The face of Planet Earth has changed significantly through geological time. Dynamic processes active today, such as plate tectonics and climate change, have shaped the Earth’s surface and impacted biodiversity patterns from the beginning. Organisms, on the other hand, have the capacity to significantly alter Earth’s hydrological and geochemical cycles, its atmosphere and climate, sediments, and even hard rocks deep down under the surface. Abiotic–biotic interactions characterize Earth’s system history and, together with biotic competition and food webs, were the main trigger of evolutionary change, innovations and biodiversity fluctuations. Within the Palaeozoic, the Devonian was an especially interesting time interval as it was characterized by the ‘mid-Paleozoic predator revolution’ (Signor & Brett 1984; Brett 2003) and the related ‘nekton revolution’ (Klug et al. 2010), characterized by the blooms of free-swimming cephalopods, including the oldest ammonoids, and fish groups (e.g. toothed sharks and giant placoderms), the rise of more advanced vertebrates, including the oldest tetrapods (e.g. Blieck et al. 2007, 2010; Niedzwiedzki et al. 2010), the most extensive reef complexes of the Phanerozoic (e.g. Kiessling 2008), and the ‘greening of land’ by the diversification and spread of land plants, including the oldest forests (e.g. Stein et al. 2012; Giesen & Berry 2013), which resulted in new soil types and changing weathering.

These major evolutionary trends did not unfold in a long interval of environmental stability, but in times of numerous and repeated, geologically brief, global events that punctuated prolonged periods, up to several million years in duration, of relative stability, termed ecological-evolutionary subunits (EE subunits: Boucot 1990; Brett & Baird 1995; Brett et al. 2009). The bounding events, even those of lesser intensity, produced major re-structuring in local to global ecosystems and are seen as critical drivers of long-term evolutionary patterns (Brett 2012). These linked abiotic and biotic events and extinctions of different magnitude have been summarized by House (1983, 1985, 2002), Walliser (1984, 1996) and, more recently, by Becker et al. (2012). The Devonian event succession is summarized in Figure 1. Two first-order mass extinctions at the Frasnian–Famennian boundary (Kellwasser Crisis) and at the end of the Devonian (Hangenberg Crisis), characterized by the loss of major fossil groups (classes and orders) and complete ecosystems (e.g. metazoan reefs, early forests), have to be viewed in the context of a complex global event sequence. There are important similarities between discrete pulses/phases of the major biotic crises and individual smaller-scale events. In our understanding, second-order global events are characterized by sudden extinctions in many groups and ecosystems, including the complete disappearance of several widespread and diverse organism groups (orders and families). Examples are the basal Emsian atomous Event, where the planktonic graptolites finally died out, the Taghanic Crisis, Frasnes events and Lower Kellwasser Event. Third-order global events show globally elevated extinction rates, often at lower taxonomic level (genera and species), but within many clades and in several ecosystems. Examples are the Silurian–Devonian boundary Klonk Event, and the Daleje, Choteˇc, Kaˇcak, Condroz and Annulata events. Fourth-order global extinctions refer to the sudden disappearance of relatively fewer but widespread groups, which implies a global, not regional, trigger. This category may include the Lochkovian–Pragian boundary
Fig. 1. The succession of Devonian global events and crises (well-known examples in bold), including maxima of anoxic sedimentation (e.g., black shales), plotted against the chronostratigraphic scale, old and new conodont zonations (e.g., Klapper 1989; Yolkin et al. 1994; Klapper & Becker 1999; Aboussalam 2003; Slavík & Hladil 2004; Girard et al. 2005; Murphy 2005; Aboussalam & Becker 2007; Slavík et al. 2007, 2012; Kaiser et al. 2009; Hartenfels 2011; Corradini & Corriga 2012; Aboussalam et al. 2015; Spalletta et al. 2015; Valenzuela-Ríos et al. 2015), and the zonal key for global ammonoid zones (Becker & House 2000). The substage levels shown here follow proposals to SDS but have only partly been ratified (Givetian, Frasnian) and not yet formally approved by the International Stratigraphic Commission. The given absolute age number for the base of each stage is adopted from the calibration and interpolation in Becker et al. (2012).
event, and the Chebbi, Upper Zlíčov, Middlesex and Dasberg events. Other intervals, such as the *pumilio*, Timan, Rhinestreet, *semichatovae* and Nehden events, are better characterized as faunal blooms, radiations and sudden organism spread with transgression rather than as extinctions (Fig. 2). The Bakoven and Stony Hollow events are strong in the Appalachian Basin, where their impact is locally far greater than the Chotěc Event (DeSantis & Brett 2011), and represent major abrupt faunal turnovers. They have been recognized elsewhere (e.g. Spain) but may not be as strong, making them third- or fourth-order events. The ranking of the named individual events may change with continuing research and additional small-scale global extinctions will probably be recognized in the future.

The widely known Devonian black shale events (Fig. 2) are linked with hypoxia/anoxia, rapid

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**Fig. 2.** Example of thin black shales interrupting a strongly cyclic middle–upper Famennian pelagic nodular limestone succession: the two *Annulata* Event beds (top lower third) and the Dasberg Black Shale (base of the upper third) at Effenberg Quarry, northern Rhenish Massif, Germany (photograph by S. Hartenfels).
eustatic fluctuations, faunal blooms, geochemical anomalies, and stepped extinctions and survival. But not all global events were associated with the spread of anoxia in times of climatic warming and eustatic rise, others correlate with sharp regressions and climate cooling. Clearly, multiple oceanographic factors were involved. But sudden climate change appears to have been the most important common trigger, possibly linked with episodes of massive volcanism and times of significant drawdown of atmospheric CO₂. Currently, there is no unequivocal example of bolide impact events as global extinction triggers in the Devonian, although some impacts are now well known, such as the lower Frasnian Flynn Creek crater of Tennessee (Schieber & Over 2005) and the middle Frasnian Alamo impact of Nevada (e.g. Warme & Sandberg 1996; Poole & Sandberg 2015).

Despite the summarized general patterns, knowledge of many of the individual events and even a deeper understanding of the two major crises is still at an early stage, with more open questions than answers (e.g. Racki 2005). For many of the second- or third-order global events there are no summaries of their recognition in different regions or of event patterns on different continents and in different facies realms. The correlation with the listed major evolutionary developments is partly arbitrary, and the integration of biotic, sedimentological and geochemical data in sound event models is still missing or preliminary. An understanding of the major abiotic and biotic factors that shaped our planet and its ecosystems in the past is essential to the understanding of natural processes and the effects of human-induced global change at present and for forecasting possible future developments. For the Devonian period, two volumes in this book series (Becker & Kirchgasser 2007; Königshof 2009) have previously introduced interdisciplinary and international approaches to achieve progress in Devonian event research. This resulted from the fruitful cooperation of IGCP 499 on ‘Devonian Land–Sea Interaction – Evolution of Ecosystems and Climate’ (DEVEC) and the IUGS International Subcommission on Devonian Stratigraphy (SDS). Since then, a follow-up project, IGCP 596 on ‘Climate Change and Biodiversity Patterns in the Mid-Palaeozoic’ picked up open new and research directions, which were the subject of numerous international symposia and during joint IGCP 596–SDS field trips: for example, the 2013 field symposium on the Devonian and Lower Carboniferous of southern Morocco (Fig. 3), an area world famous for its mid-Palaeozoic sediments and fossils. As research on mid-Palaeozoic anoxic events was mainly concentrated around the former Rheic Ocean (e.g. Europe, USA and Morocco), some satellite projects were established in order to get a better understanding of mid-Palaeozoic events around the eastern Proto- or Palaeotethys Ocean: for example, in Vietnam and Thailand. Combined biostratigraphy, sedimentology, physical stratigraphy and isotope geochemistry in different facies settings will be one of the future challenges in order to better understand the evolution of ecosystems and climate change. In this respect, and as an outlook, research on varied and regionally distinctive shallow-water successions should be a focus in the near future. As mentioned earlier, the fruitful cooperation between IGCP and SDS produced a very large number of scientific papers and greatly increased knowledge in many respects. But there is still much work to be done in order to fully understand the complexity of abiotic–biotic interactions. There will be key roles for the integration of new and different techniques, for an expansion into currently poorly known territory (new and neglected sections/regions), and, equally important, for a thorough integration of the wealth of strongly dispersed data on different fossil groups and regions, both in datasets and in models.

Some contributions of this volume were first presented at the 2013 meeting or subsequently, for example at the IGCP 596–SDS Symposium in Brussels in September 2015 (Mottequin et al. 2015).

The primary goal of IGCP 596 was to assess the intensity of mid-Palaeozoic climate change and its impact on biodiversity both in marine and terrestrial successions. Key questions included:

- Was CO₂ the dominant driver of climate and how did it affect global or regional diversity?
- What other factors ruled short- and long-term biodiversity at that time?
- What caused the cooling and sudden glaciation episodes, and were there similarities between these events (e.g. CO₂ thresholds)?
- How did environmental change stimulate or influence evolutionary innovations?
- Were major marine and terrestrial biotic changes linked with Milankovitch cyclicity?
- Were there different extinction–innovation patterns in different facies and distant basins?
- How did ocean chemistry change in the Mid-Palaeozoic (e.g. ocean acidification), and what was its impact on marine organisms and the fossil record?
- Is climate modelling a viable tool for understanding mid-Palaeozoic environmental change?
- Do current climate models fit the available geological and palaeontological evidence?

From the SDS side, investigations were added that were aimed at achieving a much greater time resolution for global correlation based on an increasingly refined geological timescale. Stratigraphic progress provides a more precise range of organisms
in time and space, and also of their ecosystem distributions, and, therefore, a more precise dating of abiotic and evolutionary events, including geochemical spikes or isotope-based palaeotemperature reconstructions. The focus of SDS is on a revision of the eustatic sea-level curve, which can be linked with climate pulses, and the integration of biostratigraphy with modern stratigraphic techniques, such as isotope, sequence, magneto-, element geochemistry, gamma-ray and quantitative stratigraphy. This approach is followed in the present volume, which combines recent efforts of both IGCP 596 and SDS members. This has resulted in 14 chapters that are sorted roughly according to stratigraphic age. Contributions cover all of the Devonian and successions from 10 different basins in Europe, North Africa, North and South America, Australia, and the isolated Falkland Islands in the South Atlantic. The 37 co-authors are from Europe, North America and Australia, but other areas of Africa, South America and Asia, especially of China, were treated in the previously mentioned two earlier volumes, which should be considered for further reading.

The first chapter by Suttner & Kido (2015) deals with a widely neglected (fourth-order) extinction and positive carbon isotope signal near the Lochkovian–Pragian boundary that was first noted by Walliser (1996). In the Carnic Alps, it correlates with a regressive phase that culminated in a peculiar megaclast unit. This study stands out as an example of the interdisciplinary approach by combining conodont biostratigraphy, sedimentology, carbon isotope analysis, magnetic susceptibility data and sediment colour analysis. Interpretations include a sedimentary model and, to address the main IGCP 591 topics, a discussion of the regional conodont diversity curve.

The paper by Marshall (2016) summarizes the, as yet, poorly known stratigraphy of the Devonian of the Falkland Island, mostly based on palynomorphs. As is typical for the Malvinokaffric cold-water realm, there is a thick siliciclastic succession that ranges from the Lochkovian to the upper Famennian. It is correlated with the originally adjacent Cape Basin of South Africa and with the, today, closer South American Devonian. This comparison enabled the recognition of transgressive and regressive events, which are tentatively correlated with the established Devonian event succession. This research forms a significant contribution because, for the first time, it traces some of the
(sub)tropical event intervals, notably the Chotěc and Kačák events, into the high latitudes, where the restricted invertebrate record has, so far, only occasionally been tested for extinction and survival patterns.

The extensive review of the Lower Devonian brachiopod succession of the Rhenish Massif by Jansen (2016) provides a modern synthesis of regional litho-, bio- and event stratigraphy. It provides a new and revised synopsis of a wealth of data from older literature. Because the western Rhenish Massif is one of the classic regions for the study of brachiopod faunas, this review will become a new standard for the understanding of Lower Devonian nearshore clastic successions, their faunas and biofacies. There are important implications for the correct correlation of well-known regional chronostratigraphic terms (Gedinian, Siegenium, type Emsian), which have been used outside their type regions. It is also an important case study that traces established outer-shelf events into the more complex inner-shelf and marginal-marine settings, where biotic turnovers appear to have been much more numerous.

Brocke et al. (2015) attempt successfully to correlate Basal Chotěc Event successions of the Bohemian type area into the distant Appalachian foreland basin of eastern North America. This chapter provides many new records of palynomorphs and dacyroconarids, and a welcome brief summary of the global distribution of the third-order event, which is marked by moderate extinctions in selected organism groups. In the studied sections, there are sudden blooms of prasinophyte algae and specific spores. The associated eustatic rise permitted important migrations, providing a case study of the biogeographical implications of Devonian short-term hypoxic and transgressive events. As known from other events, the episodic breakdown of biogeographical barriers can have a profound effect on global biodiversity.

Königshof et al. (2015) apply a multidisciplinary method set, including conodont biostratigraphy, microfacies analysis, stable isotopes, magnetic susceptibility, total organic carbon content and whole-rock geochemistry, in order to find signatures of the third-order global Kačák Event in a typical shallow-water carbonate succession of the Eifelian type region of Germany, where physical event manifestations are much less obvious than in contemporaneous pelagic limestones. This proved to be a challenge, but rare conodonts, a positive carbon isotope excursion and a cerium anomaly enabled the authors to pinpoint the beginning of the larger event interval. If lateral correlation can be achieved, it will help to refine the extinctions, innovations and palaeoecological changes of the rich Eifel macrofaunas in the course of the Kačák Event.

Two successive chapters deal with the second-order global Taghanic Crisis at the middle–upper Givetian boundary. Narkiewicz et al. (2015) reviewed the conodont record of SE Poland in order to elaborate the existing Givetian conodont biofacies model and to document onshore–offshore biofacies shifts with the major, eustatic Taghanic Onlap. Results were transferred to interpret the conodont records of widely separated basins of North America, southern Europe and North Africa. This encountered some difficulties that have to be pursued in future studies. The significance of the contributions lies in the development of a refined biofacies tool that can trace Givetian sea-level movements by quantitative faunal analysis. Zambito et al. (2015), on the other hand, further develop carbon isotope stratigraphy as a tool to define pulses of the Taghanic Crisis. This paper provides the first detailed isotope study of the Taghanic type region in New York State, USA. Results suggest that in particular the upper crisis interval can be found easily, possibly even in facies, where other dating methods are not at hand.

Two chapters focus on the Kellwasser Crisis at the Frasnian–Famennian boundary. Mottequin & Poty (2015) summarize the brachiopod and coral evidence of the Ardennes, which in the middle and upper Frasnian can be assigned to a succession of clearly defined third-order sequences. The end of regionally famous reef episodes (mostly mud-mounds) was linked with regressions and sequence boundaries, whilst the Lower and Upper Kellwasser levels represent maximum transgressions. The upper Frasnian brachiopod and coral extinctions occurred in discrete steps, and only a few taxa were left at the time of the basinwide final spread of dysoxic/anoxic Matagne facies. The authors propose that the regional Upper Kellwasser beds were triggered by tsunamis, an idea that will probably be challenged and tested. It has long been known that the Kellwasser Crisis was a first-order extinction for trilobites, which terminated long-lived orders and families, including several that had existed since the Ordovician. Based on the faunal record of the Canning Basin of NW Australia, which is currently the best on a global scale, McNamara & Feist (2015) summarize not only the regional trilobite succession, with new taxa, but focus on the astonishing parallel morphological and evolutionary trends in associated families. This evolutionary-ecological approach gives new insights into end-Frasnian shallow-marine ecosystems, where nutrient (and food) availability seems to have been a major factor controlling adaptation, radiation and extinctions. A third paper, by Hairapetian et al. (2015), deals indirectly with aspects of the Frasnian–Famennian global biotic crisis, and includes descriptions of the newly discovered
and globally youngest thelodonts from Iran and Australia. These findings prove a survival of this fish group into the middle Famennian, which is remarkable given that armoured agnathans had been thought to have died out during the Upper Kellwasser Event. Old and new records are also placed into a palaeobiogeographical context.

Hartenfels & Becker (2016) summarize the global record of the third-order basal upper Famennian Annulata events, which can be recognized in more than 40 (sub)tropical basins in all continents belonging to that climatic realm. Records are assigned to 10 different tectonosedimentary event settings, which is important for distinguishing extinction v. survival and palaeoecological effects in specific environments. Based on the first event records of the Rheris Basin in southern Morocco, which yielded some regionally unique ammonoids and conodonts, the authors also establish distinctive event biofacies types. These reflect local differences of palaeobathymetry, nutrient availability, organic productivity and ventilation. Such an approach should be extended in the future to other Devonian hypoxic/anoxic events.

The final three chapters deal with the first-order global Hangenberg Crisis and short-lived end-Famennian—Lower Carboniferous glaciations. Becker et al. (2016) summarize the wealth of past and new information to provide a detailed review of chrono-, litho- and biostratigraphy around the Devonian—Carboniferous boundary. Based on these data, the authors refine the precise time framework for the stepped mass extinction, and contribute to the current revision of the Devonian—Carboniferous chronostratigraphic boundary. The Rhenish Massif, as the type region of the Hangenberg Crisis, is used as a standard to establish clearly defined lower, middle and upper crisis intervals. Building on this review, Kaiser et al. (2015) summarize the variably well-known or still insufficiently studied extinction and survival patterns for all relevant organism groups around the Devonian—Carboniferous boundary. Based on a detailed literature review, they compile the current knowledge of abiotic event aspects from impact signatures to the timing of glacial deposition, isotope excursions and the question of nutrient sources. Considering parallels with better understood Cretaceous events, all available data are synthesized in a new crisis model, which is open to future testing. A list of knowledge gaps and research directions shows how far we still are from a full understanding of this undoubted first-order mass extinction and global ecosystem overturn. Larkin et al. (2016) review the precise ages of uppermost Famennian—Visean glacial deposits, especially of South America, and provide evidence for three ‘precursor glaciations’ before the onset of long-term (Upper Carboniferous—Permian) icehouse climates. They stress the current uncertainties of the mostly palynomorph-based dating, especially for the onset of glaciations, when still few diamicites were formed. As with the review by Kaiser et al. (2015), this contribution ends with a plea for more data that can better constrain the extent of glaciation in time and space.

We wish to dedicate this volume to the memory of members of IGCP 596, SDS and the Devonian—Carboniferous Boundary Task Group who, sadly and unexpectedly, passed away since our 2013 Morocco Meeting, which was the starting point for this book. These esteemed colleagues are: Kolya Bakharev (Russia), Mena Schemm-Gregory (Portugal/Germany), Vladimir Nikolaevich Puzukhin (Russia), Paul Sarthnaer (Belgium), Chen Xiujin (China) and R. Lane (USA).

The editors express thanks to all contributing authors and to the many reviewers, who invested their knowledge and time to ensure a high-quality publication. We are convinced this volume will form an enduring source of valuable information concerning Devonian biotas and stratigraphy, and will, in particular, form the foundation for a deeper understanding of the complex global climatic and environmental changes that repeatedly shaped mid-Palaeozoic ecosystems and evolutionary patterns. The editorial team of the Geological Society, notably Angharad Hills and Jo Armstrong, was most helpful in getting this volume completed and published.

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