

Dependent and independent data in paleontology: Tools for the sedimentary modeler

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Abstract The relationship of paleontology to sedimentologic and stratigraphic modeling can be viewed as dependent, independent, or some combination of the two. Independent paleontologic data are taxonomy based and include standard paleontologic techniques, such as biostratigraphy. Tremendous advances in temporal acuity have resulted from our ability to analyze standard biostratigraphic data bases through the different methodologies of quantitative biostratigraphy. Dependent paleontologic data result from biotic responses to externally mediated physical parameters (e.g., sea level, climate, sediment accumulation rate). Thus, for example, trace-fossil distribution can be used with care as a tool to help discern transgressive-regressive events. In addition, biotic event horizons (epiboles) can be used as indicators of temporal equivalency across complex depositional facies mosaics and thus serve as important markers for regional correlation.

Sedimentology without palaeontology is lifeless and timeless. Palaeontology without sedimentology is unsupportable.

R. Goldring, 1985

Our purpose here is to illustrate some potential uses of paleontologic data in solving problems associated with sedimentary modeling, paleoenvironmental interpretations, and stratigraphy, both genetic and sequence. Our goal is to address the question, How can paleontology help me with sedimentary modeling? We do not intend to present a complete litany of paleontology's contributions or potential contributions to sedimentary modeling. Rather, we focus on a few specific case studies that address this question. Many of the examples we discuss are from the literature or our own experiences and either have been successfully used or have great potential to evaluate sedimentology and genetic and sequence stratigraphy in both the surface and the subsurface, across different geologic periods, and with a wide variety of fossil groups.

We consider two aspects of paleontologic data useful to sedimentary modelers: (1) independent time constraints and checks and (2) dependent time constraints and checks. Ultimately, the goals of both aspects are to avoid falling into the trap of inadvertently equating genetic or sequence stratigraphy with lithostratigraphy and to provide some means of nonlithologic control on recognition and evaluation of events used as boundaries by both genetic and sequence stratigraphers. More important, however, we hope to leave the reader with a feeling for how paleontology has helped other researchers address similar questions.

We define independent data as data derived from standard taxonomic investigations. What taxa are present? How do they change through time? Can we assess and quantify these

changes? These data, when gathered carefully and at a sufficiently fine scale, provide the basic building blocks of biostratigraphy. Such data provide *independent* tests of the temporal equivalency of laterally adjacent units. These data are independent of events used as boundaries by both genetic and sequence stratigraphers. Independent data are the only means of testing chronostratigraphic correlations. Yet, as we discuss later, biostratigraphy has lagged genetic and sequence stratigraphy in its ability to improve stratigraphic resolution.

Dependent data are data in which the biotic response is to environmental changes, which commonly are reflected in lithology. What were the biotic responses to marine transgression or episodic sedimentation? How can these responses be assessed in the fossil record? Such data are constrained by stratigraphic boundaries and thus depend on changes in sea level, sedimentation, or other environmental parameters that affect biota. Dependent data cannot be used to test chronostratigraphic correlations but can be used as additional information for making such correlations.

Independent time constraints and checks

Traditional biostratigraphy (FADs, LADs, and luck)

The objective of most biostratigraphers is to make more accurate or refined correlations. Correlation establishes equivalency of stratigraphic units irrespective of lithology—this is what distinguishes correlation from simple lithostratigraphic matching of units. Taxonomy-based (=traditional) biostratigraphy can provide obvious temporal horizons against which to evaluate facies changes. This probably is the oldest, most established way in which paleontology has been applied to geologic problem solving [see summary by Ludvigsen et al. (1986)]. Traditional biostratigraphy, through faunal ranges of key taxa, has provided over the years the basis of large-scale temporal subdivisions of the geologic record.

Traditional biostratigraphy, although well established and easy to use, generally suffers from a temporal resolution that

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is insufficient to evaluate some genetic or sequence stratigraphic correlations; that is, these correlations typically are at greater temporal resolution [see related discussions by Arthur et al. (1990, pp. 90–92) and Kauffman (1990)]. Although within-basin correlations can be productive [e.g., Waters and Sando (1987, 1988)], extending local biostratigraphic zonations to other areas can be difficult. However, one can get lucky by having the range of a key taxon begin or end within a genetic unit that is being evaluated, although hanging a biostratigraphic evaluation on one taxon can be tenuous because of paleoecologic constraints [see discussion by Kaesler (this volume)].

The preceding discussion about biostratigraphy should be tempered with two generalities. First, most biostratigraphers use the last appearance of a taxon for this purpose (last appearance datum, or LAD, also known as “picking tops”), although in some instances the first appearance of a taxon (first appearance datum, or FAD, also known as “picking bottoms”) can be used. Over the years, last appearances have proven more reliable than first appearances (especially for industry biostratigraphers) for two reasons, one theoretical and one practical. From the theoretical aspect evolutionary development of new forms may begin in geographically isolated areas and proceed slowly, but extinction is thought to be rapid. From the practical aspect well cuttings are collected and examined stratigraphically from youngest to oldest; therefore LADs do not suffer from the caving and mixing problems that affect FADs. It is important to note that immigrations and emigrations can complicate this picture, as does biogenic mixing and reworking of sediment during deposition.

Second, most biostratigraphers use the particular fossil group (e.g., conodonts, corals, brachiopods) that they know best to erect biostratigraphic zonations. Thus zonation schemes using multiple fossil groups are uncommon, and when published, often rely on collaboration, which may force compromise. Although major extinction events have occurred throughout earth’s history, they generally are much rarer than the myriad extinction events of individual taxa [sometimes referred to as background extinction; see Jablonski (1986)]. This usually means that in a given fossiliferous stratigraphic sequence the biostratigraphic zonation based on one fossil group commonly does not exactly coincide with zonations based on any other fossil group. One solution to this drawback is to combine all the available single-taxon zonations into a holistic biostratigraphy, the net result of which is increased biostratigraphic resolution [see Sando (1985)]. More powerful still is the combination of biostratigraphy with datable chronostratigraphic indicators, such as magnetostratigraphy or chemostratigraphy [e.g., Haq et al. (1987) and Berger and Vincent (1981); also see comments by Miller (1990)]. As Kaesler (this volume) has indicated, paleoecologic distributions can mask true biostratigraphic ranges. This problem still exists even when using a holistic faunal approach; however, the paleoecologic distributional

problem can be reduced by using the range-through method of constructing biostratigraphic range charts [see discussion by Boltovskoy (1988)]. Most industry biostratigraphers use the range-through method.

Quantitative biostratigraphy Although cognitive cut-and-paste biostratigraphy (“biochartography”) continues to be used extensively by many biostratigraphers, the future of high-resolution biostratigraphy lies in more quantitative approaches. High-resolution biostratigraphy will become more critical as sequence stratigraphers continue to produce results that are of higher temporal acuity than can be tested using traditional biostratigraphy.

Recent work using confidence intervals on stratigraphic ranges and assessing completeness of stratigraphic sections (Strauss and Sadler, 1989; Sadler and Strauss, 1990; Marshall, 1990) suggests a tremendous potential for assessing the number and degree of gaps in a given stratigraphic sequence [see also McKinney (1986) and Springer and Lilje (1988)]. Many quantitative biostratigraphic techniques, such as probabilistic stratigraphy, no-space graphs, ranking and scaling (RASC), and correlation and scaling in time (CASC) are well known and generally regarded as industry standards [see discussions and references by Christopher and Lagoe (1988)]. Others, such as unitary associations, are not so widely used but have great potential in some cases [see Gaux (1977) and Baumgartner (1984)]. Ordination techniques and cluster analysis are particularly useful in quantitative biostratigraphy where the input data are in the form of assemblage zones.

It is not our purpose here to discuss in detail the numerous methodologies that fall under the general headings of quantitative stratigraphy or quantitative biostratigraphy [see Agerberg and Gradstein (1988) and Christopher and Lagoe (1988)]. However, two methods in particular deserve additional discussion because of their potential for enhancement of sedimentary models. One method, the graphic correlation method of Shaw (1964), is extremely well known, and either it or some variant of it continues to be an industry standard [e.g., Kemple et al. (1989) and Reimers (1990)]. The literature is full of examples that use graphic correlation for biostratigraphic analysis of many different fossil groups across all time periods [see, for example, Upshaw et al. (1974), Miller (1977), Sweet (1979), and Murphy and Berry (1983)]. The success of any biostratigraphic methodology most often is judged by the biostratigrapher’s gut feeling (which generally is synonymous with experience). Does the method seem to work? Does it give results that are within the realm of expectation?

Graphic correlation has been consistently unsurprising in its results, and where errors do occur, they usually represent more accurately real biostratigraphic ranges than the usually shorter sampled biostratigraphic ranges [see Edwards (1984, fig. 5)]. One of the major strengths of graphic correlation is construction of the composite standard reference section (CSRS). The CSRS does not exist in nature but is an ideal that is

a hybridized representation of the perfect stratigraphic section. By comparing real stratigraphic ranges against the CSRS, one can determine places where abnormally thick or abnormally thin lithologic packages occur [see examples by Christopher and Lagoe (1988)]. Either case becomes extremely important to the sedimentologic modeler who is attempting to determine synchronicity of depositional packages to the highest degree possible. Abnormally thin rock units in particular may be extremely difficult to recognize or evaluate (in terms of degree of missing time relative to other condensed or hiatal lithotypes) using sedimentology alone. Obviously, the better the CSRS, the better one can evaluate real sections against it. This is another area where paleontologists in industry are far ahead of most other biostratigraphers.

The second method, which we call morphometry-based biostratigraphy, is somewhat less used but has great potential because it represents a breakthrough in quality of the basic input data rather than yet another method to manipulate the same types of data that have been gathered for more than a century. The old computer adage "garbage in, garbage out" is a particularly good analogy here. As Williamson (1987, p. 53) stated so well, "Any biozonation, derived by whatever means, indeed any interpretation originating in paleontological data, can only be as good as the quality of taxonomy involved in specific determinations." In other words, biologically sound taxonomy is a prerequisite for all morphometry-based biostratigraphy. Any method that increases taxonomic resolution potentially will increase biostratigraphic resolution, but mathematical elegance cannot overcome biologic naïveté.

There are many different morphometric methods, such as cluster analysis, Fourier analysis, univariate statistics, bivariate statistics, and ordination techniques [see Jones (1988)]. Obviously, some morphometric methods are directly applicable to quantitative biostratigraphy. For the most part, however, morphometric methods have been used by paleobiologists to address questions of phylogeny, ontogeny, and evolutionary patterns in biota [e.g., Waters et al. (1985) and Wei and Kennett (1988)]. Nonetheless, they hold great potential in practical, geologic problem-solving applications because any increase in taxonomic acuity and fidelity will translate into better biostratigraphic interpretations. In their simplest form morphometric methods are used to recognize subtle changes in morphology of a given taxon through time or across different environments (i.e., ecophenotypes). These types of analyses must be done using populations of specimens and must be made using numerous measurements. If morphologic changes in populations are recognizable, quantifiable, and predictable, then population-based species, subspecies, or morphotypes (varieties) allow greater temporal acuity [e.g., Lagoe (1990)]; however, ecologic and growth constraints must not be ignored. Taxa that have large, relatively easily collectable populations (e.g., conodonts, foraminifers, diatoms) are particularly amenable to these types of analyses as applied to biostratigraphic problems.

Dependent time constraints and checks

Trace fossils One of the most useful aspects of trace fossils is that they almost invariably are found where they were formed. Thus the only taphonomic components of any importance are the diagenetic processes that may have acted on the sediment in which the trace was made. We do not mean to minimize this aspect because diagenetic changes can occur and do need to be recognized, but compared to body fossils, trace fossils are potentially much more useful for the recognition and differentiation of depositional environments.

We do not want to minimize the role of body fossils in detailed environmental reconstructions. However, it is vitally important to remember when dealing with body fossils that the last role they played before final burial was, in all probability, that of a sedimentary particle. As a sedimentary particle, their size, shape, and density were vastly more important than their biologic identity or ecologic requirements. When this is clearly considered, body fossils take on a useful role in environmental reconstruction, reconstructions vital to sedimentary modeling.

With careful examination it is not too uncommon to find body fossils associated with trace fossils, and when this occurs, the usefulness of the biotic component of the sedimentary unit under study is greatly enhanced. This is especially true when studies of body and trace fossils are combined with careful and detailed analyses of sedimentary textures and structures (process sedimentology). Indeed, it is important to include such process sedimentology with any and all ground truth studies of fossils if such studies are to be useful in sedimentary modeling.

For example, West and Matsumoto (1986, 1989) recognized a lateral transition from a quartz sandstone, possibly a *Skolithos* ichnofacies, to a *Glossifungites* ichnofacies preserved within a thin [2 cm (0.8 in.) thick], clayey, carbonate mudstone to a *Trypanites* ichnofacies represented by borings (trace fossils in hard substrata) and encrusting organisms (body fossils) on and in flat pebbles, cobbles, and shingles of a clayey, carbonate mudstone. This facies gradient occurs along a 1,200-m (3,900-ft) transect and provides additional support for the inferred paleotopography and land-sea relationships in this area at that time. Laterally, several kilometers away, this same interval appears to be represented by a fossiliferous, silty claystone to mudstone that displays properties suggesting a strandline accumulation of shells and a somewhat different type of coastline (Bisby, 1985).

In our studies of Carboniferous, particularly Pennsylvanian, trace-fossil assemblages, we have noticed that some ichnogenera occur together quite often. Indeed, sometimes a specific ichnogenus (e.g., a resting trace, such as *Lockeia*) occurs at the end of a different ichnogenus (e.g., a movement trace, such as *Uchirites*). We have found fossil shells of *Phestia*, a burrowing bivalve, associated with *Lockeia* at the end of *Uchirites* in beds of a very fine grained quartz sand-

stone (Maples and West, 1988). This led us to experiment with an articulated, partially open *Phestia* and a number of different substrates (fine sand, silt, and clay, both wet and dry). Preliminary results suggest that *Phestia* produced the *Uchirites* and *Lockeia*. Further investigation involved the careful observation of near-surface bivalves and other invertebrates on the fine sand and mud beaches of St. Catherine's Island at different intertidal positions and along tidal creeks. These observations suggest that what have been called different movement trace ichnogenera and ichnospecies may be a function of (1) the type of organism making the trace, (2) the rate of movement of the organism, and (3) the substrate grain size and/or sediment thixotrophy (i.e., as reflected by intertidal position).

Trace fossils, especially ichnofacies, also can be used as indicators of (and thus as correlative tools for) sedimentary processes, such as current regime and degree of wave dominance, all of which broadly correspond with water depth [for an excellent discussion of the ichnofacies concept as applied to water-depth interpretations, see Frey et al. (1990)]. Even processes that are difficult to quantify yet pervasive in their lateral extent, such as oxygenation, can be assessed using trace-fossil data, or, more preferably, trace-fossil data with body-fossil data [e.g., Savrda and Bottjer (1989) and Kauffman and Sageman (1990)].

A particularly useful and direct application of trace-fossil studies to any stratigraphic interpretation is in the recognition of flooding events (e.g., marine transgressions) in the absence of preserved marine shelly fossils [e.g., Rindsberg (1990), Savrda and Huchison (1990), and Savrda (1991)]. Furthermore, this application of trace-fossil interpretation can be done using outcrop data, outcrop and core data, or core data alone. Recently, using outcrop data, Maples and Suttner (1990) used trace-fossil distribution and sedimentologic analysis to recognize 12 transgressive-regressive events in virtually unfossiliferous siliciclastic sections of the Fountain Formation (Pennsylvanian) near Manitou Springs, Colorado. Other well-documented examples of this approach by George Pemberton and his students at the University of Alberta successfully interpreted subsurface Cretaceous tar-sand deposits (Wightman et al., 1987; Moslow and Pemberton, 1988; Vossler and Pemberton, 1988; Ranger and Pemberton, 1988, 1990). These examples in particular have demonstrated that a seemingly vast morass of uncorrelatable sand bodies can be understood as an ichnofacies mosaic that provides a basis for understanding the marine transgressive and regressive history of the region.

We feel compelled to sound one cautionary note in an otherwise harmonious orchestra. Recently, we have become aware of what we feel to be a misuse of trace fossils as applied to genetic and sequence stratigraphy. There is a tendency on the parts of many sedimentologists to equate degree and amount of bioturbation with rate of deposition (i.e., abundant bioturbation indicates low rates of sedimentation and little

bioturbation equals high rates of sedimentation). Variation in the extent of bioturbation, commonly referred to as ichnofabric or bioturbate texture [see Ekdale et al. (1984), Droser and Bottjer (1986), and Frey and Pemberton (1990)], is an extremely useful descriptive parameter for evaluating depositional environments. However, ichnofabric must be used in concert with good trace-fossil taxonomy, and where intensity of bioturbation precludes accurate ichnotaxonomic assignment, interpretations must be tempered accordingly. Although trace fossils provide powerful tools for recognition of marine transgressions (flooding surfaces), not all extensively bioturbated units indicate such marine events. This is especially true for post-Paleozoic rocks [see Maples and Archer (1989)]. As always, a modicum of common sense goes a long way toward a reasonable interpretation.

Event horizons and taphofacies One particular type of event horizon is the epibole. According to Bates and Jackson (1987, p. 218) an epibole is a synonym for an acme zone or for deposits that accumulated during a hemera. Hemera, from the Greek root meaning "day," was defined by Bates and Jackson (1987, p. 303) as a geologic time unit corresponding to an acme zone or the time span of the greatest abundance in a local section of a taxon. Thus event horizon, if used as a component of event stratigraphy (Seilacher, 1981), event stratinomy (Seilacher, 1984b), or event communities/species (Kauffman and Sageman, 1990), is synonymous with epibole, except that (1) horizon implies a two-dimensional feature (width and breadth), whereas epibole clearly implies three-dimensionality (width, breadth, and thickness or time), and (2) epiboles generally are limited to biotic or biotically influenced events [see also the discussion on epibole by C. H. Holland (1989)].

The importance and usefulness of this approach, that is, identifying and using event horizons or epiboles, is well demonstrated by recent studies on the classical Devonian sequences in New York (Brett, 1986; Brett and Baird, 1986). These studies have resulted in new interpretations of the stratigraphy, depositional environments, paleogeography, and sedimentation history of the Hamilton Group in New York (Brett, 1986). Brett and Baird's approach is similar to that described for the ichnofacies mosaic, except that event beds are recognizable over a much larger area; indeed, some can be traced across most of New York (Baird, 1979; Baird and Brett, 1983; Brett, 1986). The recognition and applicability of epiboles or event horizons to refining our stratigraphic understanding is well illustrated by a 1989 Paleontological Society symposium entitled "Paleontological Event Horizons: Stratigraphic, Ecological, and Evolutionary Implications," in which nine papers were presented on event horizons in the Ordovician, Devonian, and Recent, covering a geographic area including Georgia, Pennsylvania, New York, Ohio, and Indiana (Arens and Cuffey, 1989; Brett and Baird, 1989; Frey, 1989; S. M. Holland, 1989; Kirchgasser, 1989;

McGhee, 1989; Rollins and West, 1989; Schumacher and Shrake, 1989; Wolosz, 1989).

In our studies of the upper Pennsylvanian (Virgilian) of Kansas, we have recognized several possible epiboles. One such epibole is a concentration of the semi-infaunal bivalve *Myalina* (*Orthomyalina*) that Seilacher (1984a) classified as an edgewise recliner. Rollins et al. (1979) and West et al. (1990) have suggested that this genus occupied an ecologic niche more or less analogous to that of the extant oyster *Crassostrea* along tidal channels in marginal marine environments, that is, oyster banks or oyster biostromes. Living and dead individuals of *Crassostrea* (and by analogy, *Myalina*) are distributed by water movement, waves, currents, and tides. In the inferred setting dispersal of these valves will be dominated by tidal currents, but the area of dispersal will be greatly increased by storm surges. In the Stull Shale Member of east-central Kansas, a single bed of these bivalves, less than 30 cm (1 ft) thick, can be traced over an area of >150 km² (>60 mi²). At some localities there are articulated in situ individuals associated with hydrodynamically stable single valves. Single valves frequently display evidence of bioerosion and/or algal encrustation (Kansas State University Paleocology Seminar, 1989). Use of this *Myalina* epibole in regional mapping has resulted in recognition of heretofore miscorrelated lithostratigraphic units.

Feldman and Maples (1989) noted that syringoporoid tabulate corals occurred in several discrete horizons in the Sniabar limestone member (Pennsylvanian, Missourian), Kansas. These tiered colonies were interpreted to have spread out over a stabilized substrate during times of low sediment influx. Punctuated episodes of sedimentation resulted in nearly instantaneous smothering of the coral colonies; however, the covering layer of sediment was thin enough in places to leave a few corallites uncovered. These corallites, through asexual budding, gave rise to the next layer of the colony. Clearly, the greatest development of colonies occurred during episodes of low sedimentation (so-called background sedimentation rates). By applying these observations on a larger scale, Maples found through field mapping that one of the limestone beds in the Ozawkie–Avoca limestone interval (Pennsylvanian, Virgilian) in eastern Kansas contains a syringoporoid coral epibole that can be identified over an area larger than 200 km² (>80 mi²). A similar syringoporoid epibole occurs at the top of the Plattsmouth Limestone Member (Pennsylvanian, Virgilian), also in eastern Kansas, at the top of an oncolitic unit. In these examples areally extensive breaks or decreases in sedimentation can be recognized paleontologically far more easily than by using sedimentologic criteria.

Because most epiboles are, by definition, laterally extensive and distinctive, their potential in studies of cores is great and, in our opinion, underused. Indeed, epiboles can be used by field geologists in exploratory coring programs. For example, the presence of a Cretaceous oyster epibole in cores has been

found in the field to accurately predict stratigraphic positions of coal beds over an area of tens of square kilometers in western Colorado (C. G. Maples, unpublished data, 1981).

Another aspect of dependent paleontology, as we are using it, is the exciting and potentially useful taphofacies concept (Speyer and Brett, 1986). Taphofacies can be used to compare taphonomic features to discern differences and similarities among various depositional environments. The concept of taphofacies has grown out of the current interest in taphonomy and its importance in understanding fossils and their use in interpretation of the rock record [see Kaesler (this volume) for a more extensive discussion of taphonomy]. Brett and Baird (1986) published the seminal article on comparative taphonomy, and Speyer and Brett (1986) gave an example of taphofacies in the Middle Devonian of New York [see also Norris (1986) for an excellent example of sequence stratigraphy using taphonomic gradients]. Brett (1986) used taphofacies and event stratigraphy in a combined approach to reevaluate stratigraphy of the Hamilton Group (Middle Devonian) of New York. More recently, Speyer and Brett (1988) have expanded on their taphofacies concept with additional examples from the middle Paleozoic.

Summary

We have attempted to summarize, both philosophically and with real examples, some of the more direct applications of paleontology to sedimentary modeling. As Kaesler (this volume) has shown, the contributions of paleontology to sedimentary modeling are by no means limited to those we have discussed here. In general, we view the relationship of paleontologic data to sedimentary modeling in two broad categories: dependent and independent. Dependent paleontologic data are derived from biotic responses to environmental changes (e.g., recognition of marine flooding events using trace fossils). Independent paleontologic data are derived from taxonomy-based investigations (e.g., biostratigraphy). Paleontology is a tool with multiple functions in the toolbox of a good sedimentary modeler. In much the same way that a good mechanic would not attempt to repair an engine with just a screwdriver, so should good sedimentary modelers not confine themselves to one interpretive tool. Paleontology is not a panacea, but it can help and should be used.

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