during more than a decade by the International Subcommission on Ordovician Stratigraphy has resulted in a new global classification of the Ordovician System into three series and seven stages. Formal Global Boundary Stratotype Section and Points (GSSPs) for all stages have been selected and these and the new stage names have been ratified by the International Commission on Stratigraphy. Based on a variety of biostratigraphic data, these new units are correlated with chronostratigraphic series and stages in the standard regional classifications used in the UK, North America, Baltoscandia, Australia, China, Siberia and the Mediterranean-North Gondwana region. Furthermore, based mainly on graptolite and conodont zones, the Ordovician is subdivided into 20 stage slices (SS) that have potential for precise correlations in both carbonate and shale facies. The new chronostratigraphic scheme is also tied to a new composite $\delta^{13}C$ curve through the entire Ordovician. □ *Chemostratigraphy*, *chronostratigraphy*, *classification*, *Ordovician System*, *stage slices*.

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As described by Webby (1998), Finney (2005), and Bergström *et al*. (2006b), one of the principal goals of the International Subcommission on Ordovician Stratigraphy has been to establish a globally applicable series and stage classification of the Ordovician System. The conspicuous palaeobiogeographic differentiation of Ordovician faunas has led to the development of different regional chronostratigraphic classification schemes for virtually all the major outcrop areas of Ordovician rocks, and terms such as the Middle Ordovician have had a vastly different stratigraphic scope in different regions. This has caused confusion, not only to the non-stratigraphers, and there has been an urgent need for a globally applicable chronostratigraphic classification of the Ordovician. After more than a decade of work, the goal of establishing such a global classification has been successfully reached, and the ratified new stage and series terms are shown in Figure 1. All the new stages have an approved Global Boundary Stratotype Section and Point (GSSP), the locations of which are summarized in Bergström *et al*. (2006b). It is of interest to note that the new chronostratigraphic scheme has already gained a wide approval internationally as shown by the fact that it was used in virtually all presentations at the 10th International Symposium on the Ordovician System that was held in Nanjing, China, in June 2007. The purpose of the present contribution is to summarize how the new global terms correspond to terms used in various regional classifications. Because many of the regional stages are based on fossils with a very limited geographic range, the position of such chronostratigraphic units is in some cases difficult to establish with adequate precision in the global scheme. We also introduce subdivisions of the global stages, referred to as stage slices (SS), which are biostratigraphically defined units. Finally, we present the first modern $\delta^{13}C$ curve through the entire Ordovician and illustrate its relations to the new global stages and stage slices.

Notes on the correlation of the new chronostratigraphic units

It is outside this brief summary to discuss in detail the relations between all the new global units and the regional series and stages and we will herein restrict

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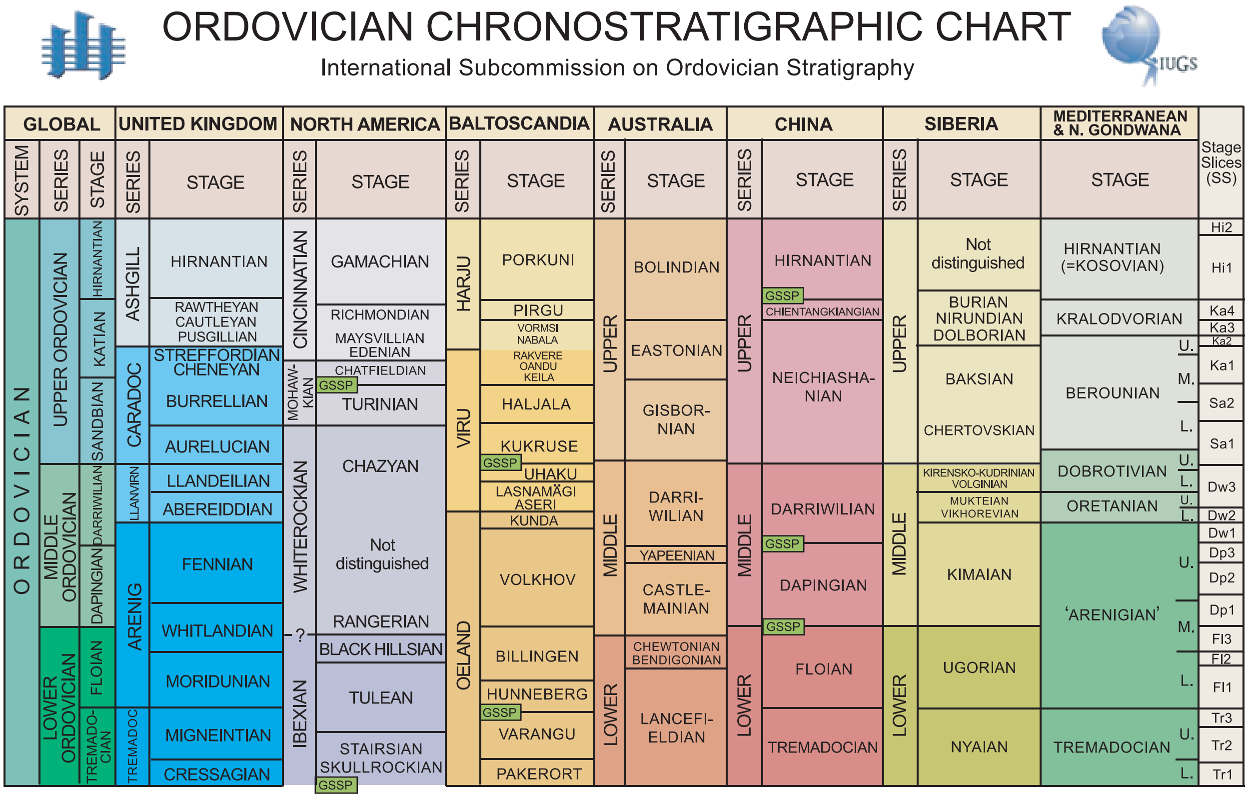

Fig. 1. Chart showing proposed correlation between the new global series and stages and regional chronostratigraphic units recognized in major outcrop areas of Ordovician rocks. Also shown are the stratigraphic positions of the stage slices (SS) defined in the present study. The Siberian and Iberian columns were compiled by Andrei Dronov and Juan Carlos Gutiérrez-Marco, respectively. The Global Boundary Stratotype Section and Point (GSSP) boxes in the North American column refer to the base of the Ordovician System and the base of the Katian Stage, respectively; those in the Baltoscandian column to the bases of the Floian and Sandbian Stages, respectively; and those in the Chinese column to the bases of the Dapingian, Darriwilian, and Hirnantian Stages, respectively.

ourselves to some major points. For convenience, we will deal with each region in the same order as shown in Figure 1. In the compilation of Figure 1, we have used much information from Webby *et al.* (2004) together with new data. The scheme presented here differs in important respects from that of Webby *et al.* (2004) as well as that published by Cooper and Sadler (2004). For a general reference to graptolite and conodont zones mentioned below, see Webby *et al.* (2004, figs 2.1 & 2.2).

United Kingdom

The series and stage classification in the UK column follows Fortey *et al.* (2000), who recognized five series (the Tremadoc, Arenig, Llanvirn, Caradoc, and Ashgill Series) and 15 stages. The majority of these chronostratigraphic units are based on shelly fossils with a limited geographic distribution and their precise correlation to standard graptolite and conodont zones is in most cases not well established.

In many areas the base of the Arenig Series coincides with a significant stratigraphic gap but based on somewhat non-diagnostic faunal data, Fortey *et al.* (2000) suggested that the base of the Arenig in northern England may correlate with the base of the Baltoscandic *Tetragraptus phyllograptoides* Graptolite Zone and the global *Tetragraptus approximatus* Graptolite Zone, that is, the base of the global Floian Stage. The same authors considered the base of the Llanvirn Series to be equivalent to the base of the *Didymograptus artus* Graptolite Zone but the precise global correlation of the base of this graptolite zone is currently not without problems although it is likely to correspond to a level in the lower–middle global Darriwilian Stage. The base of the Caradoc Series, although currently lacking an officially designated reference section, is taken to be the base of the *Nemagraptus gracilis* Graptolite Zone, that is, it is the same as the base of the global Sandbian Stage. The base of the Ashgill Series is defined on shelly fossils in the type area, and the precise correlation of this level into the graptolite and conodont zone successions has been problematic and controversial. However, recent chitinozoan investigations in the Ashgill type sections (Vandenbroucke 2005; Vandenbroucke *et al.* 2005) suggested that the base of the Pusgillian Stage, the lowest stage in the Ashgill Series, corresponds to a level close to the base of the Baltoscandic Nabala Stage. This horizon is in Baltoscandia taken to be at, or very near, the base of the *Pleurograptus linearis* Graptolite Zone. Previously, the base of the Ashgill has been correlated with a significantly higher level in the graptolite zone succession, namely the middle to upper part of the *P. linearis* Graptolite Zone. The new interpretation is in general agreement with the fact the important zone conodont *Amorphognathus ordovicicus*, which elsewhere appears in the middle of the *P. linearis* Graptolite Zone and at a corresponding level in the North American *Amplexograptus manitoulinensis* Graptolite Zone (Goldman & Bergström 1997), has its first occurrence in the Ashgill Series type area in the lower to middle Cautleyan Stage (Orchard 1980). It should be noted that Fortey *et al.* (2000) correlated this interval with substantially younger strata (uppermost *Dicellograptus complanatus* to *D. anceps* Graptolite Zones), which is in conflict with both the conodont and the chitinozoan evidence. In terms of the new global stage classification, the base of the Ashgill Series would correspond to a level in the middle Katian Stage.

Most of the many stages recognized in the UK succession are based on shelly fossils but unfortunately, there is very little direct evidence how these units correlate precisely to standard graptolite and conodont zones and hence, their relations to the new global stages remain uncertain. The general correlation presented in Figure 1 agrees in most cases with those presented by Webby *et al.* (2004) and Cooper & Sadler (2004) but it must be stressed that it is highly preliminary in nature and involves many problems.

North America

In the current standard North American classification, the Ordovician is subdivided into four series, the Ibexian, Whiterockian, Mohawkian and Cincinnatian Series (Ross *et al.* 1982). The reference sections of the Ibexian and Whiterockian Series are located in Utah and Nevada in western USA, that of Mohawkian Series in New York State and adjacent Ontario in eastern USA, and that of the Cincinnatian Series in Ohio, Kentucky, and Indiana in the eastern Midcontinent. For a long time, the very different location of the series reference sections, along with significant faunal differences, led to difficulties establishing the close relations between these series but most of these problems have now been solved.

Available information suggests that the base of the Ibexian Series is slightly older than the base of the *Iapetognathus fluctivagus* Conodont Zone, that is, the ratified base of the Ordovician System (Ross *et al.* 1997). Although the Ibexian succession is magnificently exposed in its type area in western Utah, and contains abundant and diverse shelly faunas and conodonts, these carbonate sequences contain relatively few stratigraphically diagnostic graptolites useful for correlation with the global Tremadocian and Floian Stages. Graptolite studies indicated that the base of the Whiterockian Series in its classical reference section at Whiterock Canyon in central Nevada is considerably younger than previously thought and the base of the Whiterockian is now defined in the Ibex area succession. As shown by sections in other areas, that level approximates the base of the *Isograptus v. lunatus* Graptolite Zone and hence is equivalent to a horizon in the uppermost Floian Stage. A succession of standard stages has not yet been defined through the Whiterockian Series but the Chazyan Stage falls in the uppermost Whiterockian Series if the base of the overlying Mohawkian Series is taken to be the base of the *Baltoniodus gerdae* Conodont Subzone as suggested by Ross *et al.* (1982). That level approximates the base of the Atlantic Province *D. foliaceus* Graptolite Zone as well as the base of the Pacific Province *Climacograptus bicornis* Graptolite Zone, and it corresponds to a level in the lower to middle Sandbian Stage. In recent years, the Mohawkian Series has been subdivided into two stages, the Turinian and Chatfieldian Stages (Leslie & Bergström 1995). The base of the latter stage is just below the base of the global Katian Stage.

The base of the Cincinnatian Series has not been closely defined faunally in the type area but it is just above the base of the *Amorphognathus superbus* Atlantic Conodont Zone and the *Belodina confluens* Midcontinent Conodont Zone (Bergström & Mitchell 1986, 1990, 1994) and near the top of the *Diplacanthograptus spiniferus* Graptolite Zone. This level corresponds to a horizon in the lower Katian Stage. The four standard stages recognized in the Cincinnatian Series are largely based on shelly fossils but the graptolites present (Bergström & Mitchell 1986, 1990, 1994) are useful for correlation to standard graptolite zones. A key level for global correlation is the first appearance of the zone conodont *A. ordovicicus* in the lower, but not lowermost, Richmondian Stage (Bergström & MacKenzie 2005), a level that corresponds to the lower–middle Cautleyan Stage in the UK and the upper Nabala to lowermost Vormsi Stage in Baltoscandia (Nõlvak *et al.* 2006). The base of the North American Gamachian Stage is currently not well defined biostratigraphically in its type area on Anticosti Island, Quebec (McCracken & Nowlan 1986) where its base is taken to be at the base of the Ellis Bay Formation. The fact that this level is substantially below the beginning of the Hirnantian $\delta^{13}C$ excursion (Bergström *et al.* 2006a) that elsewhere approximates the base of the Hirnantian Stage suggests that the base of the Gamachian Stage is well below the base of the Hirnantian Stage. Currently, available biostratigraphic and chemostratigraphic (Bergström *et al.* 2007) information indicates that the Gamachian Stage is not represented in the Cincinnatian Series reference sections in the Cincinnati region.

Baltoscandia

Compared to those of the UK and North America, the regional series and stage classification in the Ordovician of Baltoscandia (see, for instance, Männil & Meidla 1994; Nõlvak 1997) has been remarkably stable for decades and the changes, such as the replacement of the Idavere and Jõhvi stages with the Haljala Stage (Jaanusson 1995), have been minor. The current chronostratigraphic classification (for a recent review, see Nõlvak *et al.* 2006) was mainly developed in the East Baltic region (especially Estonia) but much of this scheme has proved to be applicable also to the successions in Sweden and elsewhere in Baltoscandia.

Three series are recognized, the Öland, Viru, and Harju Series. The base of the Viru Series corresponds to a level in the middle of the Darriwilian Stage, and the base of the Harju Series, which is taken to coincide with the base of the *Pleurograptus linearis* Graptolite Zone, to the middle of the Katian Stage. Most of the 18 regional Ordovician stages in Baltoscandia are based on shelly fossils (particularly trilobites) but the presence of graptolites at many levels, particularly in Sweden, provides useful ties to the standard graptolite zone succession. Conodonts are common and taxonomically diverse and many conodont zones (more than 20) and subzones (Bergström 2007) have been recognized and proved very useful for local and long-distance correlations.

A level in the middle of the Baltoscandian Hunneberg Stage is coeval with the base of the Floian Stage and a horizon in the upper Volkhov Stage corresponds to the base of the Darriwilian Stage. The base of the Kukruse Stage is coeval with the base of the Sandbian Stage, a level just above the base of the Keila Stage corresponds to the base of the Katian Stage, and the base of the Porkuni Stage correlates with the base of the Hirnantian Stage. As a whole, there are few problems in applying the global chronostratigraphic classification to the Baltoscandic succession and it should be noted that two of the global GSSPs are situated in Sweden.

Australia

The nine standard stages recognized in the Australian Ordovician successions are all based on graptolites and more than 30 standard graptolite zones are currently distinguished in Australia and New Zealand (VandenBerg & Cooper 1992). The graptolites provide useful ties to the global stage classification and there are few problems in correlating the Australian stages with those in the new global classification.

China

Several chronostratigraphic classifications have been proposed for the Chinese Ordovician (see, for instance, Mu *et al.* 1979, 1980; Zhang *et al.* 1982; Wang *et al.* 1992; Chen *et al.* 1995). In the present paper, the global Tremadocian, Floian, Dapingian, Darriwilian, and Hirnantian Stages are used for China in their ratified stratigraphic scopes. Three Ordovician GSSPs are situated in South China (Chen & Bergström 1995; Wang *et al.* 2005; Chen *et al.* 2006a,b). Also, an auxiliary GSSP section for the base of Upper Ordovician is located in Xinjiang, China (Bergström *et al.* 1999). Two regional stages, Neichiashanian and Chientangkiangian, remain for the current usage in China. The base of Katian Stage in China is mainly within carbonate strata that are dominated by shelly faunas. However, the base of the Chinese Neichiashanian Stage is the base of the *N. gracilis* Zone, hence the same level as the base of the global Sandbian Stage. The base of the overlying Chientangkiangian Stage is the base of the *Dicellograptus complanatus* Zone. This stage is coeval with the middle Katian Stage. It should be noted that most of the Chinese stages are defined in terms of graptolite zones, a fact that facilitates their international correlation. Thus, the correlation of the Chinese Ordovician stages to the global classification is much easier than is the case in some other major regions.

Siberia

Ordovician strata are quite widespread in vast areas of the Siberian Platform and adjacent regions. Although they are commonly covered by bogs and forests, there are numerous outcrops along many of the rivers. Modern information about the Ordovician geology of the Siberian Platform was recently published by Kanygin *et al.* (2006). In the current stratigraphic classification (Fig. 1), the Ordovician is subdivided into 12 regional stages, which are based on shelly fossils, predominantly brachiopods, trilobites, and ostracodes. It should be noted that the stage classification in Figure 1 is, with the exception of two Tremadocian units, the same as that employed by Ross & Talent (1988), and that the widely used designation 'horizon' in Russian literature corresponds to 'stage' as the latter term is used elsewhere in the world.

The Siberian palaeocontinent was rather isolated from the other continental plates during the Ordovician, and the fauna of the epicontinental seas of the Siberian Platform was mainly endemic and dominated by shelly taxa with a limited geographic distribution. This creates serious problems for the correlation of units in the Siberian succession with those in the global chronostratigraphic classification. The principal ties to the global stages are provided by graptolites from the surrounding territories of Taimyr, Verchojansk Range, Chukotka, Altai, and Sayany, and conodonts, which in most regions show closer affinities to coeval North American Midcontinent species associations than to those of Baltoscandia.

Recent information about the stratigraphic distribution of conodonts of the *Cordylodus* lineage suggests that the base of the Ordovician Series should be placed somewhere within, or at least not lower than, the base of the Nyaian Regional Stage. The key species *Cordylodus proavus* has been identified from the lowermost part of the latter stage, and *C.* aff. *angulatus* from its upper part in the important section along Kulumbe River on the northwestern part of the platform (T. Tolmacheva, personal communication, 2006).

Recognition of the precise level of the Lower/Middle Ordovician Series boundary is difficult due to the highly endemic conodonts and absence of graptolites in this interval in the Siberian sections. However, it appears that this level corresponds approximately to the boundary between the Ugorian and the Kimaian Regional Stages.

On the Siberian Platform, the most useful correlation level within the Middle Ordovician Series is the base of the Volginian Regional Stage. This level coincides with a well-developed erosion surface and sequence boundary, and it also represents the beginning of a prominent transgression, which was associated with significant biotic changes across the entire platform. The Volginian assemblage of brachiopods and ostracodes shows close affinities to the apparently coeval one of the Verchojansk–Chukotka region, where it is associated with graptolites of the *Hustedograptus teretiusculus* Graptolite Zone of the upper Darriwilian Global Stage (Oradovskaya 1988).

The other regionally important correlation level in the Siberian Ordovician succession is the base of the Chertovskian Regional Stage, which coincides with a sequence boundary and marks a most prominent deepening event. The brachiopod and ostracode faunal assemblage of this regional stage is easily recognizable also in the Verchojansk–Chukotka fold belt where it is associated with graptolites of the *N. gracilis* Zone (Oradovskaya 1988). This suggests that the base of the Chertovskian Regional Stage corresponds to the base of the Sandbian Global Stage and to the base of the Upper Ordovician Series. Recognition of the boundaries between the Baksian, Dolborian, Nirundian, and Burian Regional Stages is based on conspicuous changes in the shelly faunas, but the correlation of these stage units to global stages remains uncertain. Conventionally, the base of the Dolborian Regional Stage is taken to correspond to the base of the British Ashgill Series and it might correlate with a level in the middle of the Katian Stage.

Across most of Siberia, the upper boundary of the Ordovician succession is marked by a regional hiatus, which corresponds to most of the Hirnantian Stage. Stratigraphically virtually complete boundary successions are known from some localities in northeastern Siberia, such as those along Mirny Creek and Ina River in the Omulev Mountains region of the palaeogeographically enigmatic Kolyma Terrane, where the level of the systemic boundary can be precisely located based on pandemic graptolites and conodonts (Zhang & Barnes 2007).

Mediterranean-North Gondwana

This region includes southwestern and central Europe (Ibero-Armorica, Sardinia, Bohemia) to the Balkan and the vast area from Maghreb in northern Africa to Saudi Arabia and part of the Middle East. The general scarcity of graptolites and almost total absence of conodonts in the Lower and Middle Ordovician, and the largely endemic shelly faunas, impose serious difficulties to correlate the successions in this region with the new global chronostratigraphy. The latter is illustrated by the fact that only two of the taxa used for the definition of the global stages and series have been recorded in this region and none of them near formal stage boundaries.

The regional biostratigraphic scheme (Havlicek & Marek 1973; Gutiérrez-Marco *et al.* 1995, 1999, 2002) is largely based on endemic shelly fossils combined with some graptolites and a good organic microfossil record. The North Gondwanan chitinozoan zonation (Paris 1990) is useful for correlation with other regions, and sporadic occurrences of graptolites and shelly faunas of Baltic or Avalonian affinities (Gutiérrez-Marco *et al.* 1995) allow for indirect correlation with some global stage levels.

The global Tremadocian Stage faunas are rather uniform across much of the Gondwana and typical Tremadocian graptolites, trilobites, and palynomorphs have been documented at several stratigraphic levels. For the next regional stage, the designation 'Arenigian' is tentatively used because of the general absence of chronostratigraphically diagnostic fossils in the areas of the widespread Armorican Quartzite facies. Floian graptolites and chitinozoans are rather common, but the successions that are broadly coeval with the Dapingian and lower Darriwilian global stages are sparsely fossiliferous. During the Oretanian Stage, which corresponds to the 'pendent didymograptid' interval, the Avalonian affinities of the shelly faunas decreased and these faunas were replaced by Gondwanan endemics with great local correlation potential. The following Dobrotivian Stage contains few stratigraphically useful graptolites and its top is marked by the disappearance of the widespread trilobite *Neseuretus* in northern Gondwana. This level is also characterized by the appearance of the trilobite *Dalmanitina* and the *Drabovia* brachiopod fauna, which is characteristic of the Berounian Stage.

In the absence of the key graptolite *N. gracilis*, the base of the Upper Ordovician can be only approximately located within the Dobrotivian Stage by rare occurrences in the upper third of this stage of some graptolites and chitinozoans (*Lagenochitina ponceti* Zone), which are characteristic of the *N. gracilis* Zone elsewhere. The Berounian Stage, which corresponds broadly with the British Caradoc and earliest Ashgill Series, contains in Spain some brachiopod assemblages of Anglo-Welsh affinities but overall, the Upper Ordovician benthic faunas in Spain compare more closely with those of Bohemia and northern Gondwana regions (Morocco, Sardinia). The base of the Kralodvorian Stage is marked by the sudden appearance of a new shelly fauna that includes Avalonian immigrants and cosmopolitan taxa. A brief global amelioration, with a decrease of latitudinal temperature differences (the Boda Event of Fortey & Cocks 2005), resulted in the deposition of mudstones and conodont-bearing shelf limestones (Bergström & Massa 1992) in regions close to the South Pole. The latest Ordovician (Hirnantian) glacial cycles led to a drastic change in both sedimentation and faunas. All the biostratigraphic and sedimentological criteria used to characterize the formerly used regional Kosovian Stage are shared with the Hirnantian Stage elsewhere. This justifies the adoption of the latter global stage term in the Mediterranean-North Gondwana regional chronostratigraphic classification.

Stage slices

In their monumental summary of the Ordovician biodiversification, Webby *et al.* (2004) recognized six primary (labelled 1–6) and 19 secondary (labelled 1a to 6c) Ordovician units that they referred to as 'time slices'. The designation 'time slice' implies that these are to be considered geochronologic units but their original definition is not entirely clear. Nevertheless, these units have proved to be useful for a refined subdivision of the Ordovician System.

In the present contribution, we introduce subdivisions of the global stages referred to as *stage slices* (Fig. 2). In terms of stratigraphic scope, a stage slice falls between a stage and a faunal zone, that is, it corresponds to a substage or superzone. The stratigraphic scope of each stage slice is not the same and varies from a single to several faunal zones. As recognized here, the stage slices are informal, but defined, chronostratigraphic units, most of which are based on geographically widespread graptolite or conodont zones. Each of the global stages is subdivided into two to four stage slices that for clarity are designated by a letter and figure prefix, which are based on an abbreviation of the stage name followed by a figure indicating the general position of the unit within the stage. Some of the stage slices have a similar range as some time slices recognized by Webby *et al.* (2004) but others are different in scope. Except Hi2, the base of each stage slice is coeval with the base of a conodont or graptolite zone as shown in Figure 2.

Definitions of stage slices

Tr1. Base of the Ordovician (first appearance of *Iapetognathus fluctivagus*) to the base of the *Paltodus deltifer* Conodont Zone. This unit includes the *Rhabdinopora flabelliformis, Adelograptus hunnebergensis, Adelograptus tenellus*, and *Psigraptus* Graptolite zones in the lowermost Tremadocian Stage.

Tr2. Base of the *Paltodus deltifer* Conodont Zone to the base of the *Paroistodus proteus* Conodont Zone, which is approximately the same level as the base of the *Araneograptus murrayi* Graptolite Zone. This stage slice includes the middle Tremadocian Stage.

Tr3. Base of the *Paroistodus proteus* Conodont Zone to the base of the *Tetragraptus approximatus* Graptolite Zone. This interval corresponds to the upper Tremadocian Stage. It includes the *Hunnegraptus copiosus* Graptolite Zone and the upper part of the *Araneograptus victoriae* and *A. murrayi* Graptolite Zones.

Fl1. Base of the *Tetragraptus approximatus* Graptolite Zone to the base of the *Oepikodus evae* Conodont Zone. This interval corresponds to the lower part of the Floian Stage and includes the *T. approximatus, T. fruticosus 3–4 br.*, and *Didymograptus nitidus* Graptolite Zones. It is also

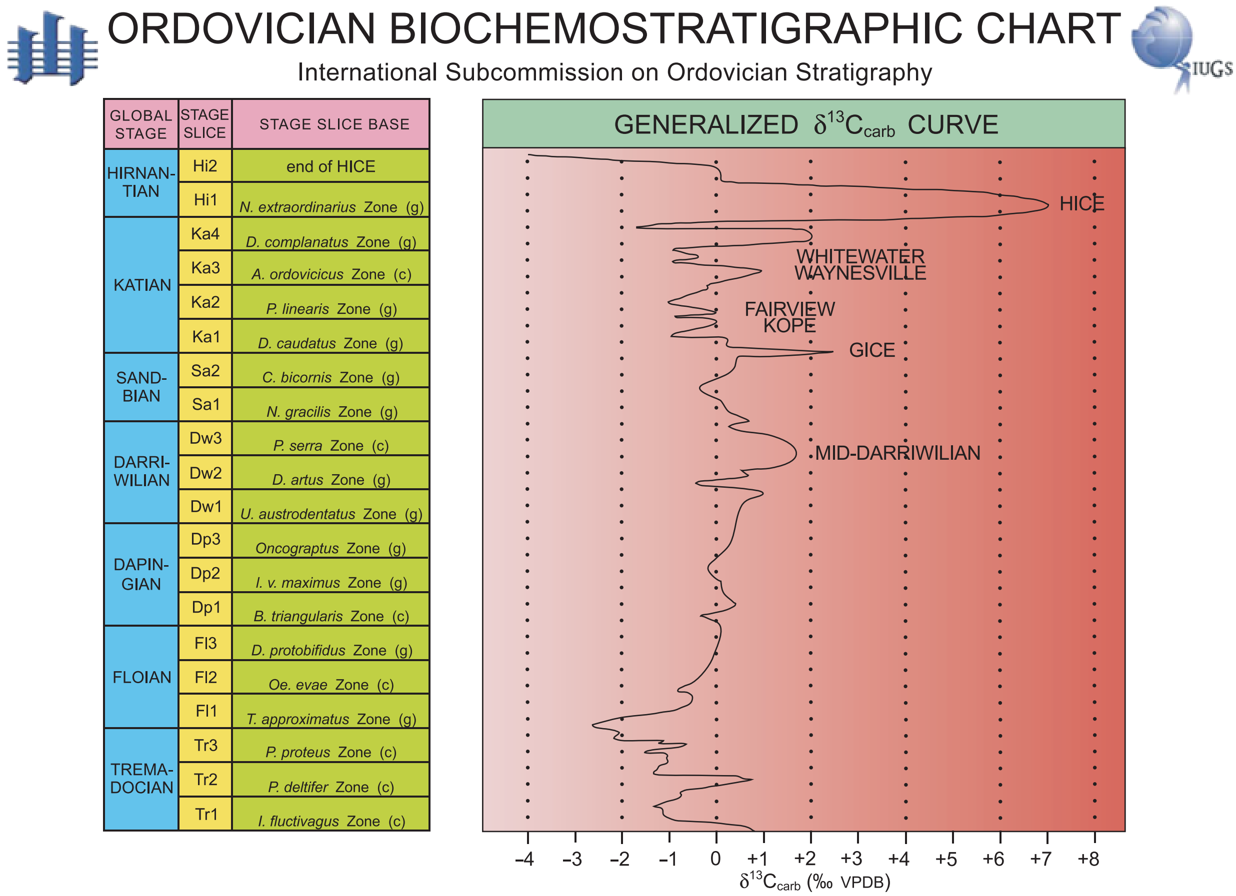

Fig. 2. Ordovician graptolite or conodont zones used in the definition of stage slices, and the relationships of each stage slice to global stages and a generalized composite δ^{13}C curve. The base of each stage slice is defined as the base of a particular faunal zone except in the case of Hi2. Note that for clarity, all the stage slices are drawn to the same size although they clearly have different stratigraphic ranges. (g), graptolite zone; (c), conodont zone. The Hirnantian segment of the δ^{13}C curve is based on Finney *et al.* (1999) and Berry *et al.* (2002), the Katian one on Bergström *et al.* (2007), the Sandbian, Darriwilian and Dapingian one on Kaljo *et al.* (2007), and the Floian and Tremadocian one on Buggisch *et al.* (2003).

equivalent to the lower part of the Arenig Series of the UK, and the upper Lancefieldian and Bendigonian Stages of Australia.

Fl2. Base of the *Oepikodus evae* Conodont Zone to the base of the *Didymograptus protobifidus* Graptolite Zone. This interval corresponds to the middle part of the Floian Stage, and the lower and middle part of the *Oe. evae* Zone.

Fl3. Base of the *Didymograptus protobifidus* Graptolite Zone to the base of the *Isograptus v. victoriae* Graptolite Zone. This interval corresponds to the upper part of the Floian Stage, the upper part of the North American Ibexian Series, the upper Chewtonian and lower Castlemainian Stages in Australia, and the Upper Billingen Stage in Baltoscandia.

Dp1. Base of the *Isograptus v. victoriae* Graptolite Zone to the base of the *Isograptus v. maximus* Graptolite Zone. The base of this stage slice is also at, or very near, the base of the *Baltoniodus triangularis* Conodont Zone, which defines the base of the Dapingian Stage. This stage slice corresponds to the middle part of the Arenig Series of the UK, the lower Whiterockian Series of North America, the lower Volkhov Stage of Baltoscandia, and part of the Castlemainian Stage in Australia.

Dp2. Base of the *Isograptus v. maximus* Graptolite Zone to the base of the *Oncograptus* Graptolite Zone. The latter level approximates the base of the *Paroistodus originalis* Conodont Zone. This stage slice corresponds to the middle Dapingian Stage and the upper part of the Australian Castlemaininan Stage.

Dp3. Base of the *Oncograptus* Graptolite Zone to the base of *Undulograptus austrodentatus* Graptolite Zone. This stage slice corresponds to the upper part of the Dapingian Stage, and the Australian Yapeenian Stage as well as the *P. originalis* Conodont Zone and the lower part of the *B. norrlandicus* Conodont Zone.

Dw1. Base of the *Undulograptus austrodentatus* Graptolite Zone to the base of the *D. artus* Graptolite Zone. This stage slice corresponds to the lower portion of the Darriwilian Stage and includes the *U. austrodentatus* Graptolite Zone. The top of this unit is at about the same level as the base of the Llanvirn Series in the UK.

Dw2. Base of the *Didymograptus artus* Graptolite Zone to the base of the *Pygodus serra* Conodont Zone. This stage slice includes most of the interval from the *Lenodus variabilis* Conodont Zone to the top of the *Eoplacognathus suecicus* Conodont Zone.

Dw3. Base of the *Pygodus serra* Conodont Zone to the base of the *N. gracilis* Graptolite Zone. The base of this stage slice approximates the top of the *Histiodella kristinae* Conodont Zone and the middle of the *Pterograptus elegans* Graptolite Zone (Chen *et al.* 2006b). The stage slice corresponds to the upper part of the Darriwilian Stage and the upper part of the Llanvirn Series of the UK.

Sa1. Base of the *Nemagraptus gracilis* Graptolite Zone to the base of the *C. bicornis* Graptolite Zone. This stage slice ranges from the middle part of the *P. anserinus* Conodont Zone to the base of the *B. gerdae* Conodont Subzone. It includes the lower part of the Sandbian Stage and corresponds to the lower Gisbornian Stage in Australia, the lower Caradoc Series (Aurelucian Stage) in the UK, the Kukruse Stage of Baltoscandia, and the lower Neichiashanian Stage of China.

Sa2. Base of the *Climacograptus bicornis* Graptolite Zone to the base of the *Diplacanthograptus caudatus* Graptolite Zone. It includes essentially the *Dicellograptus foliaceus* Graptolite Zone and corresponds to the upper part of the Sandbian Stage, the upper part of the Gisbornian Stage in Australia, the Mohawkian and lowermost Chatfieldian Stages in North America, and the Haljala and lowermost Keila Stages in Baltoscandia.

Ka1. Base of the *Diplacanthograptus caudatus* Graptolite Zone to the base of the *Peurograptus linearis* Graptolite Zone. The latter level approximates the base of the North American *Amplexograptus manitoulinensis* Graptolite Zone. The stage slice corresponds to the lower part of the Katian Stage, the upper Caradoc Series of the UK, most of the Chatfieldian through Maysvillian Stages in North America, the lower Eastonian Stage in Australia, and part of the Keila through Rakvere Stages in Baltoscandia.

Ka2. Base of the *Pleurograptus linearis* Graptolite Zone to the base of the *Amorphognathus ordovicicus* Conodont Zone. This stage slice corresponds to the middle Katian Stage, the upper part of the Australian Eastonian Stage, part of the lower Ashgill Series in the UK, and the middle Cincinnatian Series in North America.

Ka3. Base of the *Amorphognathus ordovicicus* Conodont Zone to the base of the *Dicellograptus complanatus* Graptolite Zone. It includes the middle Richmondian Stage of the Cincinnatian Series in North America, the uppermost Eastonian Stage in Australia, part of the Ashgill Series in the UK, the uppermost Nabala and Vormsi Stages of the Harju Series in Baltoscandia, and the uppermost part of the Neichiashanian Stage in China.

Ka4. Base of the *Dicellograptus complanatus* Graptolite Zone to the base of the *Normalograptus extraordinarius* Graptolite Zone (=base of the Hirnantian Stage). This stage slice includes the uppermost Katian Stage, the uppermost Richmondian Stage of North America, the middle Ashgill Series in the UK, the upper Eastonian and most of the Bolindian Stages in Australia, and the Pirgu Stage of the Harju Series in Baltoscandia.

Hi1. Base of the *Normalograptus extraordinarius* Graptolite Zone to the end of the global Hirnantian $\delta^{13}C$ excursion (HICE). This stage slice corresponds to the *N. extraordinarius* Graptolite Zone and part of the *N. persculptus* Graptolite Zone. It includes the lower and middle Hirnantian Stage, the lower and middle Gamachian Stage in North America, the lower and middle Porkuni Stage in Baltoscandia, and the middle Bolindian Stage in Australia.

Hi2. Extends from the end of the Hirnantian $\delta^{13}C$ excursion (HICE) to the top of the Ordovician (base of the *Akidograptus ascensus* Graptolite Zone). This stage slice represents the upper part of the Hirnantian Stage and probably corresponds to the middle and upper parts of the *N. persculptus* Graptolite Zone as well as the upper part of the Gamachian Stage in North America.

A new Ordovician $\delta^{13}C$ curve

Recent studies in particularly the Baltoscandian and North American successions have demonstrated the great value of $\delta^{13}C$ chemostratigraphy for both local and long-distance correlations (Buggisch *et al.* 2003; Ainsaar *et al.* 2004; Kaljo *et al.* 2004, 2007; Ludvigson *et al.* 2004; Young *et al.* 2005; Melchin & Holmden 2006; Bergström *et al.* 2006a, 2007, in press; Barta *et al.* 2007; Schmitz & Bergström 2007). Most of these studies have been centred on two major, apparently global, positive $\delta^{13}C$ excursions, namely the Hirnantian excursion (HICE) and the lower Katian Guttenberg excursion (GICE). Several other positive excursions have been recognized in the Katian of Estonia and

North America and used for trans-Atlantic correlations (Bergström *et al.* 2007). In the pre-Katian portion of the Ordovician, several local excursions have been recorded, but thus far, only one significant positive excursion, which is recognized across a wide region, has been documented. This is the mid-Darriwilian excursion (Kaljo *et al.* 2004; 2007; Ainsaar *et al.* 2007) that has been traced from eastern Baltoscandia to Sweden.

The pioneer attempts to compile a $\delta^{13}C$ curve covering the entire Ordovician System suffered from lack of adequate data which resulted in non-descript curves of very limited utility. More recently published $\delta^{13}C$ curves, which are based on extensive data sets and covering large parts of the Ordovician, have been published by Buggisch *et al.* (2003) and Saltzman & Young (2005). The former curve lacks data from post-Darriwilian strata. The latter curve is stratigraphically incomplete in that most of the Katian interval is not covered. Furthermore, because few biostratigraphic data are included in that paper, the interpretation of the curve is not straightforward. Based on drill-core data from Estonia, Kaljo *et al.* (2007) presented an important $\delta^{13}C$ curve through much of the Ordovician but their curve is incomplete in that it does not include information from the Tremadocian and Floian Stages.

There are several problems in compiling a reliable $\delta^{13}C$ curve through the entire Ordovician. The fact that a continuous $\delta^{13}C$ record through the whole System is currently not available from any continent of the world makes it necessary to employ a composite section based on information from several, geographically widely spaced, regions. This creates some problems in that the marked provincialism in Ordovician faunas complicates inter-regional biostratigraphic correlations that may affect interpretations of the proper relations between curve segments from different continents. Also, in some stratigraphic intervals there are notable differences between $\delta^{13}C$ values from different regions. These differences may be due to several factors, such as gaps in the succession and regionally different baseline $\delta^{13}C$ values. One example of this is the apparent absence in the Great Basin (Saltzman & Young 2005) of the distinctive Mid-Darriwilian excursion recognized in Baltoscandia (Kaljo *et al.* 2007).

Despite these potential problems, we have attempted to produce what we believe is the first modern $\delta^{13}C$ curve covering the entire Ordovician and this curve is calibrated to individual stage slices (Fig. 2). It is obvious that because of printing format limitations such a composite curve will have to be generalized in many details but we have tried to illustrate the currently known significant fluctuations in $\delta^{13}C$ values, especially those that have been recognized as named excursions. This curve is a composite one based on the Hirnantian curve from Monitor Range, central Nevada (Finney *et al.* 1999; Berry *et al.* 2002), the Katian curve from the eastern Midcontinent of North America (Bergström *et al.* 2007), the Sandbian–Darriwilian curve from Estonia (Kaljo *et al.* 2007) and the Dapingian–Tremadocian curve from Argentina (Buggisch *et al.* 2003). The stratigraphical relations between these curve segments are well understood and we believe that the curve is representative of the changes in $\delta^{13}C$ values through the system. This curve is closely controlled chronostratigraphically and it is tied to the stage slices. Although it is outside the scope of the present paper to discuss the many interesting details in this composite curve, one feature stands out, namely the fact that there are more distinctive positive excursions in the Darriwilian through Hirnantian stratigraphic interval than in the older parts of the Ordovician.

Conclusions

The goals of the present study have been threefold. First, we have attempted to elucidate the relations between the new global series and stages and the various regional, often quite different, chronostratigraphic classifications employed in some of the major Ordovician outcrop regions in the world. Although the general relations between the new and previous classifications appear reasonably well established, there are many remaining problems that require further study. This is especially the case in Siberia and the Mediterranean–North Gondwana regions where much of the regional classifications are based on more or less endemic shelly fossils. Second, we have introduced a new and refined subdivision of the stages into stage slices that can be used when there are difficulties to recognize particular faunal zones. Third, we have tried to present a generalized $\delta^{13}C$ curve through the Ordovician that is closely tied to the new chronostratigraphy. The compilation of this curve is an attempt to illustrate the principal fluctuations in $\delta^{13}C$ values through the Ordovician, but we expect that when further information has become available, the curve will be modified in detail.

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