

## Drawing a line in the sand: identifying and characterizing boundaries in the geological record

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**Abstract:** The identification and characterization of boundaries is a fundamental activity in geoscience. Spatial and temporal boundaries are rarely sharp but are more usually zones of transition, which may have variable characteristics. The examination of palynological and micropalaeontological data is often crucial for the delineation of geological boundaries, especially for the definition of Global Boundary Stratotype Sections and Points (GSSPs). The sixteen papers in this volume highlight many productive methodological approaches to boundary identification. This essay reviews the theoretical background to boundary identification in geology, and provides the contextual perspective for the subsequent papers.

Much of geoscience has to do with classification, of organisms, of rocks, or of processes. Inevitably, classification devolves into an exercise in drawing boundaries: putting a limit on what is included and what is not. In the geological record, this exercise takes place in three dimensions, with space and time interacting to produce a plethora of boundaries and boundary definitions. Although conventionally, on stratigraphic charts, for example, temporal boundaries are often shown as sharp lines, in reality they are rarely so. Similarly, spatial boundaries on maps are seldom as abrupt as they are drawn. Process boundaries are yet more subtle and usually less clear. Indeed, even to speak of 'a boundary' is contentious, since boundaries come in many forms and types. Boundaries are more often intervals or spaces of transition, leaving plenty of room for argument over their placement. Perhaps for this reason, some of the more truculent and long-lasting debates in geology have been over the positioning and identification of boundaries. Drawing a line in the sand may seem a simple exercise but turns out to be fraught with complexities!

### Boundary definitions

In geoscience, the criteria for identifying chronostratigraphic, biostratigraphic and lithostratigraphic units are outlined in rules set up by international agreement, such as the International Stratigraphic Guide (Salvador 1994), or

guidelines such as the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature 1983), or the Stratigraphic Procedure (Rawson *et al.* 2002). The demarcation of boundaries is generally a consequence of the identification of units, rather than the other way round. Historically, the identification of boundaries has often arisen from the practical exigencies of geological mapping: the need to produce visual representations of geology, primarily based on sections or surface exposures. Boundaries, therefore, were often synonymous with the limits of mappable units, that were generally field-identified on the basis of lithology. This approach gave rise to the designation of 'body stratotypes', a methodology that proved limiting for the subdivision of geological time because of gaps in the rock record (Harland *et al.* 1990).

Modern geochronology emphasizes boundaries, especially lower stage boundaries, rather than units, as fundamental for subdivision and correlation (Remane 2003). Under the auspices of the International Commission on Stratigraphy (ICS), various subcommissions have been established to examine the placement of particularly critical temporal boundaries in the geological record (see list in Gradstein & Ogg 2003). Considerable effort has been devoted to the establishment of Global Boundary Stratotype Sections and Points (GSSPs), with more than 40 defined so far (Gradstein *et al.* undated). For each boundary, a type section and a specific

*From:* BEAUDOIN, A.B. & HEAD, M.J. (eds) 2004. *The Palynology and Micropalaeontology of Boundaries*. Geological Society, London, Special Publications, **230**, 1–10. 0305-8719/04/\$15 © The Geological Society of London 2004.

point within that section are chosen by international agreement as a means to define the boundary formally. The type section is therefore a particular section at an identified location (ICS 2004). Although parastratotype sections may be established at considerable convenience to local and regional stratigraphers, ultimately all securely identified boundaries must be correlatable to the GSSP. In practice, almost all GSSPs are defined from shallow-marine sediments. Macrofossil biostratigraphy is used for many GSSP definitions, particularly in the Mesozoic (see list in ICS 2004). However, changes in micropalaeontological indicators – especially conodonts, calcareous nannofossils, and foraminifera – often underpin these definitions. Micropalaeontology is becoming increasingly important, particularly for GSSPs in the Cenozoic and Palaeozoic, due to the more continuous nature of microfossil recovery. Since it acts as an exemplar, the selection of a type section is often a difficult matter, and candidate sections are minutely scrutinised (see *Sikora et al.* and *Mei et al.*). The establishment of a GSSP rarely ends discussion or extinguishes debate; GSSPs may be challenged, re-examined, and defended (*Zhang & Barnes a*).

### Boundary types

Surprisingly, despite all the attention paid to boundaries, there is no cohesive theoretical treatment of them in the geological literature, although stratigraphic principles have been widely discussed (e.g. Hedberg 1976; Salvador 1994; Remane 2003; Walsh 2004). This situation differs from ecology, where there is an emerging body of literature dealing with boundary theory (see Gosz 1991, and Cadenasso *et al.* 2003a, 2003b). Because ecology deals with living organisms and their environment, this theoretical approach is also applicable to palynology and micropalaeontology. Strayer *et al.* (2003) distinguish two major types of boundaries: investigative and tangible boundaries. Investigative boundaries are those that are imposed by practical or administrative considerations and often have no physical expression in the landscape. Investigative boundaries can also occur when language barriers preclude discussion or access to information. *Nikitenko & Mickey*, for example, review an enormous quantity of literature from Russia, which has not hitherto been accessible to people who do not read Russian. Spatially speaking, tangible boundaries are associated with some biotic change, environmental discontinuity, or landscape expression. It is the exploration of tangible boundaries with

which this volume is primarily concerned. However, it is worth noting that some geological boundaries may be a consequence of investigative boundaries, where research or analyses are constrained by jurisdictional or political limits, such as those that confine national geological surveys. Establishing boundaries may be more than an esoteric exercise; boundary definitions may have important management implications, as in the establishment of ecological reserves, or legal consequences, as in the definition of continental margins (e.g. Hedberg 1979).

Spatial boundaries differ in type and degree. Boundaries may be abrupt or gradual, solid or permeable, permanent or ephemeral, constant or fluctuating, stationary or moving, narrow or broad, relatively straight or highly convoluted. Where a boundary is defined by a physical landscape expression or environmental discontinuity, its character may affect the way in which organisms react to it. Moreover, conditions that form a boundary for one type of organism may have no impact on another. Physical boundaries can also act as a filter, only allowing certain organisms to pass through. For these reasons, the identification and characterization of a boundary through biotic indicators may depend on what organism is being examined as a proxy and the sensitivity of that organism to change. Boundaries may also regulate flows of materials or energy (Cadenasso *et al.* 2003b). Where a boundary is defined by a perturbation, the magnitude, extent, and duration of that perturbation may influence biotic response. Some biota may show considerable complacency or resiliency until critical threshold values are crossed.

### Analogues from modern ecological and environmental boundaries

The identification of boundaries on the modern landscape provides many examples of these different types. Here, we can examine boundaries in the simplest spatial cases, with the complication of geological time removed. However, the identification of boundaries across the landscape, and the characterization of transitions, provides analogies for the 'space for time' substitution which is the foundation of the 'present is the key to the past' approach to geoscience. Some boundaries are obvious, the land–sea transition, for example, and have long been a focus of research. State-change boundaries, such as the water–atmosphere or ice–water interfaces, are also clearly marked. Other

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boundaries, such as temperature limits, are more subtle and less visible. These boundaries are often formed when the gradient or rate-of-change of a parameter becomes steep (Cadenesso *et al.* 2003a). Process boundaries have been a research focus for decades, especially with respect to fluid dynamics in fluvial (Thornes 1979) and aeolian (e.g. Walker & Nickling 2002) systems. The recognition that unique suites of processes occur at boundaries also permeates meteorology and climatology (e.g. Oke 1993, 1997) and soil science (e.g. Belnap *et al.* 2003).

Despite their definition with respect to the present landscape, spatial boundaries are usually dynamic and do often also incorporate a time dimension, albeit short term. Boundaries that are formed by physical discontinuities, such as breaks in slope, tend to have greater longevity and be fixed to a specific landscape position. Other types of boundaries, including process and biotic boundaries, however, are often more mobile and short lived. They may oscillate or fluctuate around a mean position on several scales from diurnal, such as tidal limits, to subseasonal, such as wetland margins (Shay & Shay 1986; Kantrud *et al.* 1989), to seasonal, such as the active layer–permafrost boundary (French 1993). Other ecological boundaries may move at decadal or century scales and can often be directional. These may include, for example, the migration front for plant species, such as the post-glacial expansion of lodgepole pine in western North America (MacDonald & Cwynar 1985). Boundaries which are most likely to have correlates in the geological record are ones where the mean position is relatively fixed for a long time, or where the directional shift is accompanied by distinctive biotic changes.

Of all modern ecological boundaries, perhaps none is as well studied as the treeline, both the alpine (altitudinal) treeline and the northern boreal (latitudinal) treeline (e.g. Frenzel *et al.* 1996; Arno & Hammerly 1984). This boundary exemplifies many of the issues of identification and characterization that pervade ecological and geological boundary definition. Wardle (1974, p. 396) emphasized that ‘timberline is the sharpest temperature-dependent boundary in nature’, and thus its location is climate-related. But, because of the physiological plasticity and response of trees to environmental stress, the treeline is not, in fact, a sharp line, but rather a zone representing a complex transition between forested and treeless areas. Strictly, the alpine treeline (or tree limit) is the upper elevation limit of krummholz forms of nominally arboreal species, and the timberline is the limit of standing tree growth (Wardle 1974). Between

these limits, in the krummholz zone, trees often occur in isolated ‘tree islands’ and may be deformed, flagged, or stunted. Where elevational controls are sharp, as on steep slopes, the alpine treeline zone can be quite narrow, in contrast to the northern boreal treeline zone, which is often broad. Here, an expanse of ‘forest-tundra’ is identified, which in northern Canada may be up to about 200 km wide (Timoney *et al.* 1992). Thus, the boundary between forested and non-forested areas represents the interplay of topographical, latitudinal, biotic, temporal and ecological factors.

Such definitional minutiae may seem picayune, but they have significant implications for interpretation of palynological data. Because altitudinal treeline shows a strong correlation with growing season temperature, many studies have attempted to characterize its modern position through palynological signatures, and then use these signatures to interpret past pollen records as a ‘proxy’ temperature signal (e.g. Beaudoin 1986; Pellatt *et al.* 2000). There are several problems to this approach, not least being the assumption that the present boundary is in equilibrium with, or controlled by, current conditions and thus is a surrogate measure for contemporary conditions. But because tree response to a perturbation or a temperature change may be lagged, this assumption may be suspect. The response may also vary depending on the floristic composition of the treeline, because not all taxa will necessarily react in the same way. Computational issues may also oversimplify the situation. Usually, some form of regression between modern pollen signatures and growing season temperatures is performed and the results used to interpret signatures from past records. This approach forces a one-to-one correspondence (albeit with some probability attached) with the values from the past record, and does not allow for the fact that the character of the treeline may have varied over time, for example, through floristic change. The inferred record may therefore appear more sharply focused and delineated than it probably was. Modern analogies are always laden with such ambiguities, but nevertheless remain the best approach for ecological or environmental boundary characterization.

### Geological boundaries

In the geological past, boundary identification becomes even more complex with the addition of the time dimension. The same dichotomies apply, although we can also add swift or slow, abrupt or gradual, continuous or gapped to the

mix. We can also distinguish between abiotic (lithostratigraphic) and biotic (biostratigraphic) boundaries. Biostratigraphic boundaries are analogous to modern ecological boundaries because they are defined by changes in biota. These could, of course, coincide with lithostratigraphic changes, but this need not be the case. These boundaries can be both spatially and temporally transgressive, and may be of local or regional significance. Critical boundaries, such as those that define stages, must be of more than local extent (Remane 2003). This can make their identification in geological records problematic, not least because geological studies often have a very limited spatial view. Often, boundary inferences are made from samples obtained from one or a few cores or boreholes. So the geological or subsurface view of boundaries is often highly patchy and discontinuous and represents only a limited subset of the available environmental variance. Where multiple views are available (e.g. **Zhang & Barnes a**, **Nikitenko & Mickey**), it may be important to tease out the ecological variability, such as shallow v. deep water or warm water v. cool water, so that the more substantive regionally or globally significant variation can be clearly identified.

#### *Techniques for boundary identification*

Boundaries in the geological record are identified using many techniques, but the examination of palynological and micropalaeontological data is often crucial. Perhaps the easiest boundaries to identify are those where there is an abrupt lithostratigraphic change or where there is a clear temporal break in the record – as at an erosional unconformity. The identification of chronostratigraphic boundaries may be more difficult, and in some cases relies on biotic events. Thus, chronostratigraphic and biostratigraphic boundaries may coincide. Significant biostratigraphic changes are often marked by the appearance or disappearance of important indicator taxa or, more often, assemblage changes.

The reliance on indicator taxa for boundary definition raises questions of consistency, fidelity and reproducibility, especially when these taxa form only a small part of an assemblage. For example, in a multi-core pollen study of a well-defined Holocene temporal level from Lake O'Hara (Beaudoin & Reasoner 1992) showed that minor taxa (present as less than 1% of the assemblage) were unreliable indicators, because their occurrence was highly variable and they did not show high fidelity between contemporaneous samples. Where a boundary is defined by

a discontinuity, it may also act as a filter, adding further complications to the recognition of indicator taxa. The incorporation of biotic remains in sediments may be complicated by taphonomic factors, such as downslope transport (**Zhang & Barnes a**), and by post-depositional factors affecting preservation (**Van Eetvelde & Dupuis**).

Sampling factors also influence the potential for boundary identification. First and last appearance of taxa in a stratigraphic record may be influenced by how much of the record has been examined, and are fundamentally statements of probability, associated with confidence limits (Holland 2003). Over millennia, geological processes, primarily erosion, reduce the amount of any exposed stratigraphic unit. Hence, only some of the original sediment, and therefore part of the original variability, is available for examination. Thus, the probability of finding remains of any organism is influenced by how much of the sediment unit is left. Peters & Foote (2002), for example, suggest that the evaluation of extinction rates may be influenced by these sampling factors. Using data from marine sedimentary formations, they conclude that derived extinction rates may be spurious, an artefact of the amount of the stratigraphic record available for examination. It may be more difficult therefore to identify boundaries within intervals for which the sedimentary record is slender or poorly preserved.

Numerical or statistical methods are often useful in distinguishing meaningful and consistent biotic changes. These methods are most applicable where large data-sets are available, and they can help to identify patterns in otherwise overwhelming amounts of data. Numerical methods can be used to answer two important biostratigraphic questions. First, given changing assemblages through time or up a stratigraphic section, where are the significant breaks or most important changes? Such judgements can be made qualitatively, by visual inspection for instance, but numerical methods have the advantage of being reproducible, given the same data-set, and following defined rules. Numerical zonation methods have been widely employed in Quaternary palynology to identify assemblages (e.g. Birks & Gordon 1985), especially when stratigraphic constraints are included (Grimm 1987). Pollen zone boundaries may be ecologically or chronostratigraphically important (e.g. **Fernández-Marrón et al.**). Second, given several assemblages and some knowledge of contemporaneous environmental conditions, can we make inferences about assemblage-environment linkages or controls?

Such environmental inferences can then be extended to assemblages where the contemporaneous conditions are not well known. Ordination or classification methods have been used to explore these patterns in palynological or micropalaeontological data, using techniques such as cluster analysis or principal components analysis (see Kovach 1989). These techniques can often highlight environmental shifts, such as sea-level or water temperature changes, in complex data. Several studies in this volume, including **Zhang & Barnes a**, **Elewa & Morsi**, and **Nikitenko & Mickey**, use numerical methods for this purpose.

### Using palynology and micropalaeontology to identify boundaries in the geological record

From the widest perspective, there are certain biological events in the geological past that stand out as being pivotal: the occurrence of the first fossils, the appearance of the first terrestrial fauna, the rise of flowering plants. However, no events have arguably generated more debate than mass extinctions and their causes. By their very nature, extinctions, reflecting significant changes in biota, are often defining events for boundaries. **MacLeod** takes this 'big picture' approach by examining the pattern and periodicity of extinction events shown by marine invertebrate genera through the sweep of Phanerozoic time. He investigates the association between these and the five most widely invoked explanatory factors – bolide impacts, continental flood-basalt eruptions, eustatic changes, and marine anoxia events. His analysis shows that two factors – marine regression and volcanic eruptions – explain most of the observed events. **MacLeod** observes that terrestrial mechanisms provide sufficient control to account for most extinction events through the Phanerozoic. The popular-culture image of extinction, exemplified by startled dinosaurs staring skywards as a flaming fireball approaches, apparently needs some revision!

**MacLeod's** analysis of extinction intensity through time also leads to some provocative suggestions. Rather than being a steadily declining trend through the Phanerozoic, **MacLeod** shows that the extinction intensity became marked around the end of the Devonian, with a notable reduction in extreme-intensity events around the end of the Triassic. **MacLeod** links these to changes in the global carbon cycle as a consequence of evolutionary events. He offers two possibilities for the causal mechanism: the diversification of land plants in the Late

Palaeozoic and the diversification of phytoplankton in the Late Triassic. This opens intriguing possibilities of linkages and feedback mechanisms between evolutionary events, climate changes, and extinctions – perhaps pointing the way to a more integrated theoretical perspective.

**Doran et al.** also adopt a 'big picture' approach and also examine evolutionary trends, in this case in post-extinction planktonic foraminifera, concentrating on two boundaries, the Cenomanian–Turonian (C–T) and the Cretaceous–Tertiary (K–T). Their concern is with the rate and pattern of faunal recovery after extinction. If extinction is a boundary, it can be regarded as the quintessential filter, only allowing certain life-forms to pass. What happens to the taxa that make it through extinction? **Doran et al.'s** analysis shows rapid evolutionary change in foraminifera following these major extinction events. They suggest that this pattern relates to specific characteristics, which they term 'passport' characteristics, that allowed some taxa to pass through or survive the extinction events. These taxa may not necessarily be best adapted to the post-extinction environment, but they form the foundation for subsequent populations.

After much debate, the GSSP for the Cambrian–Ordovician boundary was located at Green Point, western Newfoundland, Canada, and defined on the basis of conodont biostratigraphy (Cooper *et al.* 2001). This GSSP was contentious because of differing opinions about the conodont record, in particular the degree of transport and mixing. To clarify this issue, **Zhang & Barnes a** analyse conodont communities associated with different environmental settings, from shallow platform to distal slope, across this boundary in western Newfoundland. They use multivariate statistical techniques to identify consistent patterns and gradational relationships, and show that conodont communities were partitioning the environment according to slope position and water depth. Therefore, conodont community change may reflect sea-level changes affecting water depth, in particular sea-level rise in the Early Ordovician. Overprinted on this are community changes resulting from rapid evolution and diversification. Both factors are important to an evaluation of the conodont record across this boundary.

The end of the Ordovician is marked by the second-most severe mass extinction in the Phanerozoic, resulting in the estimated loss of some 85% of all marine species (Jablonski 1991; Sheehan 2001). This was brought about by a continental glaciation in North Africa that

resulted in cooler oceanic temperatures and more aerated bottom waters: changes that had profound implications for marine organisms (Hallam & Wignall 1999; Sheehan 2001). **Zhang & Barnes** *b* have examined the depletion of conodont taxa at the end of the Ordovician, and particularly the nature and timing of their post-extinction recovery. Their analysis of deposits of Early Llandovery (earliest Silurian) age from the essentially complete succession on Anticosti Island, Quebec, has revealed an unexpectedly complex series of speciation, extinction, immigration and emigration events that can be in part correlated to eustatic and other ocean–climate changes. The Anticosti Basin may indeed have been an important centre of evolutionary radiation for conodont animals during the earliest Silurian.

Taxonomic matters often lie at the heart of boundary definitions, as in the study by **Mei et al.** They present the case for establishment of a GSSP for the base of the Changhsingian Stage (Upper Permian) at Meishan, China, based on the analysis of conodonts. They suggest that the boundary should be defined at the first appearance of *Clarkina wangi*. This species was established following the authors' examination of conodonts from the Meishan section, using characteristics of the sample-population rather than individuals to distinguish taxa: focusing on carinal morphology. Taxa are defined when the population as a whole exhibits a predominance of the particular morphology. In this instance, the transition from one carinal configuration to another occurs over a narrow interval, allowing the boundary to be relatively well constrained. Their sample-population analysis is an interesting way of approaching a question that is relevant to many micropalaeontological indicators – how much morphological variation can be allowed before a new taxon is recognized?

The Carboniferous System is internationally defined (by GSSPs) at its top and base, but the inter-regional correlation of stages continues to present challenges. The Duckmantian is a European stage within the lower Upper Carboniferous. It overlies the Langsettian Stage, and its base is defined by the base of the Vanderbekei Marine Band and in a boundary stratotype in Derbyshire, England, UK. The position of this marine band has been correlated with important changes in macro- and microfloral assemblages across northwestern Europe. **McLean et al.** have analysed the Duckmantian stratotype in detail, using miospores to characterize the Vanderbekei Marine Band and the Langsettian–Duckmantian boundary in particular. By then analysing this same marine band in

a borehole in the southern North Sea, **McLean et al.** have been able to assess the potential of miospores for recognizing the boundary elsewhere. Results show that although the Vanderbekei Marine Band and can be recognized palynologically, a clear floristic break does not occur at its base. Indeed, a gradual turnover of taxa occurs across the boundary. **McLean et al.** conclude that marine flooding events in the Upper Carboniferous coal measures may not exclusively provide the impetus for evolutionary change in the flora, which apparently continued to evolve throughout transgressive–regressive cycles.

In the Lower Jurassic, the Early Toarcian was characterized by a mass-extinction event, marked by rising sea-levels with widespread anoxia, and consequent deposition of black shales (Hallam & Wignall 1999; Harries & Little 1999). **Nikitenko & Mickey** review studies on a broad regional scale from Russia and Alaska, concentrating especially on foraminifera and ostracodes through the Pliensbachian–Toarcian interval. Numerical analysis allows them to identify biogeographical units of ostracodes and foraminifera within the Arctic and Boreal–Atlantic Realms. **Nikitenko & Mickey** distinguish consistent patterns of zonation within ostracode and foraminifera that allow correlation both across this region and with the microfossil sequence from Western Europe. In the Early Toarcian in the Arctic, ostracode genera and families completely changed, and more than 80% of the foraminiferal species were replaced. Interestingly, the authors note that the reduction in species and generic diversity began in the Late Pliensbachian in the Arctic – somewhat earlier than in Western Europe.

The exact placement of the Jurassic–Cretaceous boundary remains contentious, largely owing to difficulties in correlating between Tethyan and Boreal realms. These realms occur at a time of marked provincialism in the marine biota, brought about by low global sea-levels. The lowermost stage of the Cretaceous is the Berriasian, whose stratotype is at Berrias, France. Correlating this stratotype beyond the Tethys has been problematic, owing to the localized nature of the ammonite fauna. **Hunt** has used dinoflagellate cyst stratigraphy at classic sites in Dorset, southern England, UK, as a means of correlating these sites with the type Berriasian. Dorset was within the Tethyan Realm, but close to the northern Boreal Realm. This has allowed **Hunt** to use miospores to correlate the Dorset sections with the Terschelling Basin in the Netherlands, which is within the Boreal Realm. This approach achieves a

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novel correlation between the Berriasian, including its base (and hence the Jurassic–Cretaceous boundary), and the ammonite biostratigraphy of the Boreal Realm.

**Hart's** historical account of the recognition of a mid-Cenomanian non-sequence in the chalk succession of southern England and northern France is a salutary reminder of the practical application of boundary problems. The non-sequence was originally identified during geological studies, especially micropalaeontological work on the foraminifera, associated with the development of the Channel Tunnel. Work throughout southern England and northern France during subsequent decades showed that this non-sequence represents a hiatus, in some places an unconformity, of regional extent. Above it, the foraminifera include a greater abundance of planktonic forms, indicating more open-marine conditions. This study raises some fascinating issues with respect to boundary definitions. Should this non-sequence or depositional break be considered a sequence boundary? Can a boundary be formed by an absence? The definition of a GSSP relies on its identification within a conformable sequence (Walsh 2004), but Hart's study shows that other types of boundaries may also be useful in regional correlations.

Macrofossil biostratigraphy provides one line of evidence for **Sikora et al.** as they tackle an aspect of the Jurassic–Cretaceous boundary – the establishment of a GSSP. To be useful as a standard, a stratotype must be continuous across the interval, be widely correlatable, and be accessible to the scientific community. **Sikora et al.** examine and compare the macrofossil and microfossil biostratigraphy of two sections proposed as potential GSSPs: at Wagon Mound, New Mexico, USA, and Salzgitter-Salder, central Germany. **Sikora et al.** are able to show that different indicator types provide different temporal signatures, and that, more significantly, the micropalaeontological indicators show a different temporal pattern to macrofossil remains. Their study suggests that neither of the proposed stratotypes are likely to be good candidates for a GSSP. This example shows the value of using multiple indicators for boundary characterization.

The Cretaceous–Tertiary (K–T) boundary is perhaps the most studied of all geological boundaries, and probably, because of its well-publicized association with dinosaur extinction, the most well-known outside geoscience (see Alvarez *et al.* 1980; Hildebrand 1993). It represents a profound disruption to terrestrial and marine ecosystems on a global scale,

although the scale and rate of biotic extinctions is debated.

An intriguing aspect of the K–T transition is the contrast between North American (and Pacific) and European pollen records. North American records reveal a pronounced extinction event near the boundary (Nichols 1996), followed at some sites by a brief increase in fern abundance (the 'fern spike') that is thought to relate to short-term environmental disturbance (Tschudy *et al.* 1984; Fleming & Nichols 1990; Sweet 2001). In contrast, no appreciable changes have been recorded in pollen records from the Old World, including Europe. To test this apparent lack of change, **Fernández-Marrón et al.** have analysed spore and pollen data from two sections that span the K–T transition in Spain. Because these sections represent differing palaeoenvironmental settings, any effects caused by local factors and taphonomy should be detected. While no noticeable extinctions could be linked to the boundary, a statistical analysis reveals significant differences in assemblage composition. These changes, which include an increase in trilete fern spores across the K–T transition and a reduction in the Danian samples, offer a new means to identify the K–T boundary in terrestrial deposits of the region.

Dinoflagellate cysts are relatively unaffected by short-term environmental disruption, owing to their ability to remain dormant for several years. This presumably explains their continuous record across the K–T boundary, which makes them well suited for studying environmental changes through this interval (Brinkhuis *et al.* 1998). Most sites presently studied represent shelfal facies (e.g. Brinkhuis & Leereveld 1988; Brinkhuis & Schiøler 1996; Brinkhuis *et al.* 1998). The study by **Gedl et al.** examines dinoflagellate cysts at a deep-water site in the Czech Republic, thereby offering a new perspective on this critical boundary. **Gedl et al.** concludes that a warm, stable, marine climate prevailed across the boundary. Although no major changes in assemblages were found, minor changes might relate to gradual sea-level fall or increasing nutrient availability. A peak abundance of heterotrophic dinoflagellate cysts near the boundary appears to indicate upwelling in this part of the Tethys.

The Palaeocene–Eocene transition is marked by significant changes in many Earth systems, including global climate, with a marked carbon isotope anomaly, and ocean circulation, accompanied by palaeogeographical changes (Norris & Röhl 1999; Zachos *et al.* 2001). Both marine and terrestrial organisms show considerable evolu-

tionary turnover through this interval (Berggren *et al.* 1998; Hallam & Wignall 1999). Despite the abundant evidence for change, the establishment of a GSSP for the Palaeocene–Eocene is currently subject to vigorous debate (see Aubry *et al.* 1999; Walsh 2004). Two studies in this volume shed further light on this interval.

**Van Eetvelde & Dupius** use diatoms to examine the Upper Palaeocene to Lower Eocene interval in two localities from northern France. Here, examination of the record is complicated by preservation issues because the diatoms are heavily pyritized, requiring specialized extraction techniques. Nevertheless, three distinct diatom assemblages can be recognized, and these offer the prospect of correlation between the sequences of the Dieppe–Hampshire and North Sea basins.

**Elewa & Morsi** also examine the Palaeocene–Eocene interval, in this case based on ostracodes recovered from sediment sequences in northeast Egypt. Numerical analysis permits the identification of ecozones, distinguished by environmental parameters, including water depth, temperature, turbulence and dissolved oxygen content. **Elewa & Morsi** conclude that changes in ostracode assemblages were mainly the result of changing local environmental conditions, rather than speciation or extinction. However, they do detect faunal changes probably associated with the Palaeocene–Eocene thermal maximum (Kennett & Stott 1991), which elsewhere is associated with extinctions.

The Eocene–Oligocene transition is generally characterized by falling temperatures and a drop in global sea-level. However, the boundary itself is contentious, owing to disagreements in definition (Berggren *et al.* 1995, pp. 197–198; Brinkhuis & Visscher 1995). It is marked either by the highest occurrence of the foraminiferal genus *Hantkenina* or that of the dinoflagellate cyst *Areosphaeridium diktyoplokum*. The latter datum, which is stratigraphically higher than the former, is used by **Gedl** in his study of dinoflagellate cysts from the Carpathian Mountains of Poland. **Gedl**'s study identifies the position of the Eocene–Oligocene boundary in the Leluchów section, and infers a drop in relative sea-level that might correlate with Early Oligocene eustatic lowering. Sea-surface temperatures are found to drop prior to the Eocene–Oligocene boundary at this site.

The Oligocene–Miocene boundary represents one of the most important eustatic rises in the Cenozoic, with high sea-levels continuing throughout the early Early Miocene (Haq *et al.* 1987, 1988; Hardenbol *et al.* 1998). In South America, a major marine transgression

in Patagonia is associated with this event, although its precise dating has remained questionable. **Guerstein** *et al.* have used palynology to assign a Late Oligocene and early Early Miocene age to the marine Centinela Formation deposited near the margin of this transgression. A maximum flooding surface is indicated by high ratios of dinoflagellate cysts in the earliest Miocene.

In conclusion, the sixteen papers summarized here highlight many methodological and definitional issues with boundaries in geology. Although not all problems are resolved, the papers point the way to productive investigative and analytical approaches that may prove worthwhile in other situations.

## References

- ALVAREZ, L. W., ALVAREZ, W., ASARO, F. & MICHEL, H. V. 1980. Extraterrestrial cause for the Cretaceous–Tertiary extinction. *Science*, **208**, 1095–1108.
- ARNO, S. F. & HAMMERLY, R. P. 1984. *Timberline: Mountain and Arctic Forest Frontiers*. The Mountaineers, Seattle, Washington, 304 pp.
- AUBRY, M. P., BERGGREN, W. A., VAN COUVERING, J. A. & STEININGER, F. 1999. Problems in chronostratigraphy: stages, series, unit and boundary stratotypes, global stratotype section and point and tarnished golden spikes. *Earth-Science Reviews*, **46**(1–2), 99–148.
- BEAUDOIN, A. B. 1986. Using *Picea/Pinus* ratios from the Wilcox Pass core, Jasper National Park, Alberta, to investigate Holocene timberline fluctuations. *Géographie physique et Quaternaire*, **40**, 145–152.
- BEAUDOIN, A. B. & REASONER, M. A. 1992. Evaluation of differential pollen deposition and pollen focussing at three Holocene intervals in Lake O'Hara, Yoho National Park, British Columbia, Canada: intra-lake variability in pollen percentages, concentration and influx. *Review of Palaeobotany and Palynology*, **75**, 103–131.
- BELNAP, J., HAWKES, C. V. & FIRESTONE, M. K. 2003. Boundaries in miniature: two examples from soil. *BioScience*, **55**, 739–749.
- BERGGREN, W. A., KENT, D. V., SWISHER III, C. C. & AUBRY, M.-P. 1995. A revised Cenozoic geochronology and chronostratigraphy. In: BERGGREN, W. A., KENT, D. V. & HARDENBOL, J. (eds) *Geochronology, Time Scales and Global Stratigraphic Correlation*. SEPM Special Publications **54**, Tulsa, Oklahoma, 129–212.
- BERGGREN, W. A., LUCAS, S. & AUBRY, M.-P. 1998. Late Paleocene–Early Eocene climatic and biotic evolution: an overview. In: AUBRY, M.-P., LUCAS, S. & BERGGREN, W. A. (ed.) *Late Paleocene–Early Eocene Climatic and Biotic Events in the Marine and Terrestrial Records*. Columbia University Press, New York, 1–17.

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- BIRKS, H. J. B. & GORDON, A. D. 1985. *Numerical Methods in Quaternary Pollen Analysis*. Academic Press, New York, 317 pp.
- BRINKHUIS, H. & LEEREVELD, H. 1988. Dinoflagellate cysts from the Cretaceous/Tertiary boundary sequence of El Kef, northwest Tunisia. *Review of Palaeobotany and Palynology*, **56**, 5–19.
- BRINKHUIS, H. & SCHIÖLER, P. 1996. Palynology of the Geulhemmerberg Cretaceous/Tertiary boundary section (Limburg, SE Netherlands). *Geologie en Mijnbouw*, **75**, 193–213.
- BRINKHUIS, H. & VISSCHER, H. 1995. The upper boundary of the Eocene Series: a reappraisal based on dinoflagellate cyst biostratigraphy and sequence stratigraphy. In: BERGGREN, W. A., KENT, D. V. & HARDENBOL, J. (eds) *Geochronology, Time Scales and Global Stratigraphic Correlation*. SEPM Special Publications, **54**, Tulsa, Oklahoma, 295–304.
- BRINKHUIS, H., BUJAK, J. P., SMIT, J., VERSTEEGH, G. J. M. & VISSCHER, H. 1998. Dinoflagellate-based sea surface temperature reconstructions across the Cretaceous–Tertiary boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **141**, 67–84.
- CADENESSO, M. L., PICKETT, S. T. A., WEATHERS, K. C., BELL, S. S., BENNING, T. L., CARREIRO, M. M. & DAWSON, T. E. 2003a. An interdisciplinary and synthetic approach to ecological boundaries. *BioScience*, **53**, 717–722.
- CADENESSO, M. L., PICKETT, S. T. A., WEATHERS, K. C. & JONES, C. G. 2003b. A framework for a theory of ecological boundaries. *BioScience*, **53**, 750–758.
- COOPER, R. A., NOWLAN, G. S. & WILLIAMS, S. H. 2001. Global Stratotype Section and Point for the base of the Ordovician system. *Episodes*, **24**(1), 19–28.
- FLEMING, R. F. & NICHOLS, D. J. 1990. Fern-spore abundance anomaly at the Cretaceous–Tertiary Boundary: a regional bioevent in western North America. In: KAUFFMAN, E. G. & WALLISER, O. H. (eds) *Extinction Events in Earth History*. Springer Verlag, Berlin and New York, 347–349.
- FRENCH, H. M. 1993. Cold-climate processes and landforms. In: FRENCH, H. M. & SLAYMAKER, O. (eds) *Canada's Cold Environments*. McGill–Queen's University Press, Montreal and Kingston, Canada, 143–167.
- FRENZEL, B., BIRKS, H. H., ALM, T. & VORREN, K. D. (eds) 1996. *Holocene Treeline Oscillations, Dendrochronology and Palaeoclimate*. Paläoklimaforschung Band 20/Palaeoclimate Research Volume, **20**, Special Issue: ESF Project 'European Palaeoclimate and Man' 13. Gustav Fischer Verlag, Stuttgart, Germany, x + 303 pp.
- GOSZ, J. R. 1991. Fundamental ecological characteristics of landscape boundaries. In: HOLLAND, M. M., RISSER, P. G. & NAIMAN, R. J. (eds) *Ecotones: the Role of Landscape Boundaries in the Management and Restoration of Changing Environments*. Chapman and Hall, New York, 8–30.
- GRADSTEIN, F. M., FINNEY, S. C. & OGG, J. G. undated. ICS on Stage. 15 pp, PDF manuscript, World Wide Web Address: [www.stratigraphy.org/stage.pdf](http://www.stratigraphy.org/stage.pdf), last accessed 13 March 2004.
- GRADSTEIN, F. M. & OGG, J. G. 2003. International Union of Geological Sciences International Commission on Stratigraphy (ICS) Consolidated Annual Report for 2003. 130 pp, PDF manuscript, World Wide Web Address: [www.stratigraphy.org](http://www.stratigraphy.org), last accessed 7 February 2004.
- GRIMM, E. C. 1987. CONISS: a Fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences*, **13**, 13–35.
- HALLAM, A. & WIGNALL, P. B. 1999. Mass extinctions and sea-level changes. *Earth-Science Reviews*, **48**, 217–250.
- HAQ, B. U., HARDENBOL, J. & VAIL, P. R. 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, **235**, 1156–1166.
- HAQ, B. U., HARDENBOL, J. & VAIL, P. R. 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: WILGUS, C. K., HASTINGS, B. S., KENDALL, C. G. St. C., POSAMENTIER, H. W., ROSS, C. A. & VAN WAGONER, J. C. (eds) *Sea-Level Changes: an Integrated Approach*. SEPM Special Publication, **42**. Tulsa, Oklahoma, 71–108, plus one separate chart.
- HARDENBOL, J., THIERRY, J., FARLEY, M. B., JACQUIN, T., DE GRACIANSKY, P.-C. & VAIL, P. R. 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In: DE GRACIANSKY, P. C., HARDENBOL, J., JACQUIN, T. & VAIL, P. R. (eds) *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*. SEPM Special Publication, **60**, Tulsa, Oklahoma, 3–29, plus 8 separate charts.
- HARLAND, W. B., ARMSTRONG, R. L., COX, A. V., CRAIG, L. E., SMITH, A. G. & SMITH, D. G. 1990. *A Geologic Time Scale 1989*. Cambridge University Press, Cambridge, UK, 262 pp.
- HARRIES, P. J. & LITTLE, C. R. S. 1999. The early Toarcian (Early Jurassic) and the Cenomanian–Turonian (Late Cretaceous) mass extinctions: similarities and contrasts. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **154**, 39–66.
- HEDBERG, H. D. (ed.) 1976. *International Stratigraphic Guide: a Guide to Stratigraphic Classification, Terminology, and Procedure by International Subcommission on Stratigraphic Classification of IUGS Commission on Stratigraphy*. Wiley, New York, 200 pp.
- HEDBERG, H. D. 1979. Ocean floor boundaries. *Science*, **204**, 135–144.
- HILDEBRAND, A. R. 1993. The Cretaceous/Tertiary boundary impact (or the dinosaurs didn't have a chance). *Journal of the Royal Astronomical Society of Canada*, **87**, 77–118.
- HOLLAND, S. M. 2003. Confidence limits on fossil ranges that account for facies changes. *Paleobiology*, **29**, 468–479.

- ICS (International Commission on Stratigraphy) 2004. The Global Boundary Stratotype Section and Point (GSSP). World Wide Web Address: www.stratigraphy.org, last accessed 7 February 2004.
- JABLONSKI, D. 1991. Extinctions: a paleontological perspective. *Science*, **253**, 754–757.
- KANTRUD, H. A., MILLAR, J. B. & VAN DER VALK, A. G. 1989. Vegetation of wetlands of the prairie pothole region. In: VAN DER VALK, A. (ed.) *Northern Prairie Wetlands*. Iowa State University Press, Ames, Iowa, 132–187.
- KENNETT, J. P. & STOTT, L. D. 1991. Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene. *Nature*, **353**, 225–229.
- KOVACH, W. L. 1989. Comparisons of multivariate analytical techniques for use in pre-Quaternary plant palaeoecology. *Review of Palaeobotany and Palynology*, **60**, 255–282.
- MACDONALD, G. M. & Cwynar, L. C. 1985. A fossil pollen reconstruction of the late Quaternary history of lodgepole pine (*Pinus contorta* ssp. *latifolia*) in the western interior of Canada. *Canadian Journal of Forest Research*, **15**, 1039–1044.
- NICHOLS, D. 1996. Vegetational history in Western Interior North America during the Cretaceous–Tertiary transition. In: JANSONIUS, J. & MCGREGOR, D. C. (eds) *Palynology: Principles and Applications*. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, **3**, 1189–1195.
- NORRIS, R. D. & RÖHL, U. 1999. Carbon cycling and chronology of climate warming during the Palaeocene/Eocene transition. *Nature*, **401**, 775–778.
- North American Commission on Stratigraphic Nomenclature 1983. North American Stratigraphic Code. *American Association of Petroleum Geologists Bulletin*, **67**, 841–875.
- OKE, T. R. 1993. *Boundary Layer Climates*. 2nd edition. Routledge, London, 436 pp.
- OKE, T. R. 1997. Surface climate processes. In: BAILEY, W. G., OKE, T. R. & ROUSE, W. R. (eds) *The Surface Climates of Canada*. McGill–Queen's University Press, Montreal and Kingston, Canada, 21–43.
- PELLATT, M. G., SMITH, M. J., MATHEWES, R. W., WALKER, I. R. & PALMER, S. L. 2000. Holocene treeline and climate change in the subalpine zone near Stoyoma Mountain, Cascade Mountains, southwestern British Columbia, Canada. *Arctic, Antarctic and Alpine Research*, **32**, 73–83.
- PETERS, S. E. & FOOTE, M. 2002. Determinants of extinction in the fossil record. *Nature*, **416**, 420–424.
- RAWSON, P. F., ALLEN, P. M. *et al.* 2002. *Stratigraphical Procedure*. Professional Handbook, Geological Society of London, 57 pp.
- REMANE, J. 2003. Chronostratigraphic correlations: their importance for definition of geochronologic units. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **196**, 7–18.
- SALVADOR, A. (ed.) 1994. *International Stratigraphic Guide, Second Edition. A Guide to Stratigraphic Classification, Terminology, and Procedure*. International Union of Geological Sciences and the Geological Society of America, 214 pp.
- SHAY, J. M. & SHAY, C. T. 1986. Prairie marshes in western Canada, with specific reference to the ecology of 5 emergent macrophytes. *Canadian Journal of Botany*, **64**, 443–454.
- SHEEHAN, P. M. 2001. The Late Ordovician mass extinction. *Annual Review of Earth and Planetary Sciences*, **29**, 331–364.
- STRAYER, D. L., POWER, M. E., FAGAN, W. F., PICKETT, S. T. A. & BELNAP, J. 2003. A classification of ecological boundaries. *BioScience*, **53**, 723–729.
- SWEET, A. R. 2001. Plants, a yardstick for measuring the environmental consequences of the Cretaceous–Tertiary boundary event. *Geoscience Canada*, **28(3)**, 127–138.
- THORNES, J. 1979. Fluvial processes. In: EMBLETON, C. & THORNES, J. (eds) *Process in Geomorphology*. Edward Arnold, London, 213–271.
- TIMONEY, K. P., LA ROI, G. H., ZOLTAI, S. C. & ROBINSON, A. L. 1992. The high subarctic forest-tundra of northwestern Canada: position, width, and vegetation gradients in relation to climate. *Arctic*, **45**, 1–9.
- TSCHUDY, R. H., PILLMORE, C. L., ORTH, C. J., GILMORE, J. S. & KNIGHT, J. D. 1984. Disruption of the terrestrial plant ecosystem at the Cretaceous–Tertiary boundary, Western Interior. *Science*, **225**, 1030–1032.
- WALKER, I. J. & NICKLING, W. G. 2002. Dynamics of secondary airflow and sediment transport over and in the lee of transverse dunes. *Progress in Physical Geography*, **26**, 47–75.
- WALSH, S. L. 2004. Solutions in chronostratigraphy: the Paleocene/Eocene boundary debate, and Aubry vs. Hedberg on chronostratigraphic principles. *Earth-Science Reviews*, **64(1–2)**, 119–155.
- WARDLE, P. 1974. Alpine timberlines. In: IVES, J. D. & BARRY, R. G. (eds) *Arctic and Alpine Environments*. Methuen, London, 371–402.
- ZACHOS, J. C., PAGANI, M., SLOAN, L. C., THOMAS, E. & BILLUPS, K. 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, **292**, 686–693.