Chapter 6

Stratigraphic Unconformities: Review of the Concept and Examples from the Middle-Upper Paleozoic

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Additional information is available at the end of the chapter

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Abstract

Only about 10% of geologic time is imprinted in sedimentary strata and the rest is hidden in non-depositional or erosional surfaces called unconformities. Stratigraphic unconformities (disconformities) are principal bounding surfaces in sequence stratigraphy, which a geologist would easily identify in the outcrop but frequently overlook in the subsurface unless core is available. The proportion of disconformities that are misidentified or overlooked in subsurface stratigraphy is quite large, which puts a warning sign on simplistic sequence stratigraphic models. The amount of time imprinted in disconformities can be evaluated using relative weathering maturity of the subaerial profile, cyclostratigraphic calibration, absolute dating, and biostratigraphy. However, using biostratigraphy alone is never enough as biostratigraphic gaps tend to fill with increasing data coverage. Identification of paleo-vadose zones and subaerial exposure profiles is regarded as critical for finding stratigraphic unconformities and is the only approach in strata where geophysically mappable fluvial systems are absent. Drowning unconformities are carbonate platform drowning surfaces that usually produce distinct reflection horizons and have better stratigraphic value in the subsurface than platform-embedded subaerial unconformities. This discussion is supported by examples of subaerial disconformities from the Devonian, Carboniferous, and Permian of Canada and Russia and with an example of a geographically extensive mid-Devonian drowning unconformity from Northwestern Canada.

Keywords: disconformities, paleosols, paleokarsts, vadose alteration, erosion, drowning unconformities, sequence stratigraphy, subsurface identification

1. Introduction

1.1. Definition of the subject

It is generally accepted that only about 10% of the geologic time is recorded in the sedimentary rocks, whereas 90% is collapsed into non-deposition, alteration, and erosion surfaces collectively called unconformities [1]. Of these diverse surfaces with time value ranging from minutes to hundred millions of years, only those of practical use, that is, traceable on a scale exceeding one outcrop and marked with distinct diagnostic features are discussed below.

1.2. Growth of the concept

This subheading, borrowed from Dunbar and Rodgers [2], brackets 230 years of unconformity research counting from recognition of an angular unconformity in late 1780s [3]. The word *unconformity* was adapted from German geology 3 decades later [4, p. 48] and until the mid-nineteenth century pertained to angular stratal discordances. Awareness of geologic time gaps between parallel bed sets, normally accompanied by signatures of erosion, emerged in late nineteenth century (e.g., [5]) under the influence of Charles Darwin's conclusion on the principal incompleteness of the stratigraphic record [6]. As most recently reviewed by Miall [1, 7], such stratigraphic breaks between parallel strata were classified into "unconformities Type a" by Blackwelder [8] and shortly after that named *disconformities* [9]. The other two types of unconformities of Blackwelder [8] were (b) contact between rocks of wholly unlike origin (for example, sandstone resting upon granite); and (c) angular discordance of beds with or without difference in lithologic character. Type (c) is the classical *angular unconformity* of James Hutton, and type (b) was named *nonconformity*. The latter term was coined by Pirsson and Schuchert [10] and refined into modern usage by Dunbar and Rodgers [2]. Surfaces between parallel bed sets recording time gaps but not bearing signs of erosion were named *paraconformities*, as opposed to erosion-marked *disconformities* [2]. However, the difference between the disconformity and paraconformity more often appears in the ability to recognize erosion and evolves with tools and methods. Here, the term stratigraphic unconformity is used as an equivalent of disconformity. Barrell [11] also coined a term *diastem* that became adapted for the time value of a sedimentation gap at an unconformity. Being most easily identified features, angular unconformities and nonconformities are excluded from further discussion.

Disconformity-bounded packages of sedimentary rocks, called cycles, cyclites, cyclothems, allostratigraphic units, and most commonly sequences, remained in focus for many decades, generating an impressive development of concepts, terminology, and discussion on local vs. global controls of base or sea level fluctuations [1, 2, 12–24]. It should be noted that sequence stratigraphy significantly expanded definition of sequences by including both disconformities and their correlative surfaces (conformities) in more complete basin-centered sections [14]. Sequence stratigraphy is reviewed in this book but is not the focus of this contribution.

2. Disconformities at seismic resolution

Disconformities mostly show concordant stratal relationships below and above the surface. They are identifiable on seismic sections if the subaerial exposure allowed for development of significant relief and/or seismic-scale incised fluvial channels [20, 25]. Incised valleys form during base level fall and become filled when base level rises [26]. Fluvial incisions are deeper and favorable for seismic mapping where they cut into an uplifted plain (**Figure 1A**), plateau, or across a shelf break (**Figure 1B**), but may not be identifiable in paleo-hinterlands with a shallow base of erosion. Transgressive tide and wave abrasion of coasts, estuaries, and shoreface are able to modify the configuration of subaerial surfaces and any terrestrial sediment accumulated on it. The surfaces produced by such an abrasion are called ravinement surfaces [17, 22, 23]. The depth of transgressive erosion greatly varies depending on induration of the exposed sediment, on the wave and tide energy of a transgressing sea, and on the slope angle of the eroded sediments. While oceanic abrasion may cut down to tens of meters into seashore cliffs, plain lands characteristic of epicontinental sedimentary environments may show negligible transgressive stripping and delicate topsoil parts of weathering profiles largely preserved (e.g., [27]).

Seismic and hands-on-rock unconformities are not the same, and the proportion of false seismic unconformities is greater than was thought by Vail et al. [15]. Situations where time lines converge into a condensed section but portrayed as an onlap-offlap surface, or pseudo-unconformities envisioned from a surface of major lithological contrast, are very common misinterpretations [30, 31]. Difficulty in recognition of subaerial unconformities in the subsurface led to proposal of an alternative *genetic stratigraphic sequences* bounded by "maximum flooding surfaces" or condensed sections [16]—however, the concept of very limited use today.

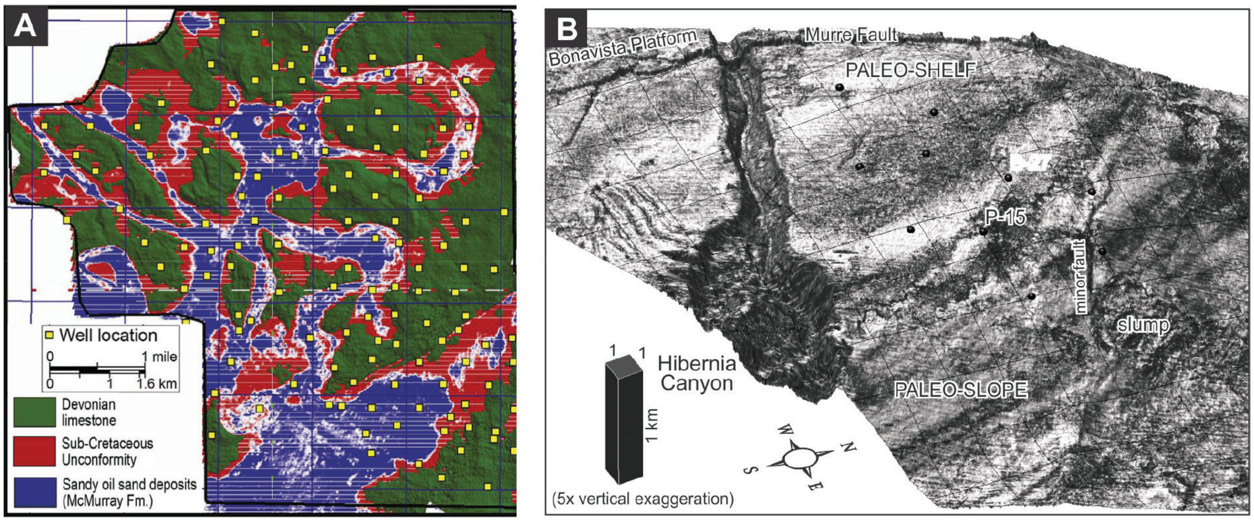

Figure 1. Examples of mature unconformity surfaces with fluvial incisions visualized in 3D seismic models: (A) A 225 m subsurface slice (above sea level) along sub-Cretaceous unconformity visualizing high-sinuosity channels cut into weathered Devonian limestone, eastern Athabasca oil sands, Alberta (formally modified from [28]). (B) Hibernia Canyon cut through shelf edge during latest Campanian-earliest Danian (Cretaceous-Paleocene), Jeanne d'Arc Basin offshore Newfoundland, formally modified from Deptuck et al. [29].

Disconformities are also invisible with conventional seismic surveys in carbonate successions if (1) no reef crest or carbonate mound relief was produced in slowly subsiding platform setting; (2) transgressive carbonates deposited upon regressive carbonates with no impedance contrast produced; (3) sequences are thinner than reading resolution at a given pulse frequency; (4) fluvial channels or sufficient erosional relief did not develop and drainage of meteoric waters was entirely underground; and (5) stacked karst systems from successive paleo-aquifers overprint with no chance to trace particular karst horizons. The best present-day example of a carbonate plain where the day surface has a chance to be buried in such a hidden way is the Nullarbor Plain of Southwestern Australia [32]. This vast (~240,000 km^2) plain was exposed for the last 14 My since mid-Miocene time, yet remains exceptionally flat and riverless with extensive underground cave systems produced during several Tertiary lowstands, including the ongoing uplift [33].

3. Evaluation of hiatuses

Most terrains show a relief or a slope gradient where prolonged flooding is recorded in onlap patterns, as opposed to geologically momentary (rapid) inundation of plain lowlands. Hiatuses therefore tend to wedge toward basin centers on chronostratigraphic charts [15], as demonstrated by case studies where unconformities receive cross-basinal biostratigraphic control [29]. Hiatuses reveal more complex histories in settings of differential subsidence in areas of large-scale salt diapirism or in tectonically active regions (e.g., foreland flexural bulging and tilting). The eustatic vs. tectonic control over transgressions and regressions is a subject of long-lasting debate [13, 20]. Tectonic control of an unconformity between two parallel bed sets can be interpreted where unconformities show poor or no correlation to major lowstands of "global sea level curves" or where the hiatus is diachronous with bedrock and caprock younging in the same direction. For example, a major intra-Cretaceous disconformity of central-southern Italy is generally younging eastward from Late Albian to Late Turonian—earliest Coniacian as revealed with refined biostratigraphic control [34]. This unconformity hosts karst-associated economic bauxites and is locally composite with two bauxitiferous paleokarsts divided by Cenomanian limestone of various thickness and time value. This diachroneity was interpreted as the translation of the lithospheric bulge in response to compression from the distal orogeny along the Adria Plate margin [34].

Biostratigraphy is the oldest yet still master method of recognizing hiatuses by missing zones, which can be processed with a graphic correlation technique [7]. Other absolute dating methods like U-Pb ID-TIMS and cyclostratigraphy are reviewed in [7, 35]. Resolution of biostratigraphy varies with the group employed, paleogeographic position, and the geologic age. The latter controls biostratigraphic resolution to a significant extent by cosmopolitism vs. provincialism of marine faunas. High cosmopolitism is characteristic of greenhouse periods with circum-tropical seaway connections, whereas provincialism is favored by forcing of the Earth into icehouse mode and shutdowns of low-latitude seaway connections, as likely happened during Pennsylvanian-Permian assembly of Pangaea [36, 37].

Noteworthy here are historically recognized but apparently non-existent disconformities. Usually, these "legacy hiatuses" heavily rely on biostratigraphy. An example is given by the "Late Middle Devonian unconformity" of the Mackenzie Corridor of Northwestern Canada. This unconformity was interpreted by Hume and Link [38] from the sharp thickness fluctuations and restricted spatial distribution of the Hare Indian and Ramparts formations, which was seen as a result of erosion prior to deposition of the black siliceous shale of the Canol Formation (**Figure 2**; [46]). A debate on the validity of this hiatus lasted ever since. The hiatus has been supported by the assignment of the upper Hare Indian Formation to the undifferentiated *varcus* conodont zone (=*rhenanus-ansatus* in **Figure 2**), whereas the lower part of Canol Formation was dated by conodonts as the Lower *asymmetrica* (≈*transitans-falsiovalis* on **Figure 2**) with speculative extension of the Canol base into the lowermost *asymmetrica* or present-day *norrisi* zone [39, 40]. *Hermanni-disparilis* interval was allegedly missing (**Figure 2**). However, scarce conodont data from the Ramparts limestone suggested its age range from the upper Hare Indian equivalent

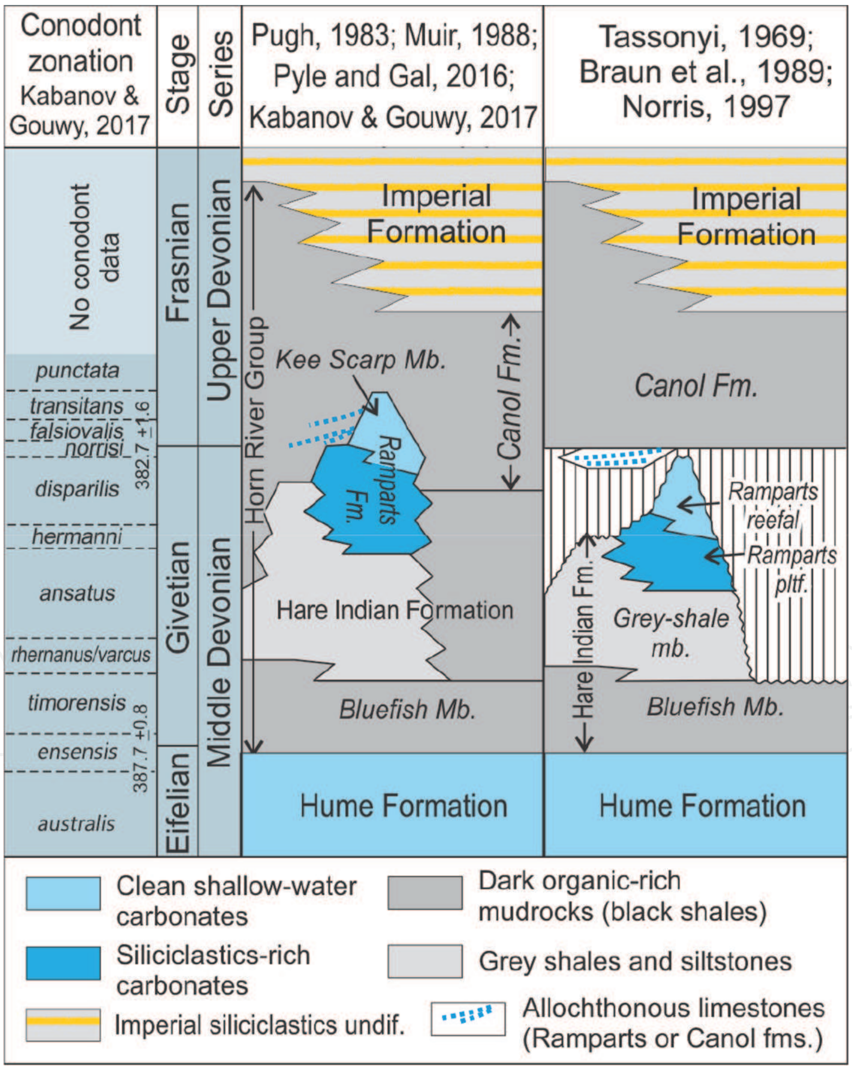

Figure 2. Legacy "Late Middle Devonian unconformity" on a simplified table of formations of Mackenzie Valley and Peel area; the unconformity advocated (right column) vs. discarded (left column).

to the *asymmetrica* zone [41]. Other workers argued that the Canol base is a conformity [42, 43] and indicated Ramparts-Canol interfingering in allochthonous debris units [41]. Nevertheless, this hiatus survived in the territorial table of formations until recently [44]. Decisive in retiring this hiatus are (1) updates in conodont data showing Canol base time gliding from the Frasnian *transitans-punctata* on top of Kee Scarp carbonate banks to the upper Givetian *norrisi* in off-bank depressions [44]; (2) carbonate-bank slope depositional setting of allochthonous bioclastic debris interfingering with laminated black shales; and (3) absence of any evidence of subaerial exposure or vadose processes, like oxidation of pyrites and organic matter and characteristic redistribution of Fe and Mn, prior to the onset of Canol deposition [45].

An absolute majority of disconformities are subzonal or do not bear index fossils immediately below or above. Relative proxy for the duration of a hiatus is the maturity of a paleosol profile, e.g., progression from entisols to any of mature soil profiles defined by soil taxonomy [47], or stages of calcrete development [48], but the ability to deconvolute time is quite limited: paleosol appearance is a multivariate product of exposure duration, precipitation regime, temperature, relief, availability and type of vascular vegetation (and other soil biota), and transgressive truncation, with variable masking of paleonvironmental signals by burial diagenetic overprints. Most tools of radiogenic dating used to reveal soil age are not applicable to deep-time examples because of short isotope decay lifetime. U-Pb dating of soil carbonates, based on U adsorbed in calcite lattice, was demonstrated to provide quantitative estimate of pedogenic processes as old as Carboniferous [49, 50]. Also, the production of He isotopes by α-decay of U, Th, and their intermediate decay species was used to develop a (U-Th)/He geochronometer that is able to date materials in the range of a few thousands of years to 4.5 Ga (see review in [51]).

4. Paleopedology and paleoaquifer studies

Soils blanket most of the terrestrial landscape [47]. As approximated by Landsat-based NARWidth model of North American river surface, only about 0.55% of the continent is covered with rivers [52]. This model includes measurements of rivers that are ≥30 m wide and extrapolated estimate of streams that are 1.6–30 m wide. Natural lakes and reservoirs excluding human-made impoundments cover about 3% of the World's land surface [53]. Therefore, at this momentary snap of the geologic time, it appears that no less than 96% of the land terrain is exposed above permanent water level if timed back to pre-industrial landscape. This emphasizes the high probability that a geologist will encounter in particular section a subaerial unconformity with a paleosol or what is left after its transgressive erosion, rather than non-pedogenized fluvial or lake sediments (**Figure 3**). This considers paramount importance to recognition of paleosols, regoliths, and former meteoric aquifers, although these are usually subtle features masked by diagenetic alteration and not readily picked with geophysical surveys.

Recognition of fossil soils in pre-Quaternary strata commenced early in nineteenth century with description of "dirt beds" with fossil wood stumps in the Upper Jurassic of the Dorset Coast

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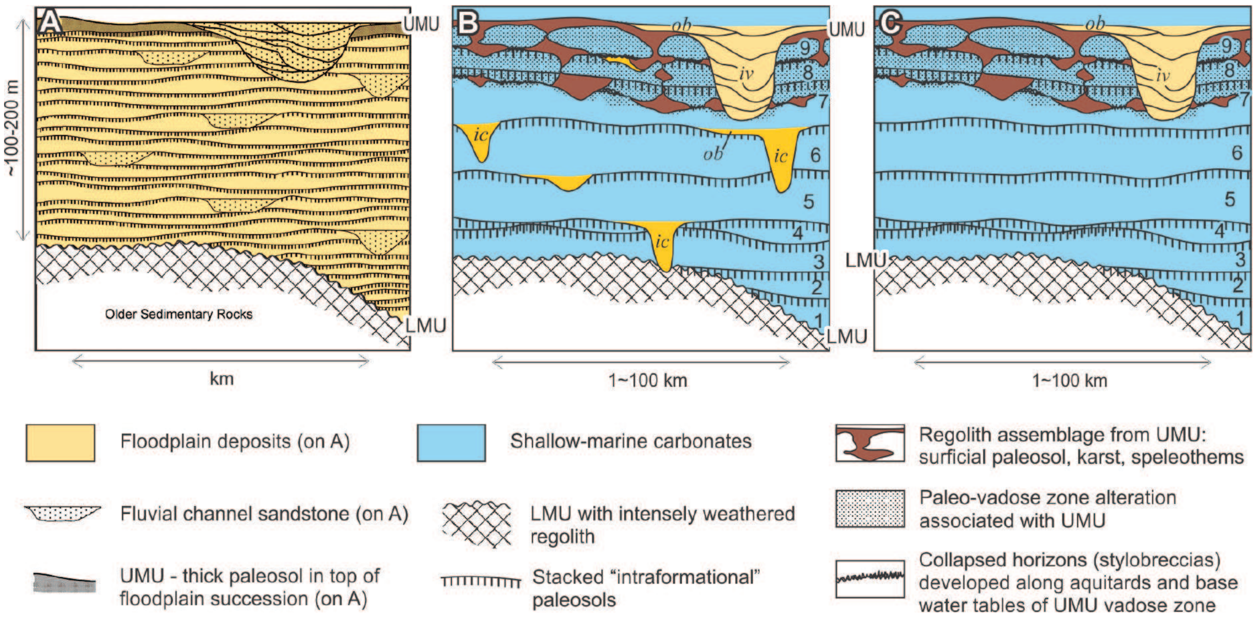

Figure 3. Conceptual expression of disconformities: (A) in floodplain succession, formally modified from Kraus [54]; (B and C) in shallow-marine carbonate succession; (B) deposited under wet climate with precipitation sufficient for open stream drainage; (C) deposited in drier climate with underground karst drainage. Paleo-vadose zones associated with "intraformational" unconformities (not shown here for simplicity) extend to various depth beneath paleosols, depending on base level fall, and frequently overprint; lower major unconformity (LMU) and upper major unconformity (UMU); incised fluvial channels (ic); a deep incised valley (iv) developed from UMU; and overbank (ob) floodplain deposits. Units in (B) and (C) bounded by disconformity surfaces are numbered; note that depending on researcher's knowledge, they may be described as sequences if subaerial unconformities are adequately characterized, as parasequences if surfaces known but their genesis is uncertain, or merged in one sequence bounded by LMU and UMU if surfaces remain below resolution with available tools.

[55–57]. Paleopedology (study of fossil soils) is a discipline nursed on soil science, specifically Quaternary soil chronosequences [58] and later expanded back in the geologic time, even to other planets, with adsorption of geologic and biotic evolutionary concepts [47, 57]. A short glossary of basic concepts is given below.

- **Paleosol** is an ancient soil or part of it that has been imprinted in the stratigraphic record [47, 51]. Soil is defined as (1) the medium rooted and modified by vascular plants (narrow pedologic definition; e.g., [59]) and (2) biologically and chemically active "excited skin" of the subaerial part of the Earth's crust (broad pedologic definition; [60]).

- **Regolith**, first defined by Merrill [61], refers to all the continental lithospheric materials above fresh (non-weathered) bedrock and including block of fresh rocks where they are interbedded with or enclosed by unconsolidated or weathered rock [62]. Regolith mantles the fresh rock and consists, from base to top, of saprock (patchily weathered rock), saprolith (pervasively weathered rock), and the soil (or paleosol in buried examples) where pedologic horizons are recognized [62]. The word *regolith* is also employed to describe weathered rock mantles of other planets and pre-land biota Earth [47]. The concept of *regolith* is sometimes considered vague, and in situ regoliths are taken as equivalent to soil *s.l.* [57].

- **Weathered crust** is a retiring wordage still in use in some geological schools of the World; it is applied to different scale features from thick lateritic mantles with bauxites to alteration rinds on pebbles; mantle-scale weathered crusts are equivalent to *in situ* regoloths *sensu* [62].
- **Meteoric vadose and phreatic zones.** Vadose zone applies to the diagenetic environment lying below the land surface and above the zone of saturation or water table where pore space contains both water and air (soil gas); rainfall waters percolate downward developing vadose patterns of dissolution, reprecipitation and alteration of host sediment. Meteoric phreatic zone applies to aquifer of permanent saturation below the water table and is divided from the vadose zone by a capillary fringe [63]. Concept of vadose and phreatic zones is employed to describe carbonate aquifers, subaerial alterations, and karst systems.
- **Aquifer** is a rock formation saturated with groundwater that is porous and permeable enough for sufficient debit to wells and springs; related are *aquicludes* and *aquitards.* Aquiclude is saturated but do not transmit groundwater; *aquitard* is a low-permeability or impermeable rock formation, usually strata, that confine water flow.
- **Critical zone** is a young concept referring to near-surface environment in which complex interactions involving rock, soil, water, air, and biota regulate the natural habitat and determine availability of life sustaining resources [64]; near-surface terrestrial environment in which resource availability is determined by interactions between the biosphere, geosphere, and atmosphere [51]; includes regolith, within- and below-regolith aquifers, fluvial systems, soils, and vegetation up to tree canopy [65].

Under different climate and hydrologic regimes, soil-forming processes create diverse soil profiles described by national and international soil classifications. The North American soil taxonomy [66] is the one that has earned greatest recognition in paleopedologic studies [47, 51]. Diagnostic criteria for pre-Quaternary paleosols and instrumental proxies for landscape and climate reconstructions are reviewed in [47, 51, 54, 67, 68].

Diagnostics of subaerial exposure profiles and paleokarst systems in carbonate rocks (**Figure 3B**, **C**) were developed by sedimentary geologists as a parallel story to paleopedology, which was driven by economic importance of karst as (1) hydrocarbon reservoir-making factor and (2) a host for bauxite [34] and rare metal accumulation [69]. This move has generated very practical terminology focused on horizons of high preservation potential, first of all caliches (calcretes) and paleokarsts, with various degree of reconciliation with the soil science lexicon [48, 69-71].

5. Drowning unconformities

Drowning unconformities are "maximum flooding surfaces" (= drowning surfaces *sensu* Posamentier and Allen [17]) specific for carbonate platforms.

In the subsurface, drowning unconformities usually make good seismic reflectors with basinal strata onlapping carbonate slopes and platform tops [72]. On the outcrop or core face, these contacts are characterized by condensed sections (e.g., shell concentrates) and non-deposition

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surfaces with hardgrounds sometimes impregnated with phosphate and/or glauconite [73, 74]. The surface of a drowned carbonate platform can be table-flat, rimmed by a reef crest (empty-bucket configuration), or outgrown with backstepped carbonate mounds or "pinnacles" [31, 75]. Drowning unconformities are within-trend drowning ("flooding") surfaces in sequence stratigraphy [20]. Fundamental genetic difference from subaerial unconformities renders certain reluctance in accepting them as formal sequence boundaries (e.g., [76]). However, drowning surfaces are more practical in subsurface surveys as they produce vivid onlap pattern on carbonate slopes and sharp impedance contrasts, in difference to feeble expression of subaerial disconformities embedded in carbonate platforms. Also, submarine corrosion can mimic subaerial karst to some degree, complicating its workflow recognition and leading to misinterpretations. These considerations led to proposal to legalize drowning unconformities in sequence stratigraphy as *Type 3 sequence boundaries* [18, 31].

Factors leading to demise and drowning of carbonate platforms are rapid relative sea level rise and/or carbonate production shutoff by eutrophic turbid waters, either loaded with siliciclastics or upwelled from deep ocean [72, 74], but these factors can only smother photozoan or tropical carbonate factories (*T-factories*; [31, 77]). Non-actualistic mud-mound carbonate factory can likely produce thick carbonate buildups in dimmed or aphotic settings and at elevated nutrient levels (*M-factories*; [31, 77]). Drowning unconformities are usually produced in settings of tectonic subsidence, e.g., in extensional rifted basins [78] or foreland basins [79–81]. It remains unclear to what extent high-amplitude eustatic rise of sea level, without aid of other factors, is capable of shutting off carbonate platforms. Another factor is the slowdown in ocean circulation under greenhouse condition of the Earth or even shutdown of thermal ocean circulation under extreme hothouse condition [82], which should lead to lateral expansion and shallowing of the oxygen minimum zone in the ocean (OMZ; [83]). The OMZ under such conditions should develop a thick and permanent euxinic environment in its core and should be able to rapidly shut down benthic carbonate factory across broad expanse of an ocean-facing carbonate shelf even in tectonically quiet setting. Such OMZ expansions are seen as the condition imprinted in severe form in oceanic anoxic events [84]. Possible link between synchronous and widespread demise of carbonate platforms and oceanic anoxic events has been indicated based on the Cretaceous "Selli event" (OAE 1a; [85]). Even during icehouse epochs, anoxic waters similar to those in present-day eastern tropical pacific OMZs were likely able to encroach far into interiors of epeiric seas during interglacial highstands and switch carbonate deposition to black phosphatic shales [86].

6. Case studies

6.1. Permo-Pennsylvanian of Sverdrup Basin, Canadian Arctic Archipelago

Eight subaerial unconformities define major sequences in the Pennsylvanian and Permian strata of the Sverdrup Basin [87–89]. These unconformities are considered to be subaerial surfaces of long duration (>1 My) bounding thick (100–1000 m) third-order sequences [90]. They are correlated across the basin in outcrops of the basin-margin facies belt. Five of these unconformities and their correlative surfaces were traced in the subsurface of Prince Patrick Island [90]. Recent re-examination of cores has confirmed the presence of subaerial exposure surfaces [91]. Subaerial profiles in cores are mostly decapitated by erosion (transgressive ravinements) but preserve features such as calcretic and ferric replacive deposits, *Microcodium*, root traces, and high-chroma ("red") mottling, which provide a clue for their interpretation (**Figure 4**). Of 49 short (<18.5 m) cores totaling 388 m of recovery, signatures of subaerial alteration were encountered in 8 (**Table 1**). Four of these cores intersect disconformity surfaces and one core penetrated the sub-Pennsylvanian angular unconformity into the Ellesmerian basement (Depot Island C-44, 2458.2 m MD).

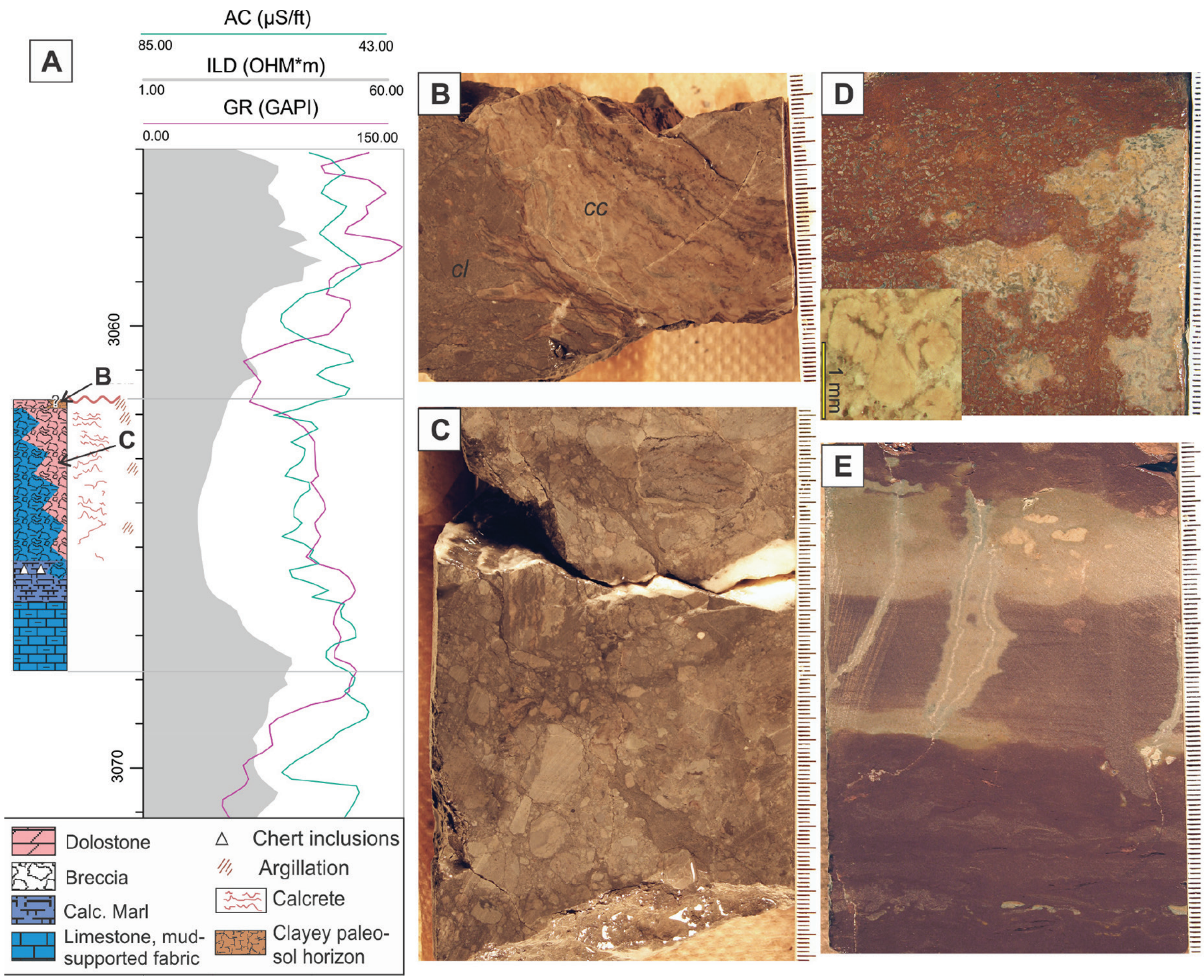

Figure 4. Permian disconformities of Sverdrup Basin in cores: (A–C) disconformity with a thick paleosol breccia at 3061.3 m, Graham C-52 well; (A) lithology and matched borehole logs; (B) core face photo of laminar calcrete crust (cc) interfingering with a claystone of probably upper paleosol horizon (cl); (C) calcretized and argillated breccia; locations of B and C are indicated on lithology. (D) Red mottled calcareous mudrock, Upper Pennsylvanian or basal Permian, Jameson Bay C-31, 2406.70 m; note dense Microcodium penetrations (mm-scale features); the inset shows typical Microcodium aggregates zoom with binocular microscope. (E) Red mottled bioturbated shale and siltstone, same age, Depot Island C-44, 1662–1663 m.

UWI	Well short name	TOP_ DEPTH (m)	BOT_ DEPTH (m)	Run (m)	Recovery (m)	Meteoric alteration (Y/N)	Unconformity surface present in core (Y/N)	TOP_ FORMATION	TOP_AGE	BOTTOM_ FORMATION	BOTTOM_AGE
300J607620110000	HECLA J-60	3603.7	3616.5	12.8	12.8	Y	Y	VAN HAUEN FM	GUADALUPIAN	VAN HAUEN FM	GUADALUPIAN
300C447630114000	DEPOT ISLAND C-44	1656.9	1675.2	18.3	17.4	Y	Y	CANYON FIORD FM	EARLY CISURALIAN	CANYON FIORD FM	EARLY CISURALIAN
300C447630114000	DEPOT ISLAND C-44	2457	2465.5	8.5	8.5	Y	Y	CANYON FIORD FM	PENNSYLVANIAN	IBBETT BAY FM	LOWER DEVONIAN
300L467630115000	SANDY POINT L-46	1786.1	1795.3	9.2	9.1	Y	N	CANYON FIORD FM	PENNSYLVANIAN	CANYON FIORD FM	PENNSYLVANIAN
300L467630115000	SANDY POINT L-46	1985.2	1988.5	3.3	3.3	Y	N	CANYON FIORD FM	PENNSYLVANIAN	CANYON FIORD FM	PENNSYLVANIAN
300C317650116300	JAMESON BAY C-31	2404	2413.1	9.1	9.1	Y	?	CANYON FIORD FM	PENNSYLVANIAN	CANYON FIORD FM	PENNSYLVANIAN
300F687720116300	SATELLITE F-68	2170.2	2173.5	3.3	3.3	Y	Y	TROLD FIORD FM	LATE GUADALUPIAN	TROLD FIORD FM	LATE GUADALUPIAN
300C527730090300	GRAHAM C-52	3061.7	3067.8	6.1	6.1	Y	N	HARE FIORD/ BELCHER CHANNEL	?SAKMARIAN (E. CISURALIAN)	HARE FIORD/ BELCHER CHANNEL	ASSELIAN (E. CISURALIAN)

Table 1. Cores with subaerial exposure profiles from the Upper Paleozoic of Sverdrup Basin, based on Ref. [91].

The thickest paleosol was encountered at 3061.3 m of Graham C-52 well (**Figure 4A–C**). The weak low-GR excursion just above the core top may record an upper clayey horizon of this paleosol or a transgressive deposit. This subaerial exposure profile may correlate to the unconformable contact of the Upper Nansen and Raanes formations (Asselian-Sakmarian boundary) of the basin margin zone [90]. Other disconformities from this core inventory occur stray within the defined third-order sequences, but may be assigned to higher frequency sea level fluctuations, as in the case of 9.1-m-thick core from the Belcher Channel Formation (lower Cisuralian) of Jameson Bay C-31 well described by Beauchamp et al. [90]. As stated in [90], these thinner (meter-scale) sequences or cyclothems are quite numerous in the Pennsylvanian—Lower Cisuralian (over 100 counted) but cannot be correlated between sections. Similarly, thin sequences in the Guadalupian part of the succession were traced based on well logs [84], but it is impossible to confirm subaerial nature of alleged sequence boundaries as no cores are available.

As the scanty core coverage in old exploration wells would not offer a chance to capture all stratigraphically meaningful disconformities, it is important to identify zones flushed by meteoric waters percolated from overlying subaerial surfaces. For example, in zones of meteoric oxidation, iron releases from decomposing synsedimentary sulfides and reprecipitates as ferric oxides and hydroxides. Seasonal waterlogging causes patchy reduction of iron into gley, and wetting-drying cycles usually imprint in characteristic red-gley mottling. Occurrence of oxidized basinal shales and siltstones with such mottling (**Figure 4D**, **E**) indicates fairly deep base level falls consistent with glacio-eustasy of the Late Paleozoic ice age [92]. Another feature indicative of paleo-vadose environment is *Microcodium* (**Figure 4D**), an aerobic microbially induced fabric abundant in Ca-rich subterranean environments of Pennsylvanian-Permian and late Cretaceous-Tertiary times but with no confirmed presence in rocks of other ages (**Figure 4D**; [93]).

6.2. Carboniferous of Moscow Basin, Russia

The Middle-Upper Mississippian and Pennsylvanian strata of the Moscow epicontinental basin of the central East European Craton (EEC) contain two cyclothemic successions dominated by shallow-marine carbonates and separated by a major Mississippian/Pennsylvanian unconformity [94]. The Upper Mississippian is a type succession for the Serpukhovian Stage, and Pennsylvanian strata host historical type sections for the Moscovian, Kasimovian, and Gzhelian stages of the Geological Time Scale [95]. The Mississippian/Pennsylvanian diastem (MPD) accounts for at least 10 My of late Serpukhovian-Bashkirian lowstand during which thick paleosols and deep (>110 m) fluvial incisions formed. Sequence stratigraphy of the two successions was developed based primarily on outcrops and disconformities which were used as main correlative horizons [96–99].

6.2.1. Middle-Upper Pennsylvanian

Similar to coeval classical cyclothems of North America [19, 86], Middle Pennsylvanian strata of the Moscow Basin have recorded a forced sea level control with drowning of seafloor into subphotic basinal environment on peaks of highstands and deep base level falls leading to subaerial exposure. These lowstands are thought to be the far-field response to expansion and shrinking of the Late Paleozoic ice dominantly from the Gondwanan icesheet [92]. Disconformities are scoured by transgressive erosion to various degrees, but some are onlapped with quiet-water facies with negligible truncation, preserving delicate features of former solums ("topclays"; **Figure 5A**). Fluvial facies or incised valleys are unknown. Topclays are palygorskitic, in some areas sepiolitic, indicating arid, well-drained pedogenic environments. A shift to montmorillonitic-illitic toplays recorded in the upper part of the studied succession flags the transition to slightly more humid climate. Other features are rare although deeply penetrating rhizoliths, shallow soil carbonate, low alumina/bases and Ba/Sr ratios, enhanced Mn and Sr, presence of soil gypsum and opal, and a characteristic peak in magnetic susceptibility, all suggesting a semiarid to arid pedogenic environment. The palygorskite clay of this paleo-pedon retains 1.1–1.5% of connate organic matter which is fulvate-dominated resembling organic matter from present-day aridisols [100]. The succession seems to be flushed throughout with meteoric fluids and repeatedly exposed to vadose environment, which left the penetrative systems of small solution vugs and oxidized organic matter and pyrites in basinal and siliciclastics-rich units.

6.2.2. Middle-Upper Mississippian

This ~90-m-thick shallow-marine succession deposited during Late Viséan and lower-middle Serpukhovian (~16 My) is composed of shallow-marine limestone-dominated units bounded by six main disconformities and even more weakly developed subaerial surfaces that could not be traced between outcrops [99]. Fluvial and deltaic floodplain siliciclastics wedge between Viséan limestone units from southwest. The Viséan strata show a number of unusual sedimentary features, such as a lack of high-energy facies, shallow-subtidal marine sediments penetrated by *Stigmaria,* and beds of palustrine marls (*sensu* [101]) composed of a mixture of authigenic saponite, beidellite, and micritic calcite with strong negative offset of $\delta^{13}C$. Disconformities range in expression from undercoal solution-collapse horizons of only a few cm thick to deep paleokarsts. Incised fluvial channels are reported at two stratigraphic levels to the west and north of the study area. The deepest incisions (>15 m) developed from the Kholm disconformity, and this stratigraphic break is also marked with the deepest paleokarst profile (**Figure 4B**). All paleosol profiles contain evidence of rooting activity with numerous *Stigmaria* (rooting systems of arborescent lycopsids). The uppermost studied paleosol below

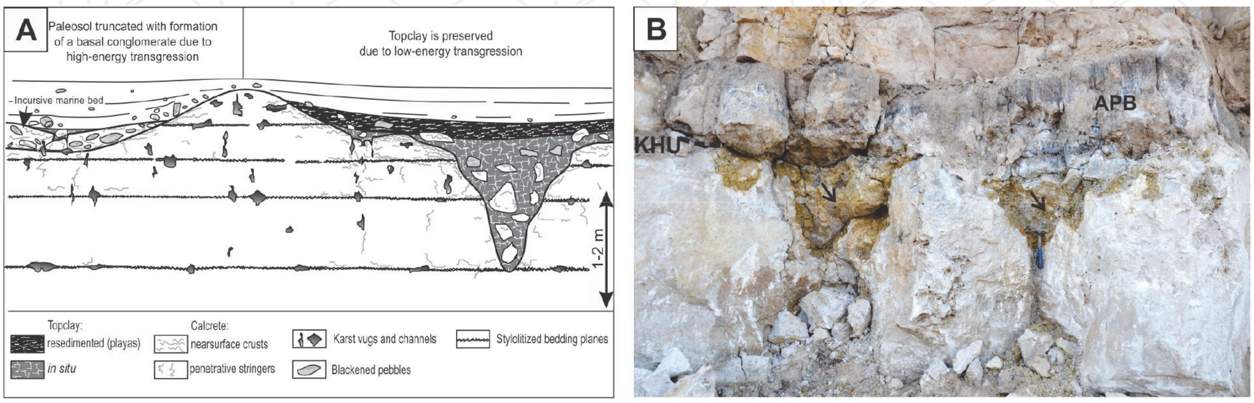

Figure 5. Paleosols and Paleokarsts at Carboniferous disconformities of Moscow Basin: (A) major elements and variability of upper Middle Pennsylvanian disconformities of Moscow Basin, slightly modified from Kabanov et al. [27]; (B) Kholm disconformity in top of Mikhailovian (KHU) and Akulshino palustrine marl (APB) at Novogurovsky Quarry, slightly modified from Kabanov et al. [99]; yellow clayey paleosol in solution pockets is arrowed.

the MPD is mid-Serpukhovian in age. It is a thin palygorskitic calcrete [99] formed under significantly drier climate than underlying *Stigmaria*-bearing paleosols. Paleosol mineralogy and proxies for pedogenic environments are discussed in [102, 103].

6.2.3. Disconformities in cores

Paleosols and karstified profiles of Middle-Late Mississippian and Pennsylvanian age are frequently intersected by cores in oil and gas exploration areas of the eastern EEC (**Figure 6A–C**). Project geologists usually ignore these surfaces. However, eroded disconformities invisible with geophysical tools may record prolonged hiatuses, as indicated by thick rhizocretions left by perennial plants requiring fairly thick soil cover to root in (**Figure 6C**).

6.3. Lower-Middle Devonian of Mackenzie Corridor, Northwestern Canada

Devonian strata of the central and northern Mackenzie Corridor located within the limits of ancestral North America are composed of Lower Devonian-Eifelian shallow-marine carbonates, dolostone breccias, and evaporites; Givetian-Frasnian basinal shales of the Horn River Group hosting isolated carbonate platforms (banks) of Ramparts Formation; and the Frasnian-Famennian Imperial Formation composed of fine-grained turbiditic siliciclastics and coarse-grained siliciclastics and chert conglomerates of the Tuttle Formation. The latter straddles the Devonian-Carboniferous boundary (**Figure 7**; [40, 104]).

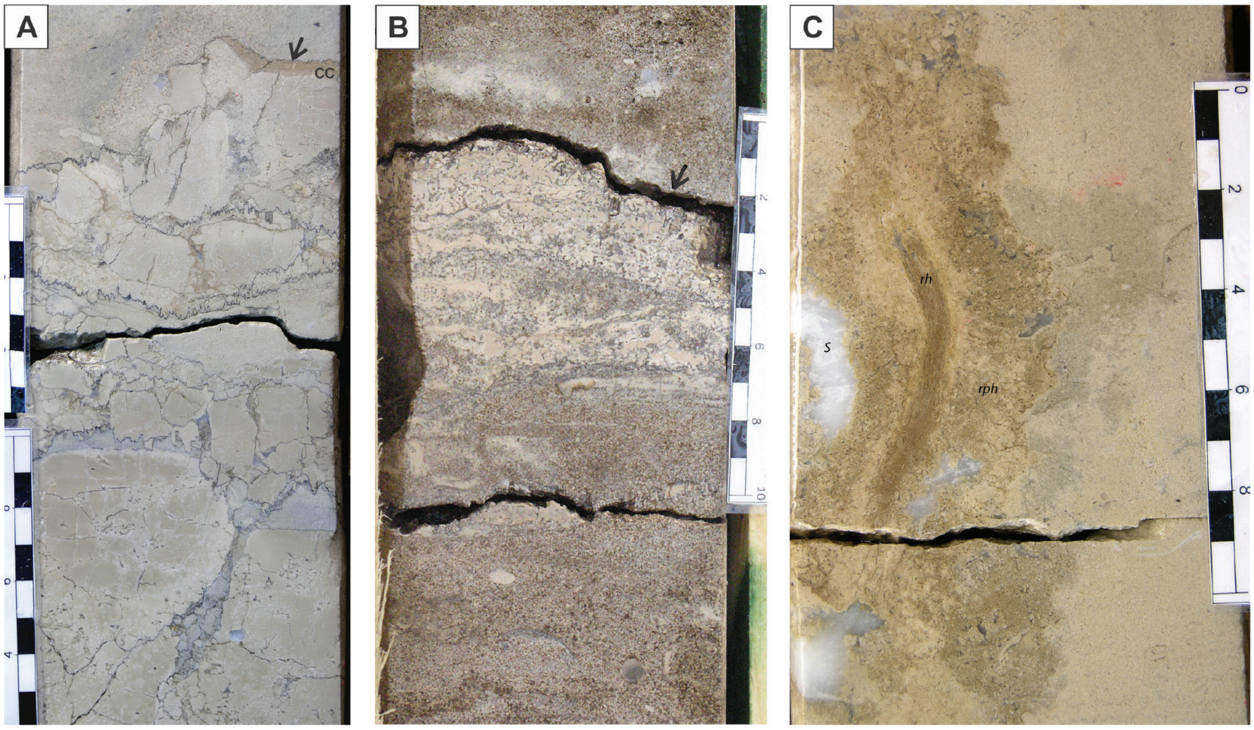

Figure 6. Eroded paleosols on core face of shallow-marine limestones, Bashkirian (Lower Pennsylvanian), southeastern EEC: (A) collapsed karst breccia with thin laminar calcrete crusts (cc); (B) more massive calcrete crust with rootlet channels; ravinement surface is arrowed; (C) rhizolith (*rh*) with thick peripheral alteration zone (*rph*) found in 3.5 m below a disconformity; (s) is anhydrite fill of karst voids; scale bar in centimeters.

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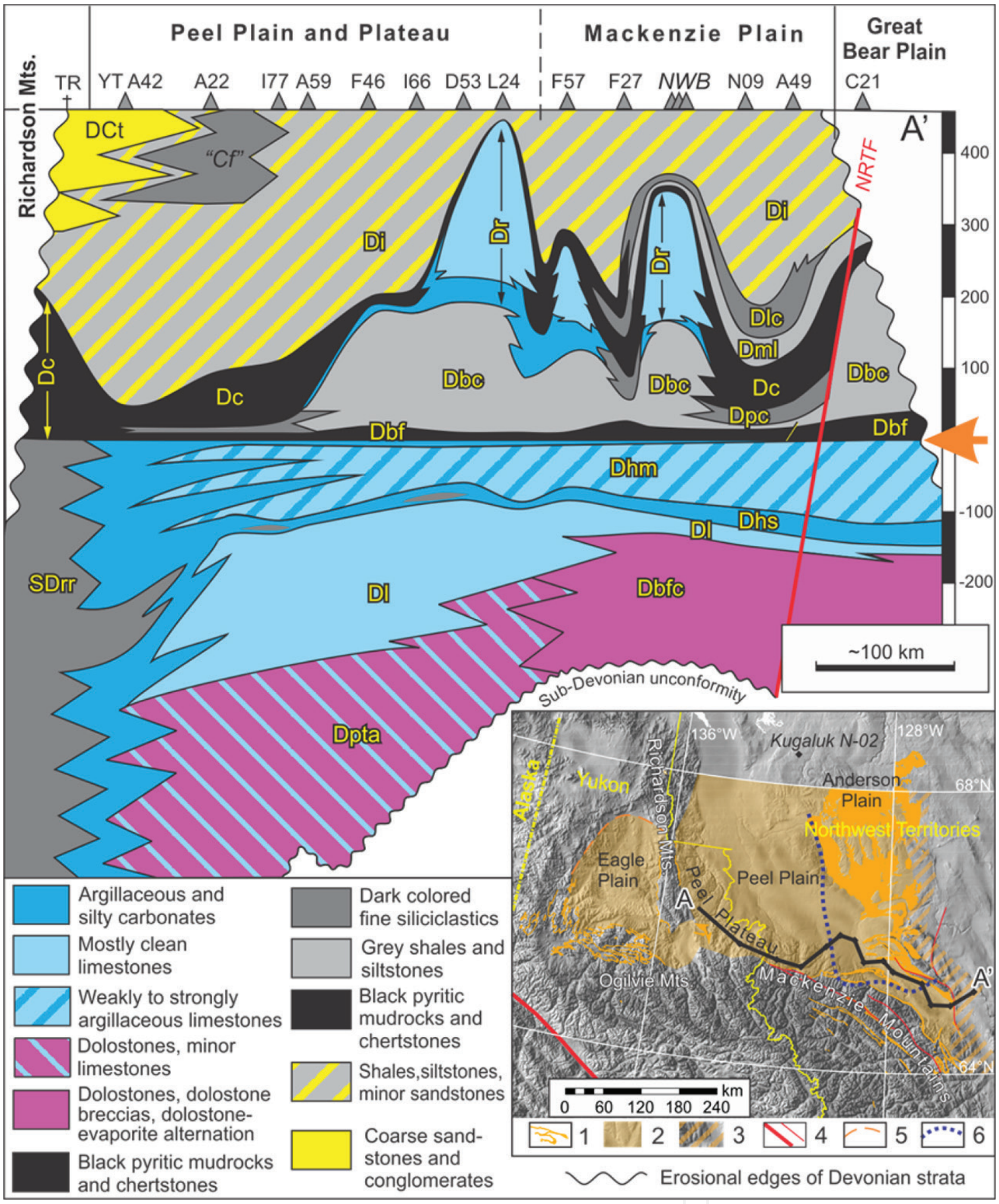

Figure 7. Devonian succession of central and northern Mackenzie Corridor on a cross-section A-A′ anchored on mid-Devonian drowning unconformity (arrowed). TR is Trail River outcrop section; wells from left to right: Cranswick YT A-42, Cranswick A-22, S. Ramparts I-77, N. Ramparts A-59, Ramparts River F-46, Hume River I-66, Hume River D-53, Carcajou L-24, Maida Creek F-57, Hoosier F-27, NWB is Norman Wells oilfield, Little Bear N-09, Bluefish A-49, and Bracket Lake C-21. Stratigraphic units: (Dbfc) Bear Rock, Fort Norman, and Camsell fms.; (Dpta) Peel, Tatsieta, and Arnica formations; (Dl) Landry Fm.; (SDrr) Road River Group; (Dhs) Headless Mbr. of Hume Fm; (Dhm) Hare Indian Fm.; (Dbf) Bluefish Mbr.; (Dbc) Bell Creek Mbr.; (Dfc) Francis Creek Mbr.; (Dpc) Prohibition Creek Mbr.; (Dr) Ramparts Fm.; (Dc) Canol Fm.; Imperial Fm. undivided (Di); (Dml) Mirror Lake Mbr.; (Dlc) Loon Creek Mbr.; (DCt) Tuttle Fm.; ("Cf") informal unit *Cf*. Inset map shows wide occurrence of the Horn River Group between 64 and 68 parallel in (1) outcrops, (2) subsurface, and (3) patchy presence in erosional outliers; (4) Tintina Fault Zone (thick) and smaller scale main faults in the Mackenzie Foldbelt (thin); (5) Canol Formation dips beneath thick siliciclastic wedge of Imperial and Tuttle formations; (6) paleogeographic offshore limits of thick Hare Indian siliciclastics (Bell Creek Mbr.) and overlying Ramparts Limestone. The eastern limit of Laramide deformation front is approximated by Norman Range thrust fault (NRTF).

A shallow-marine peritidal succession of Emsian age measured in the nearly continuous core of Kugaluk N-02 well (**Figure 7**) contains 86 disconformities that bear distinct signatures of subaerial exposure (rank 0, 1, and 2 discontinuities in **Figure 8**). Of these, 43 surfaces are marked with thick (>1 m) paleokarst profiles and 3 surfaces by thick rubbly paleosols and several meters of karstified rock below [105, 106]. This 440 m thick succession deposited over a period of 15–18 My, assuming that the top of Landry Formation approximates to the base of Eifelian [105, 107] and Delorme/Arnica contact is found in the Lochkovian or Pragian [108]. However, only seven subaerial exposure profiles have been identified in the Arnica—lower Landry part of this succession in the outcrop section measured at Rumbly Creek West Ridge, including one deep profile with thick paleosol [109]. Given very similar shallow-water facies assemblage of this outcrop and Kugaluk N-02 core, small number of disconformities appears to be an artifact of poor preservation of the weathered section and limited time spent on it by the examiner.

Subaerial exposure profiles of similar character are very common in Lower and basal Middle Devonian cores over the broad expanse of Mackenzie Corridor. Some thick profiles show signature of prolonged exposure and multiphase pedogenic overprinting resulted in complete loss of sedimentary fabrics, as exemplified by a mature paleosol profile at 600.25–603.5 m of Ebbutt D-50 well (**Figure 9B–D**). One interesting feature is the absence of root penetrations that are characteristic of younger Phanerozoic paleosols (**Figure 6**), which is interpreted as an evolutionary imprint of prevascular plant landscape. Small (<1 mm in diameter) rhizocretions occur only in thin marshland beds (palustrine facies; [101]) occupying incursive and transgressive positions in peritidal sequences of Landry Formation [99]. This "palustrine facies" has been also identified in outcrop [109]. Like in described above Late Paleozoic examples, none of available geophysical logs can be relied upon to trace even thickest paleosols of this type in the subsurface (**Figure 9**).

6.4. Mid-Devonian drowning unconformity of Mackenzie Corridor

Bioturbated and richly fossiliferous benthic limestones of Hume Formation containing a diverse benthic fauna are onlapped by black calcareous laminated shales of the Bluefish Member. The onlap surface is a strong seismic reflector commonly used as stratigraphic datum (**Figure 7**). In the project area (**Figure 7**), the surface appears table flat on outcrop scale, if not tectonically displaced, but in the southern Mackenzie Corridor it is outgrown by pinnacle-shaped carbonate buildups referred to as Horn Plateau reefs [110, 111].

The Hume/Bluefish contact has been measured in three cores from Canol Shale exploration wells and accessed in three outcrops of the Norman Range and northern Mackenzie Mountains [45, 109]. The coral-stromatoporoid facies composing the main part of the upper Hume Formation occurs in direct contact with the Bluefish shale in two of six sections, and in both cases, it shows a rugged corroded top with deep (8 cm in core) solution pockets filled with black shale from the overlying anoxic facies. The upper few decimeters below the top are chertified and also very pyritic in core or rusty in outcrops. Phosphatic crusts

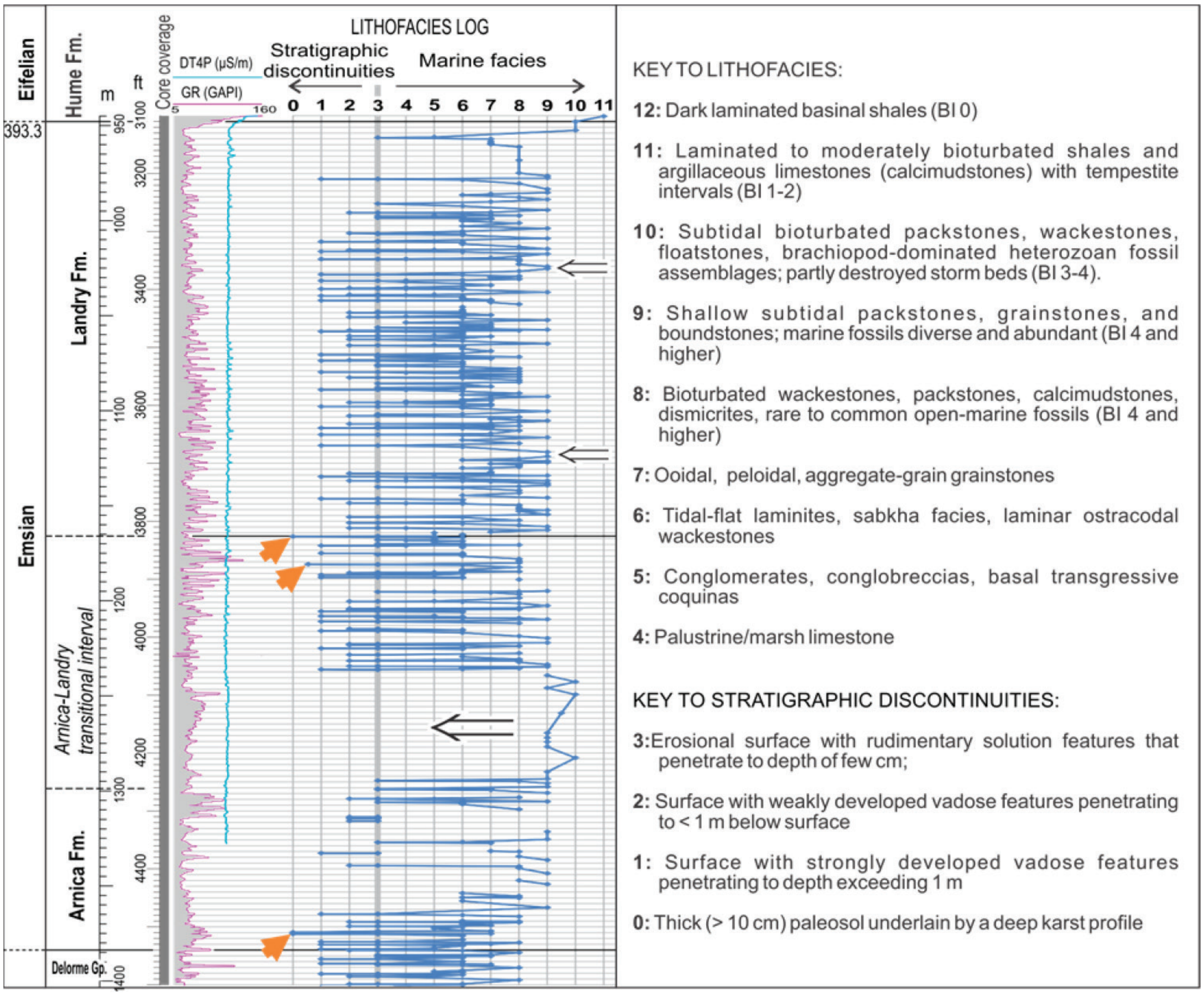

Figure 8. Lithofacies log for the Arnica-Landry succession in core of Kugaluk N-02 well with ranked disconformities, modified from Kabanov [105, 106]. Each facies point represents a mid-point of the descriptive interval. "No information" gaps in joint line indicate dolostones with obliterated sedimentary fabrics or "lost cores" from fractured zones. Black hollow arrows point at thick highstand intervals with offshore lithofacies and no disconformities. Orange arrows point at thickest subaerial exposure profiles with preserved paleosols.

characteristic of hardgrounds at other drowning unconformities did not develop, which is explained by overall phosphorus-lean sedimentary system [45]. Four other sections show 0.5–2.6-m-thick transitional interval of argillaceous bioturbated micritic limestones and shales. This transitional interval contains smooth discontinuity surfaces but no rugged hardgrounds. This transitional limestone contains brachiopod banks but no stromatoporoids. Pelagic tentaculitids appear in this unit and become rock-forming in base of Bluefish Member. The top of this transitional unit is usually smooth and probably storm-scoured. The basal few cm of the Bluefish Member characteristically contain lag concentrate of imbricated brachiopod shells mixed with diverse tentaculitids, sometimes dominated by tentaculitids with rare disintegrated brachiopod valves. Bioturbation in this basal Bluefish

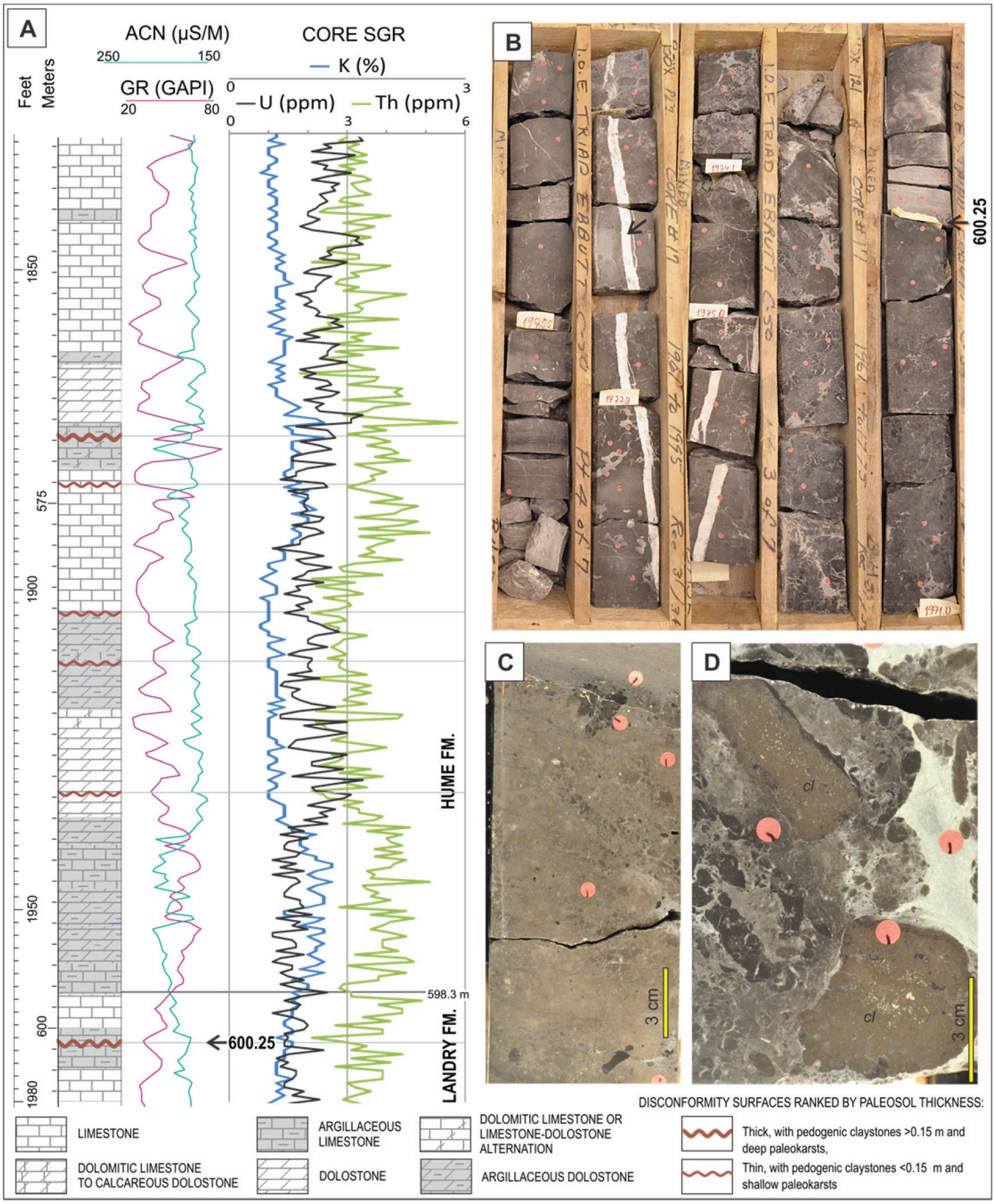

Figure 9. A shallow-marine peritidal succession measured in core of Ebbutt D-50 well (southern Mackenzie Corridor): (A) Striplog showing lack of well log response at multiple paleosols. (B–D) Polished and etched core face with details of paleosol at 600.25 m; (B) box view with pedogenic claystone-to-calcrete at 600.25–602.0 m (1969.3–1975.0 ft) and intense alteration down to at least 603.5 m (1980.0 ft); black arrow points at hydrothermal dolostone vein. (C) Top of paleosol profile composed of multiphase clayey calcrete; (D) float breccia at 600.9 m with residual clasts of marine limestone (*cl*). Sticky marks are ED-XRF reading points.

bed drops abruptly to BI ≈ 2 and right above this bed declines to zero. Enrichment in chalcophyle trace metals in enrichment factor notation (EFV and EFMo) grows gradually from moderate in the base of the Bluefish Member to a traceable spike of high values in 2.0 m above the base, indicating a gradual spread of anoxia.

7. Conclusion: a word of caution

It is generally accepted that the unconformities collectively record about 90% of the geologic time in its stratal expression. Stratigraphic unconformities are critical surfaces in sequence stratigraphy, but their identification remains largely the art of a visual rock assessment. Subaerial exposure profiles with paleosols are most common expression of non-eroded disconformities, but gamma and other conventional log signatures of even thick pedogenic claystones tend to stay at the background of host strata, and the majority of these surfaces do not coincide with surfaces of lithological change that would produce impedance contract for a seismic survey. Although major surfaces with prominent paleokarsts, erosion relief, lateritic mantles, and/or system of incised channels are certainly correlated, it has to be admitted that straightforward and universal technique to identify disconformities in coreless subsurface sections does not exist.

Stratigraphic unconformities included in table of formations are usually biased to those surfaces that were identified in outcrop, and their correlation may be undermined by a blank zone of unknown surfaces below and above, especially when dealing with non-cored intervals in the subsurface. This bias improves with increasing knowledge on the stacking pattern and ranking of measured disconformities.

Stratigraphic breaks diagnosed in old times and supported by missing faunal zones (e.g., sub-Canol hiatus of Mackenzie Corridor) are prone to dissolution or narrowing with increasing accuracy of biostratigraphic framework and absolute dating. Robustness of identified hiatuses should be confirmed with signatures of subaerial exposure or erosion.

Drowning unconformities are drowning surfaces specific for carbonate platforms. Usually, such surfaces produce vivid reflection horizons, and in the subsurface, they frequently have better stratigraphic value than platform-embedded subaerial disconformities.

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