

High-Resolution Geobiologic Time-Lines: Progress and Potential, Fifty Years after the Advent of Graphic Correlation

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ABSTRACT

Constructing a time-line of events in the co-evolution of life, climate and landscape demands less of data than correlating in detail all the stratigraphic sections that provide data. A wide range of information can be included without overstating the fidelity of any of it. Computer algorithms build global time-lines from thousands of local observations of stratigraphic superposition and supply explicit uncertainty statements about the position of each event in the time-line. Community databases and on-line search engines ease the compilation of data. There remains a need to analyze more stratigraphic sections for multiple fossil clades and to publish chemostratigraphic data more often against raw taxon range charts rather than derived biozone boundaries. Better algorithms would handle both unique and repetitive events.

TIME SCALES AND TIME LINES

The editors (Montanez and Isaacson, 2013) wrote of two developments for resolving ancient episodes of global change: analytical improvement in age determination and computational advances in sequencing events on a global scale. We review the simple logic of the computational advances, illustrate the wealth of information involved, and identify challenges that remain. Calibration of the geologic time scale benefits from both developments (Smith et al., 2014). Our title refers to time-lines rather than time scales to emphasize a more fundamental endeavor -- arranging in their most likely order as many ancient evolutionary, ecological, geochemical and geophysical events as possible. Numerical ages assist considerably in this sequencing task (Sadler, 2006), but the sequence of most events must be determined using local and conflicted evidence of stratigraphic superposition.

UNRELIABLE WITNESSES OF GLOBAL CHANGE

To reconstruct events leading to a crime, detectives compile time-lines from witnesses with incomplete recollections and unique vantage points. The composite time-line becomes far more complete and reliable than the recollection of the best witness. Similarly, geologists need composite time-lines (Fig. 1) to reconstruct global co-evolution of life, climate, and landscape. Our witnesses are local outcrops and well cores. Individually they are incomplete, fallible, and parochial (Kowalewski and Bambach, 2003; Erwin, 2006.). They routinely contradict one another concerning the sequence of species appearances and disappearances (Fig. 2A). Signals and noise mingle among these contradictions. Records of real ecological patch dynamics, biogeographic habitat shifts and evolutionary turnover are confounded by incomplete preservation and collection. We can mitigate local noise by including many neighboring sections, but painstaking and exhaustive local collection cannot resolve true origination, migration and extinction signals; that requires global coverage.

Fifty years ago, Alan Shaw (1964) published a method to deal explicitly with contradictory stratigraphic sections. Earlier biostratigraphers had sought exceptional taxon appearance or disappearance events that are typically recorded in the same order everywhere; using these, they divided geologic time into biozones. Realizing that local range-ends were *not* correlative, Shaw sought the earliest local first occurrence and youngest local last occurrence for each taxon. He projected information from all sections into the best of them to make a composite reference section. Shaw had experimented with graphic correlation as a petroleum geologist seeking to resolve controversial questions of diachronism. The attempt cost him his job (Shaw, 1995), but inspired a revolution.

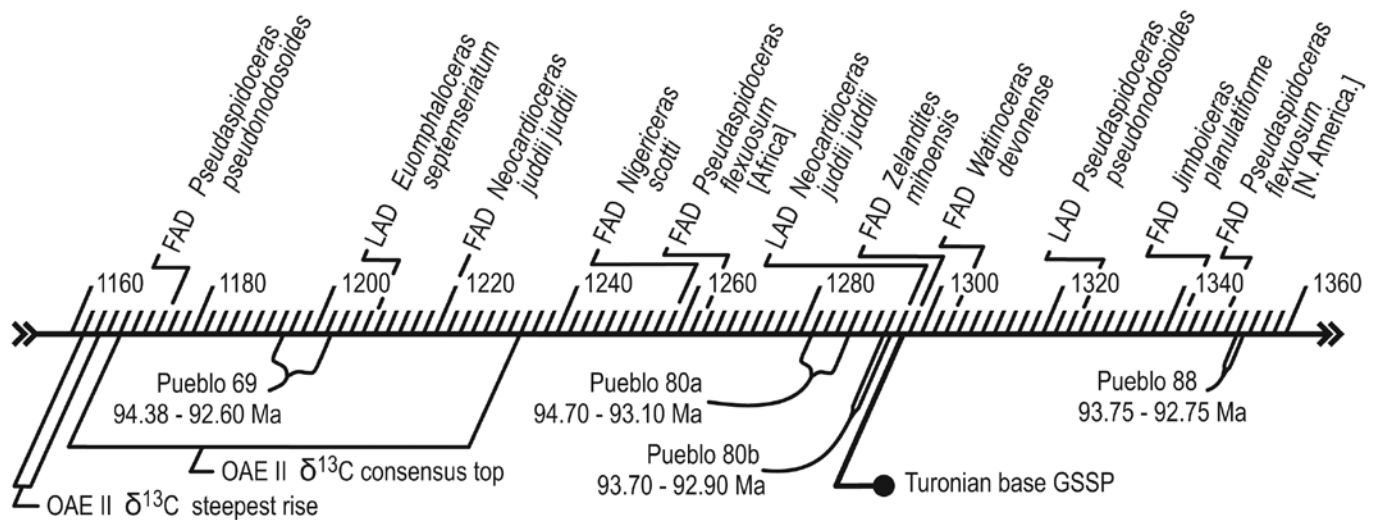


Figure 1: Key events in a fragment of a composite time-line for 1213 Albian through Maastrichtian ammonite species reported from two or more of 562 globally distributed locations, plus dated ash fall events and stable isotope excursions. FAD and LAD = first- and last-appearance datums. Fragment spans 200 of 2588 composite event levels, constrained by 15,205 local event observations. This time-line is purely ordinal – events are uniformly spaced, neither scaled by stratigraphic separation nor calibrated. After scaling, some neighboring events collapse to one level; their spacing is not resolvable.

BEYOND BIOZONES

Shaw shifted the focus from correlating sections to building composite time-lines. To appreciate his method, consider untangling figure 2A. Traditional biostratigraphy challenges us to cull the fewest tie-lines such that none of those remaining cross one another. Shaw changed the rules: keep all the tie-lines and find the smallest set of adjustments that removes all the crossings.

In fifty years since Shaw's book appeared, several key developments have made it feasible and urgent to build time-lines of global scope. 1) Event stratigraphy (Kauffman, 1988) increased the range of information we include. 2) Sequence stratigraphy (Mitchum et al., 1976) gave eustatic hiatuses a logical place in the sequence of range-end events (Holland, 2000). 3) Numerical algorithms (reviews by Tipper, 1988; Sadler, 2004) made the adjusting process faster, explicitly reproducible, and amenable to far more information. 4) Following Sepkoski's (1982, 1993) compilations, community databases and on-line search engines improved access to information. 5) On-going global change placed a premium on high resolution, total-data reconstruction of ancient global change.

The volume of stratigraphic information relevant to a global time-line is overwhelming and yet inadequate – insufficient to constrain uniquely the position of every event. This shortfall is no argument for culling: the set of equally good solutions leads directly to explicit uncertainty statements. Also, constructing a high resolution time-line makes more modest demands on data than correlating stratigraphic sections in detail. A section that contains too little information for correlation with other sections may, nevertheless, provide key evidence for the composite time-line – the only observation that two taxa coexisted, for example.

EXPLICIT UNCERTAINTY FOR INPUT DATA

Having chosen to adjust local event horizons rather than cull them, we need rules about permissible adjustments. These rules vary with event type. Geologists recognize a wealth of different types: first- and last-appearances of taxa, carbon isotope excursions, geomagnetic polarity reversals, ash fall tuffs, sequence boundaries, radioisotopic dates, and more. Fortunately, data input for the sequencing algorithms uses a small set of types (Sadler and Cervato,

2011), based on the expected fidelity of their observed stratigraphic position. Some events, like a dated ash fall tuff, are sampled at the correct level and are not adjustable; the local datum is “nailed” in the sense it may be removed, but not moved. Local first appearances of taxa most likely lie above the horizon deposited at the time of true evolutionary appearance (FAD) or even local immigration; they belong in a category of events that may be adjusted downward only. Local last occurrences may be restricted to upward adjustment or, if reworking is suspected, a category that may be adjusted up or down section (at higher cost for downward adjustment; Cody et al., 2008).

Many input events are paired. Ends of a local taxon range are a pair that may be stretched farther apart to fit the composite sequence. Imagine them separated by a jack (Fig. 3); then Shaw's method minimizes mechanical effort of adjustment. Other events need a conservative uncertainty interval that shrinks to fit, with mechanical effort represented by a clamp (Fig. 3); examples include segments of stable isotope excursions, seismic reflectors projected into a well, and locations of paleomagnetic reversals between samples of opposite polarity. Events are treated

as clamps, jacks or nails in order to include as much information as possible without overstating the fidelity of any of it.

MEASURES OF FITNESS

The sum of all necessary adjustments measures the fitness of hypothetical time-lines. In usefully large data sets (Table 1) the number of local observations of pairwise event superposition becomes dauntingly large, but programs like Graphcor (Hood, 1986) and Sinocor (Fan and Zhang, 2000) partially automate the task of minimizing adjustments. A different measure of fitness counts the number of implied global coexistences of taxa that have not been observed locally. Minimizing this count generates time-lines from sections and samples that do not overlap in time. This approach is commonplace in archaeology, was adopted as ecostratigraphy (Cisne, 1978) and has been fully automated by the Biograph (Guex, 1991) and Conjunction (Alroy, 1992) programs. Coexistence of two taxa means that both first appearances must precede either last occurrence. Thus, programs can readily incorporate both superposition and coexistence constraints; e.g. Constrained Optimization (Sadler and Cooper, 2003), Appearance Event Ordination (Alroy, 1994) and Horizon Annealing (Sheets et al., 2012).

EXPLICIT UNCERTAINTY FOR TIME-LINES

Figure 4 illustrates three options for uncertainty statements. For time series output, such as histories of taxon richness (Fig. 4A) or turnover, superimpose the results from a number of equally best-fit time-lines (e.g. Shen et al., 2011). For each event, report a best fit interval that spans all positions occupied by the event in the set of best fit time lines (e.g. taxon range ends, Fig. 4C) and add relaxed fit curves (Sadler and Cooper, 2003) to show how fit deteriorates beyond that interval. Support for the composite range of a taxon (Fig 4B) can be represented as a count of the contributing local ranges, mapped into the time-line to reveal diachronism; this also exposes erroneous outliers and disjunct ranges (Sadler, 2010).

CHALLENGES FOR ALGORITHMS

Taxon ranges have loose stratigraphic fidelity, but taxa are inherently unique. Isotopic excursions, seismic sequence boundaries, and paleomagnetic reversals have better fidelity (Cooper et al., 2000; Cramer et al., 2010), but are repetitive events, whose unique matching requires associated taxa or runs of events with distinctive spacing. Currently, this kind of

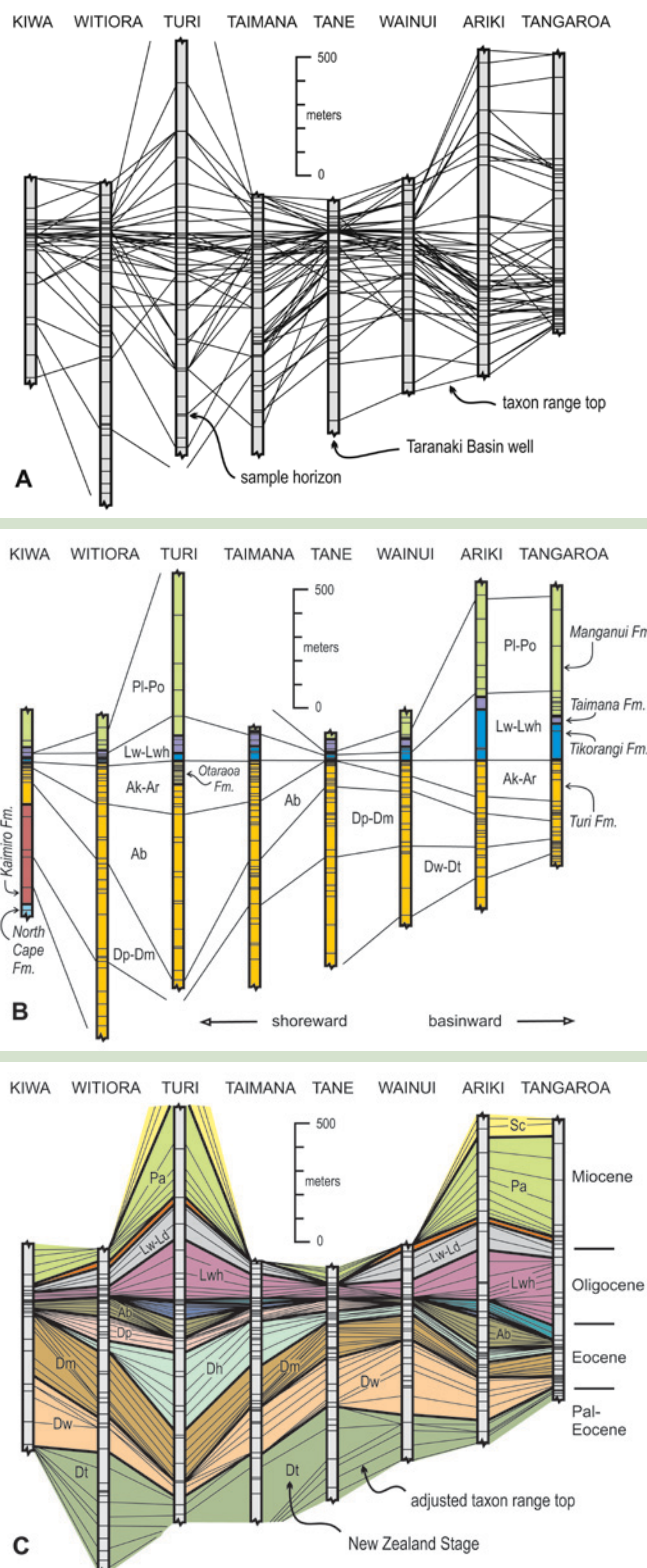


Figure 2: Correlation of foraminifera, nannofossils, dinoflagellates, spores and pollen from 8 wells in New Zealand's hydrocarbon-producing Taranaki Basin. **A:** Literal correlation of range tops of the 87 most reliable of 351 taxa prepared during the Cooper et al. (2001) study and older biostratigraphy. Range bases were potentially compromised by borehole caving. **B:** Lithostratigraphy and traditional biostratigraphic correlation prior to 2001 study. **C:** Outcome of automated correlation to a fully-resolved, composite, scaled time-line by minimal adjustment of observed ranges and insertion of missing taxa (Cooper et al. 2001). New Zealand stages explained in Cooper (2004).

matching must be undertaken before data entry and/or tested through successive and progressively specified iterations of analysis. Better algorithms would match repetitive events and optimize sequences of unique and repetitive events in one pass. Horizon annealing may have the best potential for this (David Sheets, personal communication). As data sets grow, there is always a premium on faster algorithms. The Geobiodiversity Database managers in Nanjing are pursuing faster solutions in partnership with commercial programmers (Fan Jun-Xuan, personal communication).

DEMANDS ON DATA

Constraining power derives from pairs of events known from the same section so that superpositional information exists for them (“constraint” column in Table 1). This information is typically weakest between taxa of different clades, preserved in different facies or prepared by different techniques. More robust time lines need more stratigraphic sections sampled for multiple clades (Cramer et al., 2010). Chemostratigraphic data should be published wherever possible against raw taxon range charts rather than derived biozone boundaries. Databases of fossil biotas should supply evidence of physical stratigraphic superposition, not simply assign zones or stages.

A FUTURE

Once upon a time, Amoco committed resources to continual maintenance of a grand Phanerozoic time-line. We might plan for a future in which sequencing the fossil record passes from the hands of individuals to community search engines and distributed computing tools. Human expertise can focus on quality control.

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Case History	Sections or Localities	Taxa	Other Events	Local Records	Constraints	Method*
Three Estonian Hirnantian Clades (Fig. 3)	7	9	6	27	?	
Plio-Pleistocene Omo Group Mammals (Alroy, 1994)	29	109		720	?	A
Cambrian Trilobites of S. California (Webster et al., 2003)	88**	76	55	879	1,064	Cp
Late Cretaceous dinoflagellates (Crampton et al., 2006)	15	245	0	891	5,521	Cp
Taranaki Basin, culled (Fig. 2) (Cooper et al., 2001)	8	87	0	1,018	6,129	Cp, G, R
Antarctic Neogene Diatoms (Cody et al., 2008)	33	191	59	3,064	17,168	Cp
Taranaki Basin, before cull (Fig. 2) (Cooper et al., 2001)	8	573	0	3,276	133,065	Cp
Three Baltic Silurian Clades (Sadler, 2012)	82	696	119	4,229	60,315	Cp
Permo-Triassic of Peri-Gondwana (Shen et al., 2011)	20	1,450	39	4,322	251,662	Cp
Ordovician-Silurian Conodonts (Sadler & Sabado, 2009)	276	1,312	33	12,773	83,763	Cp
Albian-Maastrichtian Ammonites (Fig. 1)	562	1,213	162	15,215	348,888	Cp
Four Sandbian-Aeronian Clades (Fig. 4)	414	1,018	139	17,465	122,331	Cp
Global Graptolite Clade (Cooper et al., 2014)	519	2,117	196	22,006	378,215	Cp
North American Land Mammals (Alroy, 2000)	4978	4,484	186	?	724,487	A
Moroccan Devonian Ammonoids (Monet et al., 2011)	15	53	0	>165	?	B
Global Marine Cretaceous (Scott, 2014)	~300	>3,500	many	?	?	G

Table 1: Scope of some published composite time-lines.

* A = Appearance Event Ordination; B = Biograph; Cp = Conop; G = Graphcor; R = RASC

** includes individual museum slabs

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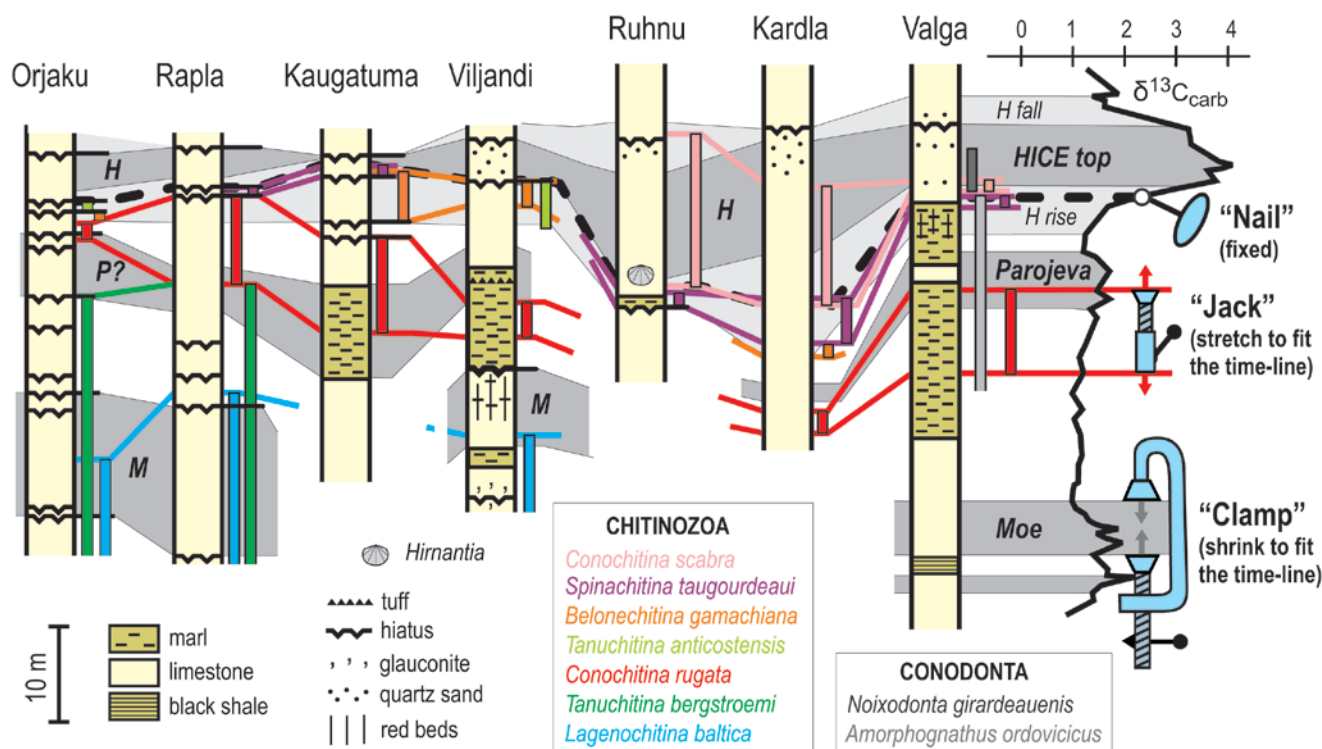


Figure 3: A tiny fraction of end-Ordovician (Hirnantian) information: 9 taxon ranges and 3 stable isotope excursions constrained by 92 local event observations from 7 Estonian cores (Kaljo, et al. 2004, 2008; Ainsa et al., 2010). To align all cores with one sequence of events, some observed event pairs may be jacked farther apart (e.g. taxon range ends); others may be clamped closer together (e.g. uncertainty intervals on parts of stable isotope excursions); and some must be left in-place – the nailed horizons of steepest onset (thick dashed line) of the Hirnantian Isotopic Carbon Excursion (HICE).

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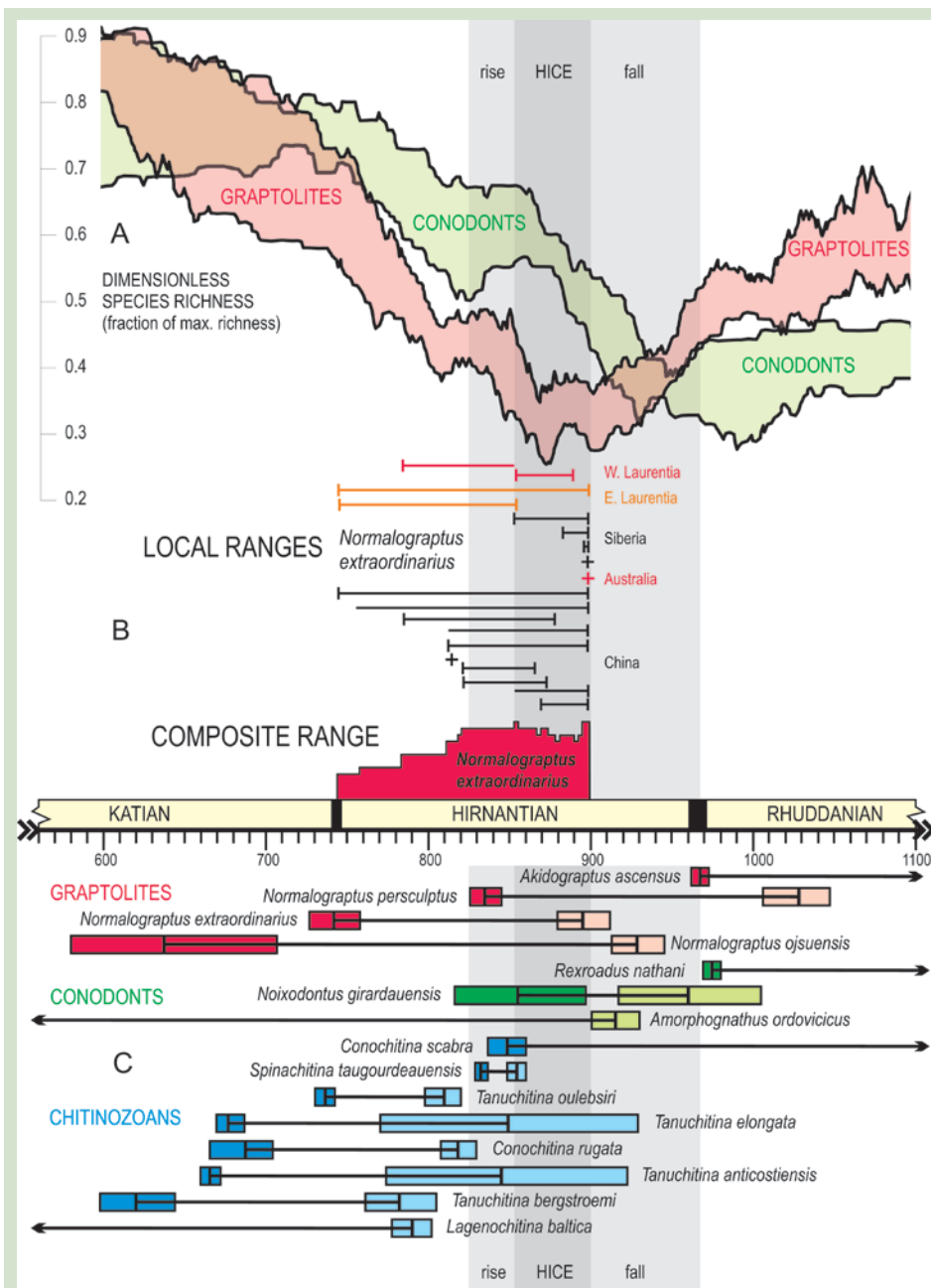


Figure 4: Some uncertainty statements for Hirnantian time-line of 1018 taxa (graptolites, conodonts, chitinozoans and acritarchs) known from at least three of 414 localities, constrained by 17,465 local event observations. **A:** Range of species richness curves derived by superimposing six different optimization outcomes. **B:** Support for a composite taxon range as number of local ranges contributing to different parts. Local ranges reveal patterns of diachronism. **C:** Best-fit intervals (colored rectangles) for ends of composite ranges of selected index taxa; rectangles span all positions taken by range end in set of equally best-fit time-lines (based on thousands of the millions of trial sequences tested during six optimization runs). Overlapping best-fit intervals explain the large set of equally best-fit time lines; the differences are generally small and local, but the number of combinations is vast.

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