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Late Devonian (Famennian) Glaciation in South America and Marine Offlap on other Continents

PETER E. ISAACSON, JINDRICH HLADIL, SHEN JIAN-WEI, JIRI KALVODA & GEORGE GRADER*)

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Spätdevonische (Famennium) Vereisung in Südamerika und marine Regression in anderen Kontinenten

Zusammenfassung

Nach der neuen Zeitskala des Phanerozoikums von GRADSTEIN und OGG (1996) repräsentieren die Ereignisse im Famenne eine größere Zeitspanne als vormals angenommen.

Es wurde kürzlich nachgewiesen, dass die wohl bekannte Karbonvereisung Gondwanas im Spätdevon begann. Das devonische Vereisungsereignis erstreckte sich über ein weites Gebiet: ein Großteil Brasiliens (Becken von Paranaiba, Amazonas und Solimoes) und Boliviens (Madre de Dios und die Antiplanogebiete des paläozoischen Vorlandbeckens). Diese Anfänge der Vereisung dauerten bis ins ältere Karbon (Tournaisium) fort. Sie sind datiert als zumindest den LE, LN und VI Palynozonen zugehörig. Bolivische Vereisungsvorkommen umfassen ungebankte und schlecht gebankte Diamikrite mit gekritzten und facettierten Klasten von Sedimenten und Graniten aus dem nahe gelegenen Vorland-Falten und Bruch-Gürtel. Aus einigen Beobachtungen lässt sich schließen, dass es im Devon zumindest zwei hauptsächliche Eisvorschübe gegeben hat.

Einhergehend mit dem Vereisungsereignis in Gondwana sind geologische Gegebenheiten in Nordamerika, Zentraleuropa und Südchina, die auf ein sehr schnelles Absinken des Meeresspiegels hindeuten; das zur Erosion ausgesetzte Freilegen von Karbonatplatformen, siliciklastische Sedimentation und Schichtlücken in der Famenne-Abfolge waren die Folge. Aus dem Tiefstand resultierten ausgedehnte Karbonatbrekzien, untiefe Absätze und Evaporite in den westlichen U.S.A. und Canada. Weitverbreitete früh-famennische und ältere Karbonatbrekzien in Idaho und West-Montana dürften Ausdruck von einhergehender subaerischer Freilegung und Interaktion mit einer fluktuierenden phreatischen Verwitterungszone in Verbindung mit wechselndem Meeresspiegelstand darstellen. Möglicherweise ähnliche Brekzien kommen auch in Nevada vor. Keile von Tiefstand-Klastika wurden einer im Wesentlichen regressiven Schwarzschieferserie eingeschaltet (östliche U.S.A.). Die Vereisung war augenscheinlich verantwortlich für Unterbrechungen in der famennischen Gesteinsabfolge an vielen Stellen.

*) Authors' addresses: PETER E. ISAACSON, GEORGE GRADER, Department of Geology, University of Idaho, Moscow, Idaho 83844, USA; JINDRICH HLADIL, Department of Stratigraphical Geology, Institute of Geology, Academy of Sciences CR, Rozvojová 135, 16502 Prague, Czech Republic; SHEN JIAN-WEI, Nanjing Institute of Geology and Paleontology, Academia Sinica, Chi-Ming-Ssu, Nanjing, P.R. China; JIRI KALVODA, Department of Geology and Paleontology, Masaryk University, Kotlarska 2, 611 37 Brno, Czech Republic.

In Mähren wuchs der siliciklastische Einfluss als Ergebnis von Erosion in durch das Absinken des Meeresspiegels aufgetauchten Hochgebieten. Zum Teil wurden Phasen des Absinkens durch Fe-Oolite angezeigt, die sich im küstennahen Bereich bildeten und dann auf anliegenden Rampen durch Sturmumlagerung verteilten.

In China erfolgte aus dem Tiefgang des Meeresspiegels im Famenne Aufschüttungen, siliciklastische Einschüttungen und Dolomitisierung infolge Evaporation und Sedimentation von Flachwasserkarbonaten.

Das Zusammengehen von Vereisungs- und Tiefstand-Ereignissen erklärt das plötzliche Erscheinen von flachmarinen sowie subaerisch beeinflussten Indizien innerhalb eines den nordamerikanischen Kraton überquerenden Meeresarmes von generell transgressiver Tendenz zur Spätdevonzeit (Frasnium).

Abstract

Given the new Phanerozoic timescale of GRADSTEIN & OGG (1996), Famennian events present a more significant timespan than earlier acknowledged. It has recently been shown that Gondwana's well-known Carboniferous glaciations began in Late Devonian time. The Devonian glaciation event occurred over a broad area, including much of Brazil (Parnaíba, Amazonas, and Solimöes basins) and Bolivia (Madre de Díos and Altiplano areas of the Paleozoic foreland basin), and this initial glaciation continued into earliest Carboniferous (Tournaisian) time. It is dated within at least the LE, LN and VI palynozones. Bolivian glaciation events include unbedded and poorly bedded diamictites with striated and faceted clasts of sedimentary and granitic rocks sourced from the adjacent foreland fold- and thrust-belt. Some evidence suggests that at least two major ice advances occurred within Devonian time. Coeval with the Gondwanan glacial event is a geologic record in North America, central Europe and southern China that suggests a very rapid sea-level fall that exhumed and eroded carbonate platforms, deposited siliciclastics, and generated lacunae in the Famennian record. The lowstand resulted in extensive carbonate breccias, shoal-deposits and evaporites in western U.S.A. and Canada. Widespread early Famennian and older carbonate breccias located in Idaho and western Montana may manifest coeval subaerial exposure and interaction with a fluctuating phreatic weathering zone related to varying sea-levels. Possible similar breccias occur also in Nevada. Lowstand clastic-wedges were deposited in a major forced regression in black shales (eastern U.S.A.). The glaciation was apparently responsible for lacunae in the Famennian rock-record in many places. In Moravia, Famennian physil and siliciclastic influx increased as a result of weathering in newly-emergent highs that resulted from sea-level drop. Partial sea level drops were manifested by ferruginous oolites, which developed in nearshore environments and were subsequently dispersed onto adjacent slopes by storm resedimentation. In southern China, aggradation, siliciclastic influx, dolomitization from evaporation, and shallow-water carbonates resulted from Famennian sea-level lowering. The coupling of glacial and lowstand events explains the sudden appearance of shallow-marine, as well as subaerially-affected features within a generally transgressive sea that breached the North American craton during Late Devonian (Frasnian) time.

1. Introduction

The late Paleozoic (Carboniferous and Permian) Gondwanan glaciation has been well-documented in Brazil and elsewhere in South America (CAPUTO & CROWELL, 1985). It is generally well-accepted that this glaciation caused short-term sea-level fluctuations (cyclothems) in North America (VEEVERS & POWELL, 1987). The glaciation commenced in the Late Devonian in South America over a broad area, including much of Brazil (Parnaíba, Amazonas, and Solimöes basins) and Bolivia (Madre de Dios and western foreland basins), and it continued into Early Carboniferous (Tournaisian) time and beyond. Its earliest deposits are dated within the late Famennian Stage (VAVRDOVÁ et al., 1993), although it affected sea-levels before this time. Evidence for the glaciation is discussed more extensively by DÍAZ-MARTÍNEZ et al. (this volume) and includes: striated clasts within palynomorph-dated, poorly-bedded diamictites; and glacial pavements. Famennian rocks in North America show evidence of a very rapid sea-level fall that exhumed carbonate platforms and resulted in extensive carbonate breccias and shoals. Also, lowstand clastic wedges and black shales were deposited during and after the major forced Famennian regression, and lacunae punctuate the rock record. This coupling of events explains the sudden appearance of shallow-marine, as well as subaerially-produced features, indicating 100 m to 140 m sea-level drop. A revision of Famennian transgressive and regressive cycles in a framework of the expanded (i.e., 10 my long) duration of the Famennian Age (GRADSTEIN & OGG, 1996) is required.

2. Famennian Glaciation of South American Circum-Polar Gondwana

Widespread sedimentologic evidence for late Paleozoic glaciations exists for Gondwanaland during latest Devonian (Famennian) and Early Carboniferous (Tournaisian) time. CAPUTO (1985) has not only described diamictites/dropstones of glacial origin across the Parnaíba, Amazonas, and Solimöes basins (3500 km, east–west dimension) of Brazil, but he also demonstrated that these include faceted and striated pebbles as clasts and are accompanied by glacially striated pavements. The diamictites are up to 350 m thick, although their thickness varies greatly, as is to be expected in the peri-glacial sedimentary record. Further evidence for this Devonian glaciation was recently found in Bolivia (DÍAZ & ISAACSON, 1994; DÍAZ-MARTÍNEZ et al., this volume), in outcrop in the Lake Titicaca region, as well as in the subsurface of the Madre de Dios Basin (ISAACSON et al., 1995).

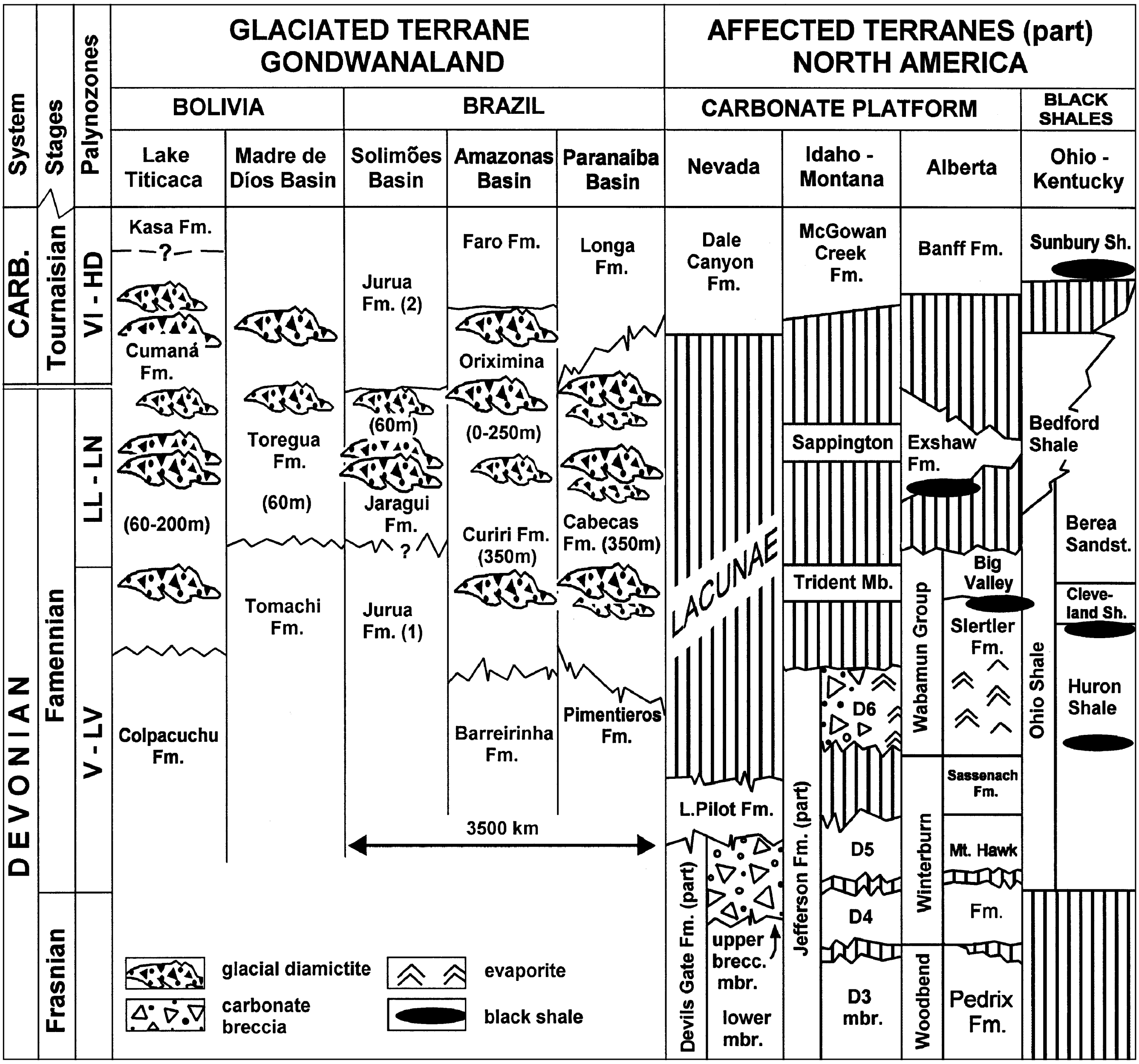
The timing of glacial deposition is relatively well-constrained by palynomorphs (VAVRDOVÁ et al., 1993; ISAACSON et al., 1995). It generally begins within the Late Devonian (Famennian) *pusillites-lepidophyta* Palynozone and continues into the Carboniferous. VAVRDOVÁ et al. (1993) reported the following taxa: *Retispora lepidophyta*, *Hymenozonotriletes explanatus*, *Verrucosisporites nitidus* and *Lophozonotriletes rarituberculatus* of Late Devonian age, and *Densosporites spitsbergensis* and *Rugospora polyptycha* of Early Carboniferous age. These palynomorph assemblages are indicative of the late Famennian and Tournaisian LE, LN, and VI palynozones. Abundant occurrences of *Umbellasphaeridium saharicum* and other acritarch species imply a marine connection between Bolivia and coeval North African basins, via Brazil (VAVRDOVÁ et al., this volume). Nevertheless, a relative decrease in the abundance of marine acritarchs and associated increase of megaspores in the rocks, corresponding to the transition from the Devonian to the Carboniferous, suggest a significant contemporary lowering of sea-level.

Much evidence has now been found in Bolivia for this early glaciation of Gondwanaland (VAVRDOVÁ et al., 1993; DÍAZ & ISAACSON, 1995; ISAACSON et al., 1995). Large granite boulders, and faceted and striated clasts within unbedded and poorly-bedded diamictites indicate a glacial source. Both the Cumaná Formation (Lake Titicaca area, Text-Fig. 1) and the equivalent Itacua Formation (central and southern Subandean region) have well-constrained late Famennian ages. In contrast to the Brazilian evidence for a large ice cap, the interpretation of the Bolivian data indicates a major glacial advance and retreat from glaciated highlands related to southwestern Gondwanaland's convergent margin, with possible earlier advances (Text-Fig. 1). The Brazilian succession manifests two discrete glacial events during the Late Devonian, as evidenced from both surface and subsurface data (CAPUTO, 1985).

The distal periglacial character of the preserved record, both in Bolivia and Brazil, may have masked the influence of previous glacial advances and retreats. Nevertheless, their coeval occurrences are noteworthy. Recently, dropstones have also been discovered in the Colpacuchu Formation, of late Frasnian and early Famennian age (RACHEBOEUF et al., 1993), thereby suggesting the possibility that the glaciation event(s) began much before the better-known late Famennian deposition. The importance of the Late Devonian glaciation event increases as more evidence for it is discovered outside of Brazil. For example, CENSIER et al. (1995) have presented evidence for this earlier glaciation in central Africa.

Therefore, its influence in global sea-level changes needs to be considered. Given that glacial deposition represents ice-sheet maxima and the beginning of withdrawals, ice formation (and consequential sea level drop) would antedate biostratigraphically-derived ages yielded by the deposits (BUGGISCH, 1991).

With the recent revision of the Phanerozoic timescale (GRADSTEIN & OGG, 1996) and our modified interpretations of Famennian Stage rocks (DÍAZ & ISAACSON, 1994; ISAACSON et al., 1995) in South America, the likely presence of lacunae caused by eustatic regressions within a longer (10 m.y.) Famennian Age are compelling.



Text-Fig. 1.
Correlation of Gondwanan Late Devonian and Early Carboniferous glacial events to North American sequences.
Glaciations in Brazil (CAPUTO, 1985) and Bolivia (DÍAZ & ISAACSON, 1994; ISAACSON et al., 1995) caused a rapid sealevel drop that produced carbonate breccias, extensive lacunae, and forced regression (PASHIN & ETTENSOHN, 1995) manifested by siliciclastic sediment (including black shale).
Other rock units are discussed in text.

3. Marine Regression from Continental Margins of Temperate and Tropical Belts

3.1. Western North America

The eustatic drawdown effects of the Late Devonian glaciation are manifest on many present-day continents (VEEVERS & POWELL, 1987); nevertheless, the stratigraphic record in North America needs re-examination. Response to very rapid sea-level drop and the sea's episodic withdrawal from the craton is a dominant feature during Famennian time. Effects include:

1) subaerial exposure of Famennian and Frasnian age (and older) carbonate rocks commonly resulting in their karstification and phreatic zone brecciation;
2) deposition of evaporites in some basins as sea-level fell;
3) clastic-wedge progradation as a result of forced regression manifested by black shale;
4) an extensive (temporally and areally) lacuna within the Famennian and part of the Tournaisian, punctuated by thin units of clastic rocks, carbonates, and evaporites deposited during interglacial events during the lowstand (HANDFORD & LOUCKS, 1993).

We suggest that there has been a Devonian glacio-eustatic overprint of the tectonically adjusted western margin of Laurussia. Evidence of Late Devonian, Antler-associated tectonics extends across the Laurussian platform and shelf from the Nevadan Roberts Mountains allochthon to the coeval Ellesmerian orogen in Arctic Canada (MCNICOLL et al., 1995). Paleogeographic reconstructions of foreland stratigraphy using subtidal to supratidal facies and isopach patterns show the existence of arches and basins of various orientations. Migrating lithospheric flexural profiles, intra-plate stresses, reactivated brittle failure of pre-existing rifted Precambrian structural grain and basin inversion are commonly used to explain variations in Famennian stratigraphy.

Because tectonic-induced subsidence and paleohigh emergence rates are generally stronger than predicted glacio-eustatic variations (GILES & DICKINSON, 1995), lacunae and shallow/deep lithotopes have been attributed to early Antler tectonic pulses. We do not contend the reality of Late Devonian Antler tectonics, but we propose an additional glacio-eustatic overprint at this time; purely eustatic regressions were of substantial influence. Widespread hiatuses of extra-basinal origin in conjunction with alternative reading of carbonate and siliciclastic rocks along the North American margin have led to this interpretation.

In the U.S.A., the Famennian subsidence curve for east-central Idaho (Text-Fig. 1) is taken from Grandview Canyon and the Tendoy Mountains (DOROBEK et al., 1991; DOROBEK, 1995). The upper part of the Jefferson Formation of the Lemhi Range records 580 m of shallow-marine carbonates, sandstones, mostly stratiform carbonate breccias, and disconformities. These mostly unfossiliferous beds (informal members D4, D5 and D6, which is equivalent to the Logan Gulch Member of the Three Forks Formation), occur above the thick Frasnian Dark Dolomite Member which represents organic rich-transgressive, organic buildup and lagoonal facies. This is a cyclic succession that contains sporadic siliciclastics sourced from the craton to the east. The uppermost (D6) member, however, shows marked contrast to much of the unit below. Limestone breccia, 168+ m thick, comprises D6. Recognizable dark and light carbonate clasts float in a matrix of silty and sandy limestone suggestive of phreatic-zone dissolution and tabular cave collapse (MYLROIE & CAREW, 1995). Such collapse yielded a carbonate breccia. Coeval with this unit is the Logan Gulch Member (Three Forks Formation), which has extensive evaporites within it (SANDBERG, 1962). Extreme brecciation in the upper Jefferson Formation is well-known over a large area of NW and SW Montana (M'GONIGLE, 1982; BLOUNT, 1986).

Lacunas separate the Trident and Sappington members, further suggesting subaerial exposure with marine onlap events of short duration (interglacials) punctuating the gaps. Furthermore, it has been suggested that eustatic cyclicity in Frasnian age units in Idaho and Montana may have manifest incipient stages of the Gondwanan glaciation (DOROBEK, 1995).

In Nevada there is a significant lacuna above Frasnian age carbonates (SANDBERG et al., 1988). Most of the Devils Gate Formation in central Nevada shows cyclic development including bulbous stromatoporoid- and *Amphipora*-rich shallow-marine limestones. At its type locality, the uppermost part of the formation has a carbonate breccia (Text-Fig. 1), which has been interpreted as deep water slump deposits. However, this type of early Famennian breccia occurs regularly as a consequence of the large Frasnian and Famennian sea-level drop. In Nevada, nearby, in the southern Roberts Mountains, the shallow-water unit is separated by an unconformity from Mississippian strata. Although a sea-level rise could have caused the slumping of the breccias, we suggest alternatively they manifest the Famennian lowstand subaerial-weathering brecciation event. Episodic flooding events, accompanying interglacial times, would be responsible for the Pilot and other siliciclastic and mixed carbonate units that are bounded by erosional disconformities (Text-Fig. 1).

It has been suggested (Text-Fig. 1 of GILES & DICKINSON, 1995) that in Nevada there are five unconformity-bound syntectonic sequences occupying the upper Frasnian and Famennian and these are attributed to changes in accommodation space in conjunction with lithospheric flexure and eustacy. Following initial thrusting of the Roberts Mountains allochthon, and the establishment of flexural topography (first sequence), the following four sequences (mostly Famennian) suggest congruous accommodation trends in coeval stratigraphic sections. Eustacy and sediment-supply have been interpreted as the primary controls on accommodation space at this time. Non-migration of the flexural features throughout the Famennian in Nevada, which otherwise would have led to inversions of topography, major Famennian hiatus, and subaerial exposure, parallel the Idaho succession (where effects of allochthon loading are not obvious), and this suggests common extrabasinal causes in marginally different tectonic environments.

Coeval Famennian rocks across the Montana and Canadian shelf change in relation to the presence of cratonic, organic buildup and other positive areas. We limit our discussion to rocks within the Antler foreland, where middle and outer shelf areas, now a part of the Cordillera, yield generally thicker, and laterally more diverse lithologies. Following the widespread biostromal/reefal units of the upper Frasnian, major regression and hiatus near the Frasnian-Famennian boundary is recorded by siliciclastic units all along the North American margin. Relationship of this major event represented in Nevada, Idaho, and Canada, to Antler loading has been suggested (GILES & DICKINSON, 1995; SAVOY & MOUNTJOY, 1995).

In Canada, initial Famennian siliciclastics and silty argillaceous carbonates of sub-tidal to peritidal environment (MORROW & GELDSETZER, 1988), are followed by a carbonate ramp and bank facies of the southwestern cratonic-shelf Palliser Formation (subsurface-Wabamun Group; Text-Fig. 1). The 200 m thick Sassenach Formation (Text-Fig. 1), which thins to the east, is feldspathic and is interpreted as filling a western basin (SAVOY & MOUNTJOY, 1995). At this time, the inner-shelf Besa River Formation accumulated over a hiatal surface; the coeval outer-shelf Earn succession constitutes part of a poorly understood western tectonic assemblage (MOORE, 1988). It is important to note that the model (SAVOY & MOUNTJOY, 1995) of convergent Antler tectonism associated with a foreland basin, differential subsidence (including sedimentary loading) and periodic western clastic influx also includes the Exshaw Formation and Mississippian lower Banff Formation. In this model, correlative Famennian western-margin black shales, such as the Exshaw Formation are interpreted as deep-water deposits, although there may be shallow-water structures. RICHARDS et al. (1991) included the Exshaw in the Banff assemblage, because of its shallow to supratidal siliciclastic association. Overall, MOORE (1988) concluded that the Famennian interval in Canada was mainly regressive. Conversely, SAVOY & MOUNTJOY (1995) suggested that the Exshaw Formation shale was deposited at depths greater than 50 m. They also infer that the Sappington Member (Three Forks Formation) and parts of the Pilot Shale represent transgressive drowning and intrusion of the oceanic oxygen-minimum zone. Using an alternative approach, we stress the possibility of paleoenvironments from 1 m to 50 m deep for any globally extant black shale. In our view, shales in the formations discussed above can also be construed in part or in whole as shallow-water deposits that are unrelated to the effects of Antler uplift and/or subsidence.

HALBERTSMA (1994) suggested an affinity between the Exshaw and Costigan/Big Valley strata (Upper Palliser Formation), calling upon an alternative lowstand interpretation: Instead of deposition during highstand transgression, HALBERTSMA envisaged the pyritic black shales to have been deposited in anoxic environments on a confined shelf during lowstand condition. These rocks are characterized by shales, pyritic argillaceous carbonates, laminated limestone, limestone breccia, major disconformities and intervals of normal fossiliferous limestone deposited in a shallow subtidal setting (HALBERTSMA, 1994). Alternatively, the Costigan/Big Valley deposits are placed within the third and fourth Famennian transgressive events above a major faunal lacuna (SANDBERG et al., 1988).

These deposits, however, do not conflict with a fluctuating glacio-eustatic hypothesis which requires rapid, antithetic forcing of sea-level. It is our view that major transgressions during interglacial periods probably match these previously identified transgressive events and produce a variety of contrasting deposits. SAVOY & MOUNTJOY (1995) address the real ambiguities of deep versus shallow lithologies and the reality of recognizing the record of cryptic subaerial exposure. Differential lateral variations across the Montana and Canada shelf at this time have been referred to as part of epeirogenic pulses rather than eustatic change (MORROW & GELDSETZER, 1988). We speculate that shelf lows and highs coexisted to produce lateral variations in disconformity style; such variations were accentuated by major glacio-eustatic drawdowns which overprinted 3rd-order (10^6 years) tectonic signatures. Limited accommodation space between episodic foreland basin adjustment (which was limited to Frasnian time) in Nevada and Idaho suggests that a glacio-eustatic pulse would not be overshadowed by continued Antler loading until Mississippian time.

3.2. Eastern North America

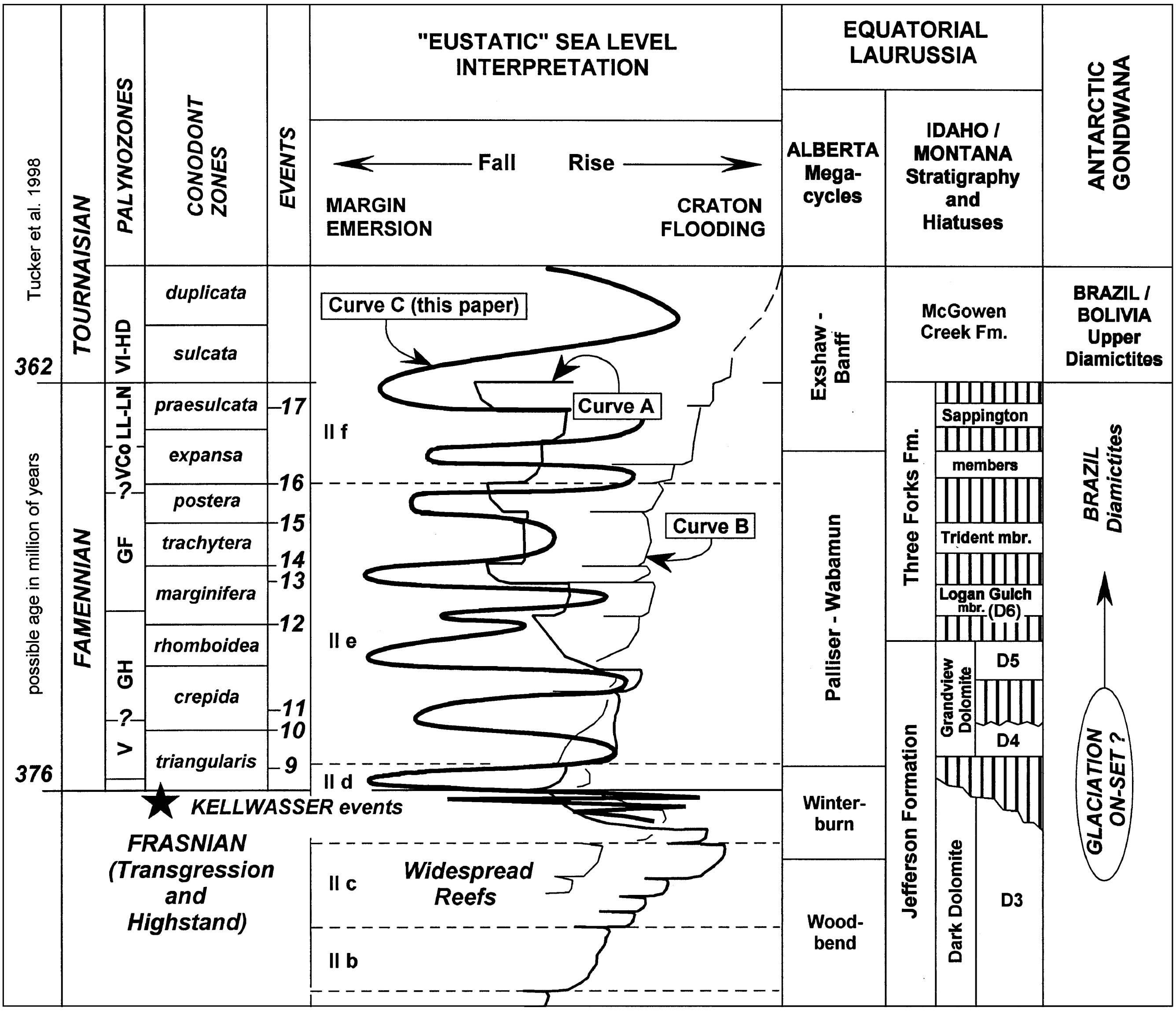
ZIEGLER (1988) questioned glacio-eustatic influence on Upper Devonian strata at the scale of the Old Red Continent. ZIEGLER and WITZKE & HECKEL (1988) have suggested that epicontinental seas and marginal seaways led to initial Gondwanan Laurussian contacts and cosmopolitan biotas, variable stratigraphy in widely separated basins and major lithologic shifts. In the Great Lakes region analogous Devonian black shale and brecciated deposits of the Thiensville Formation, and Famennian Antrim Shale, suggest restricted water circulation, slow sedimentation and disconformity (KLUESSENDORF et al., 1988).

Throughout Late Devonian time in eastern North America, the accumulation of black shales with progradational siliciclastic units manifested Acadian uplift to the east. Westward migration of the ultimate, late Famennian lowstand wedge has been attributed by PASHIN & ETTENSOHN (1995) to glacial-forcing, which is consistent with the shallow, eustatic-lowstand origin of black shales proposed here, and embodied in a revised sea-level model for the Famennian and lowermost Tournaisian (Text-Fig. 2).

3.3. South Laurussian Margin in Central Europe (Moravia)

Many European geologists have suggested that the typical Frasnian–Famennian pattern of sedimentation shows shallow-water coral and stromatoporoid reefs, which are covered by slope and oceanic hemipelagic lime-mudstone. The latter sediments are mostly lenticular-bedded limestones with abundant cephalopods, and the facies change has usually been interpreted as evidence for Famennian sea-level rise. Most European evidence comes from Rhenish (Lahn, Dill), Moravian (Hranice, Jedovnice) and Moroccan (Tafilalelt) outcrops. However, this conclusion requires revised interpretation. The inability of this model to explain Famennian events in Moravia was first suggested by DVORAK et al. (1986) who reassessed the region's paleogeography with its synsedimentary tectonics (DVORAK, 1986). Late Devonian paleogeographic development of Moravia used to be interpreted as uninterrupted deepening from carbonate buildups (reefs) to cephalopod limestone occurring in some tectonically downdropped blocks, which rimmed the platform at Hranice and Jedovnice, Moravia.

On the other hand, localities more distant from these margins typically show larger stratigraphic gaps between the end of the Frasnian reef development and Famennian sediments (e.g., Miedzianka quarry, Holy Cross Mts., Poland; central block of the Mokra quarry, Moravia; CEJCHAN & HLADIL, 1996). Central and coastal parts of carbonate platforms characteristically have significant breaks in their Famennian and Tournaisian sedimentary successions (HLADIL & KALVODA, 1989). Drill-hole information, moreover, shows numerous paleokarst levels as well as diagenetic brecciation (HLADIL et al., 1994). Sporadic onlaps of Famennian carbonates are separated by lacunae



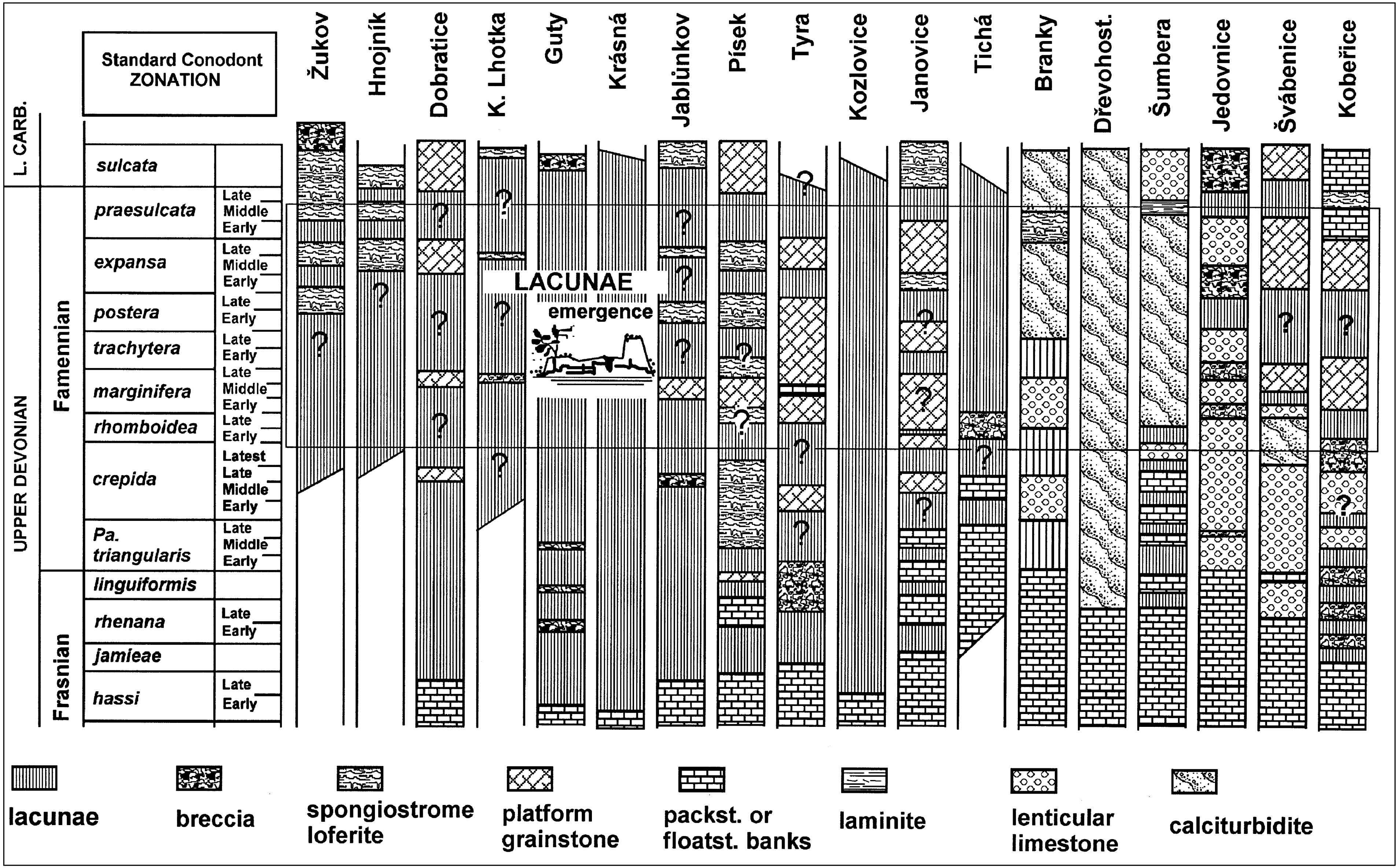
Text-Fig. 2.
Alternative sea-level curve (bold curve "C") for Famennian and lowermost Tournaisian succession, Laurussian margin, shown in comparison to curve "A" and curve "B".
Devonian-Carboniferous boundary age from TUCKER et al. (in press). T–R cycles (e.g., IIe) and events are from SANDBERG et al. (1988). Palynozones and conodont zones (from STREEL et al., 1987) reflect the different correlation schemes of North and South America, respectively.

(Text-Fig. 3); these sediments consist of lithoclastic carbonate-sand and foralgal bioclastics. Swarms of filled fissures (Neptunian dykes) occur in the Frasnian reefs and formed during occasional sedimentary onlaps during the Famennian or Tournaisian.

In Moravia, the Frasnian reef areas covered by an uninterrupted Famennnian succession represent only 5 % of the carbonate surface; sporadically-flooded areas comprise 65 %, and the continuously subaerially exposed areas 30 %. Karstification of emergent islands resulted in development of cave systems. Some of the caves have very late sedimentary fills (late Tournaisian to Namurian A; HLADIL et al., 1994). Drowning of marginal reef blocks was explained by their tilting in a transpressional system (DVORAK et al., 1976). At other localities, downdropping blocks in a transtensional setting has been suggested (HLADIL, 1988, 1994; BABEK, 1996) – see Text-Figs. 3 and 4. Beginning with late Frasnian sea-level lowering, physil and coarser-grained siliciclastic influx increased. Partial sea-level drops were mostly accompanied by formation of ferruginous oolites that developed near the shoreline and were subsequently dispersed on the narrow shelf and slope by storm resedimentation. This concept was explored by DREESEN et al. (1988), and DREESEN (1989), and the phenomenon was narrowed to the Frasnian/Famennian boundary (HLADIL et al., 1991). Middle to late Famennian sedimentary ironstones of the Ardennes region correlate with Rhenish red shales of the Nehden, Hemberg and Dasberg intervals (DREESEN, 1989). We suggest that the occurrence of these red shales manifests emergence of continents, and better oxygenation of the sea floor.

Worldwide onset of sedimentation of Late Devonian cephalopod facies at former carbonate-platform margins can be explained by causes other than global eustatic rise. A significant lowering of sea-level and marine regression on shelves suggest a lowstand scenario of oceanic circulation (Text-Figs. 2, 7 and 9); the stratified oceans of Givetian and Frasnian highstands changed to mixed-water oceans of the Famennian lowstands. New Famennian coastlines fluctuated near former Frasnian shelfbreaks. Marginal slopes located adjacent to former carbonate-platforms were reshaped into inclined ramps, on which

Text-Fig. 3.
Distribution of facies and hiatuses in Famennian of Moravia.
Interpretation of drill information and outcrops.
Question marks show shallow areas with no occurrence of conodonts (correlated on the basis of foraminiferal zonation, rare occurrences of stromatoporoids and geophysical well logs).



accumulated lime-mud sediments; and breccia slide deposits and calciturbidite fills formed in tectonic sags. Width reduction of Famennian shelves caused a shift of pelagic environments towards the coast (HLADIL, 1994; HLADIKOVA et al., 1997). Characteristic features of the Famennian included depletion of the shelf benthic organisms, increased manganese content of the sediments, and enhanced uptake of the ^{18}O isotope in the sedimentary carbonates (HLADIKOVA et al., 1997).

Table 1.
Famennian relative sea-level changes in Moravia, independent of tectonics (HLADIKOVA et al., 1977; HLADIL & KALVODA, 1989).

Interval	Zone	Sea-level change
1	upper *rhenana*	drop
2	*linguiformis*	rise
3	middle *triangularis*	drop
4	upper *triangularis*	rise
5	lower *crepida*	drop
6	upper *crepida*	rise
7	uppermost *crepida*	tectonic trough, and sea-level drop
8	early *rhomboidea*	drop
9	middle *marginifera*	rise
10	lower *trachytera*	drop
11	*trachytera–postera*	episodic peaks
12	upper *postera*, lower *expansa*	major drop
13	middle, upper *expansa*	episodic peaks
14	middle, upper *praesulcata*	small rise
15	uppermost *praesulcata*	small rise
16	early and middle Tournaisian	variable
17	late Tournaisian	rise

In the NE and SE Moravian subsurface there is evidence for significant regression of Famennian and Tournaisian seas from thicker, consolidated crustal blocks (Text-Fig. 3). A few periods of sedimentation were interrupted by large hiatuses.

Lateral correlation of subsurface logs, foraminifera, rare stromatoporoids and conodonts indicate three main Famennian sedimentation events in which shallow-water sediments accumulated: these culminated in a transgressive peak in the *crepida, marginifera*, and *expansa* Zones. It was mentioned immediately above that during the *marginifera* Zone there was an onlap within a tectonic trough, during which onlap the Enkenberg event was described by the reappearance of sporadic stromatoporoids and tabulates as well as a significant change in conodont facies (MATYJA, 1993). Tournaisian platform sediments occur within the *crenulata* Zone and during late Tournaisian time (Text-Figs. 3 and 4). Presumably there were elevated places within these platforms because a lacuna, interpreted as a hiatus extends from the Frasnian to the middle–late Visean (Text-Figs. 3 and 4).

In coeval pull-apart extensional and subsiding basins, in the southern Moravian Karst (Sumbera, Hady and related allochthonous parts) and in central Moravia (Konice area) deposition was more or less continuous. Ferruginous oolites that were dispersed within the middle and late *praesulcata* laminites reached these sags as well (Text-Fig. 4).

3.4. South China

Middle to Late Devonian carbonate platforms in Guangxi are underlain by shallow-water siliciclastics. A large carbonate shelf was segmented by inter-platform depressions resulting in a regional diversification of facies and formal stratigraphic units (Text-Figs. 5 and 6). Marine sediments are subdivided into three major facies, including intertidal siliciclastic (littoral facies), Xiangzhou, and Nandan facies (Text-Fig. 6). The littoral facies rimmed a stable craton, and a widespread alluvial facies was deposited northeast of Guangxi and the south of Hunan (Text-Fig. 6). The Nandan facies comprises mainly pelagic limestone, siliceous limestone, and claystone. The Xiangzhou facies is characterized by platform banks and reefs with abundant benthic fauna. Facies breaks define the margins of the platforms and are manifested by and interfingering of the Xiangzhou sediments with deeper-water Nandan facies, as well as by their transition into the nearshore siliciclastic and carbonate lithofacies units (Text-Figs. 5 and 6).

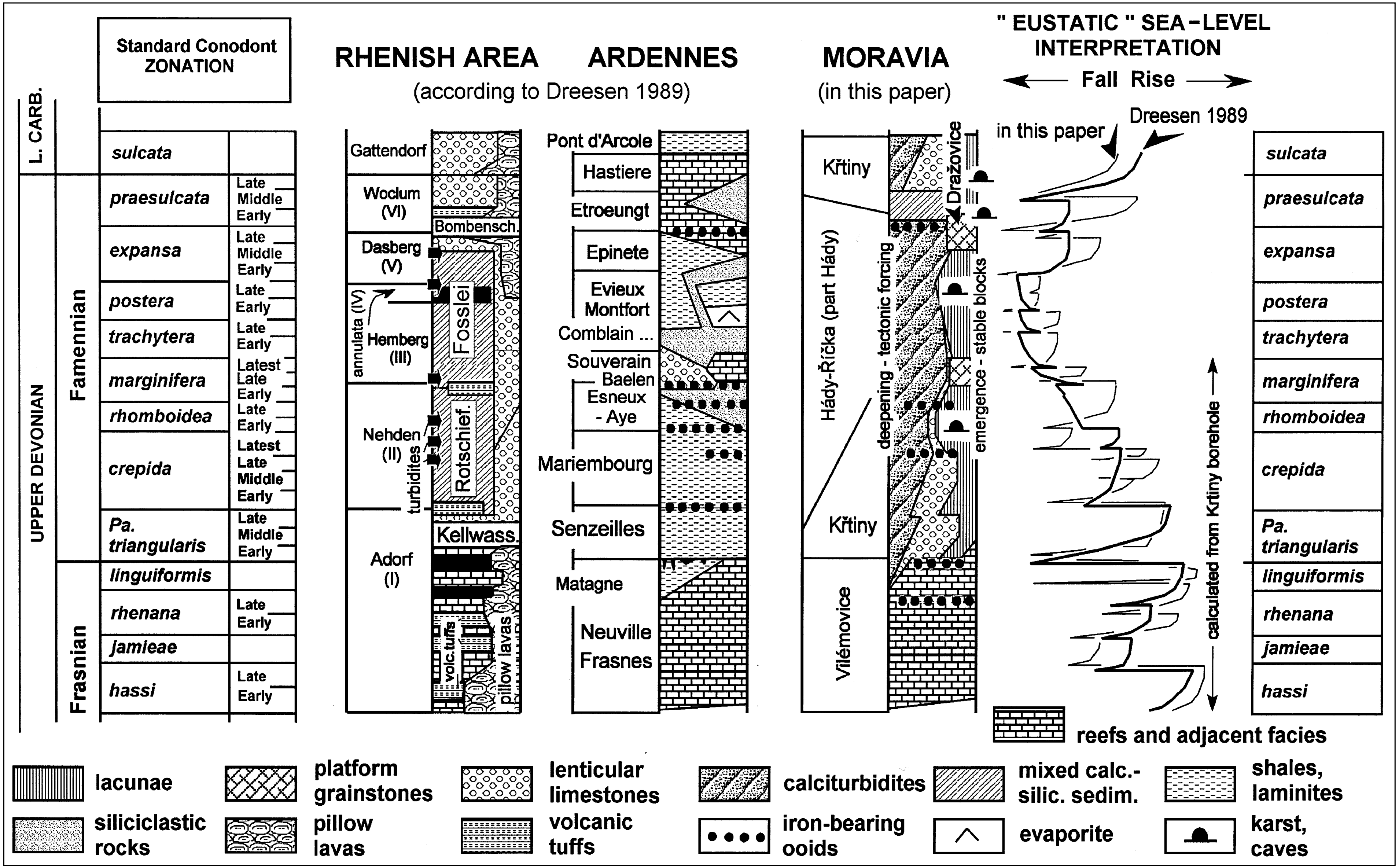
The Xiangzhou-facies platform-sediments contain numerous syn-sedimentary exposure and solution surfaces that constitute good correlation markers, as follows:

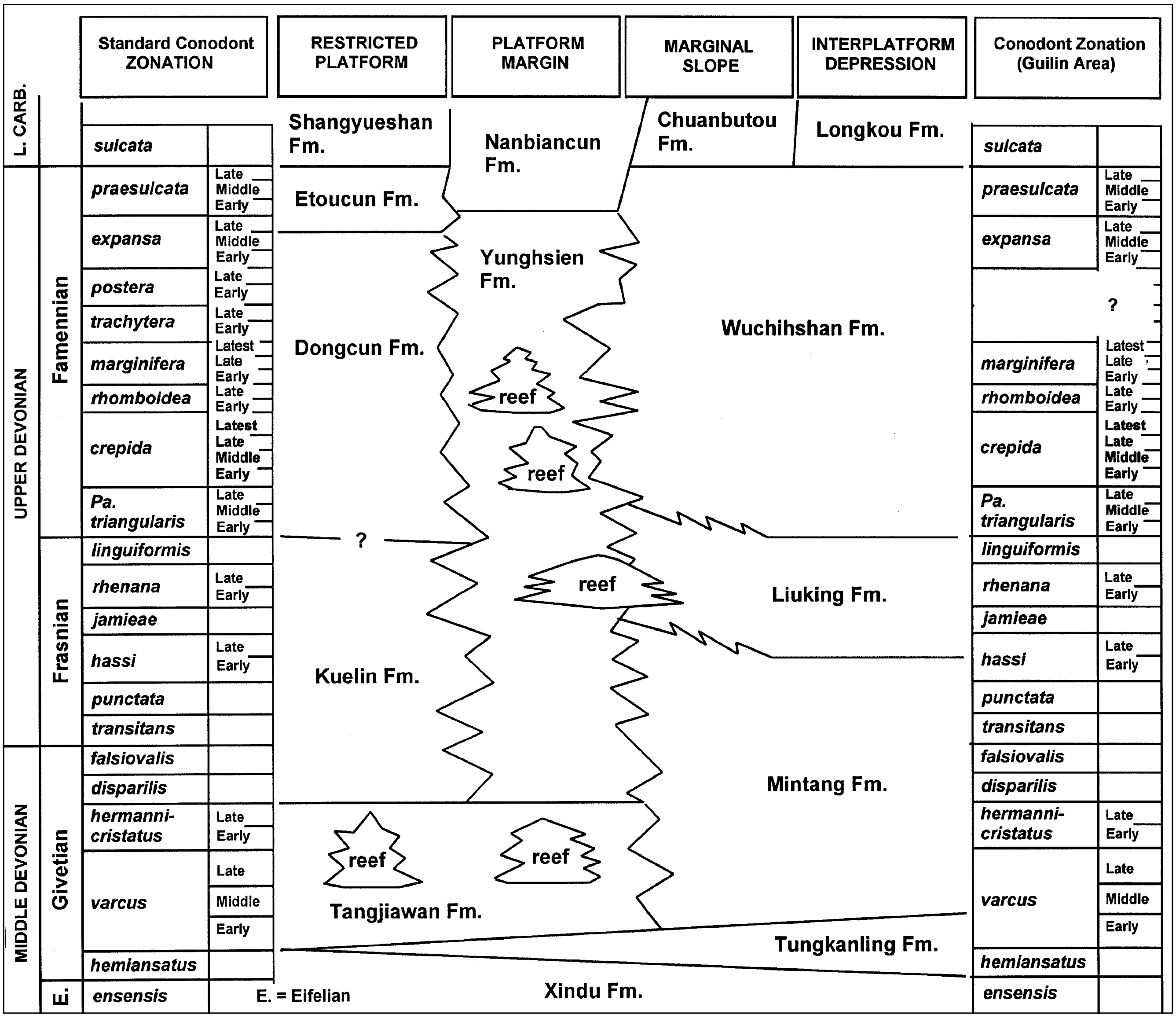
1) Conformable karst surfaces resulting from slight karstification of the underlying beds; clay-parting laminae that sporadically drape these solution-weathered surfaces.
2) Numerous fossil molds (occluded by calcite orthospar) within dolomitic boundstone/framestone (biolithite) that culminates each cyclothem. These cavities originated during subaerial exposure and freshwater solution. Undulating surfaces at the top of these thick and massive dolomitic layers are recognizable widely in the platform facies.
3) Strongly dolomitized subaerial desiccation-fill products of stagnant-water: mainly reddish silts or marl, and gravels; these occlude solution fissures and drape bedding planes. Phosphatic and/or ferricrusts commonly cover this residue.
4) Accumulations of paleokarst breccia on bank margins, and calcarenite debris on the marginal slopes.

Devonian sea-level elevations culminated during the Givetian and the Frasnian times as evidenced in the Guilin and Liujing carbonate-platform-margin sections respectively; as well as in nearshore sediments of Dushan (Text-Figs. 7 and 8). The Frasnian transgressive phase was followed by a regressive phase during the early Famennian (Text-Fig. 7). The carbonate successions of the platform/slope-break have been zoned by conodonts. WANG & YIN in YU (1988) described the D-C auxiliary stratotype at Nanbian-cun in Guilin, through conodont systematics. JI (1989) documented a Frasnian conodont succession in slope facies at Yangti, 20 km south of Guilin. SHEN et al. (1994) and SHEN (1995) discussed the events and cycles at Guilin using conodont data. Hence, biostratigraphic data for margins of the Guilin reef-complex range from the Givetian *hemiansatus* Zone to the D–C transition. Late Frasnian and Famennian resolution is based on the *rhenana, linguiformis, triangularis, crepida, glabra, marginifera, expansa* and *praesulcata* Zones (Text-Fig. 7).

Devonian strata at Guilin contain several well-exposed, areally extensive chronostratigraphic units. Ten sections along an 80 km long margin of the platform were compared in order to establish major sequence boundaries, transgressive surfaces and maximum flooding surfaces.

Text-Fig. 4.
Famennian sea level curve, showing offlap in three areas along the south Laurussia margin, with lithologic symbols.





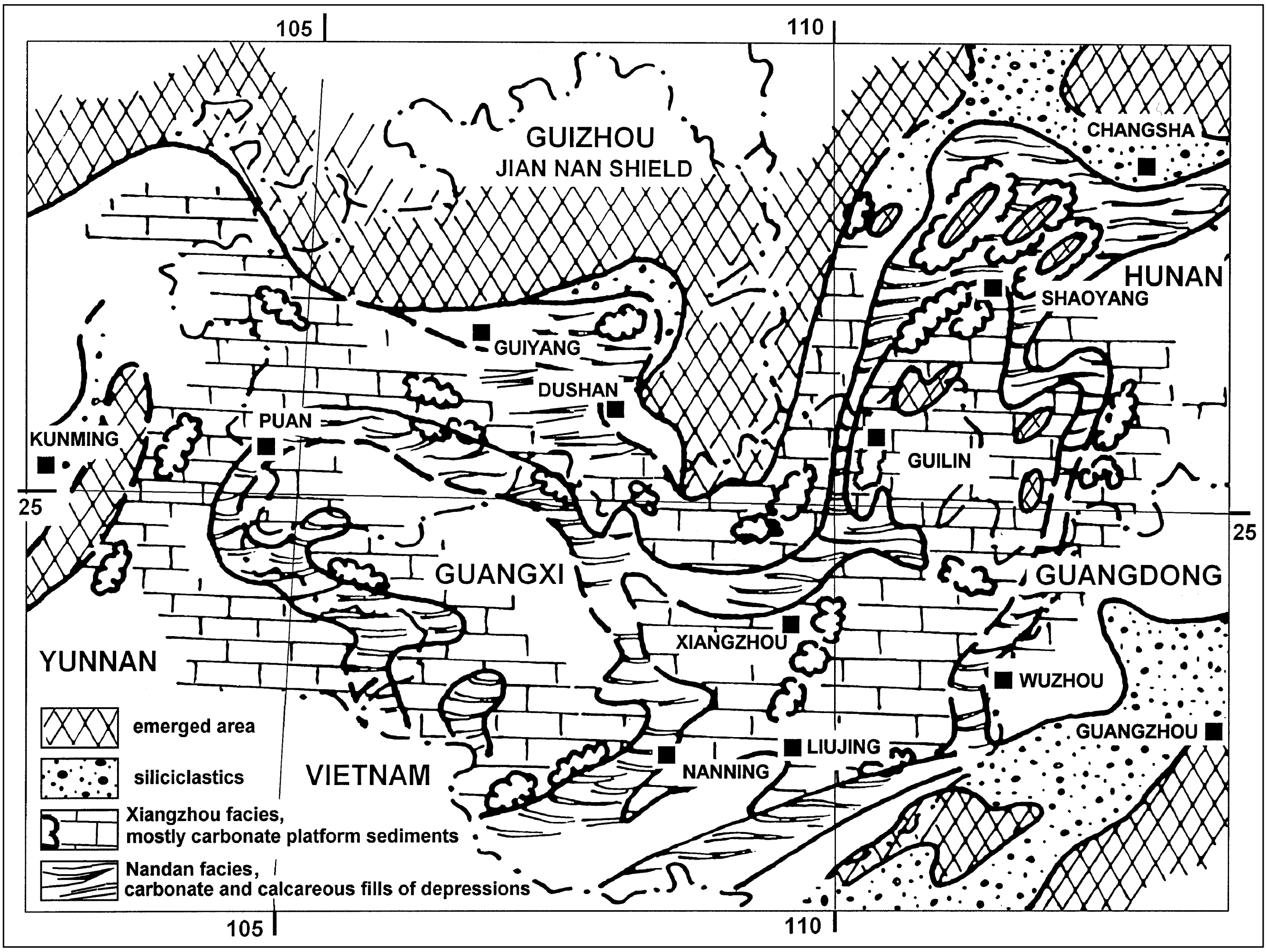
Text-Fig. 5.
Middle and Upper Devonian lithostratigraphic units of Guangxi (south China), and their correlation.

The main sequence boundaries (unconformities; see Text-Figs. 5 and 8) are:

1) Within Givetian (lower/middle *varcus* Subzone);
2) Late Givetian (*hermanni-cristatus/disparilis* Zones; barren interval in the *disparilis* Zone with limestone yielding *Nowakia otomari* is directly overlain by storm beds with typical Late Devonian brachiopods; two Late Givetian tentaculitid biozones are absent in the lowstand track on the slope);
3) Within Frasnian (early *rhenana*/late *rhenana* zones; covered by ferruginous crusts at Tangjia-wan, at the Guilin Detergent Plant, and at Dafeng-shan. There is a 1 m thick shale layer above thin-bedded, algal or microbial-laminated, argillaceous-banded limestones in the carbonate platform succession at Yangdi);
4) mid-Famennian (early/middle *expansa* Zone), locally much earlier; smooth surface, with carbonate breccia beds and debris-flow deposits from the margin; and
5) latest Famennian (middle or late *praesulcata* Zone). Consequently, the late Givetian through Famennian Guilin carbonate-platform succession has been subdivided into five third-order sequences (Text-Fig. 8); each was terminated at these boundaries.

Although lateral correlation across a variety of local facies was based mainly on synsedimentary-subaerial exposure (regression) surfaces, as well as evidence of condensation caused by maximum marine flooding (transgression), all sequence boundaries were identified by conodonts. A condensed interval in the 4th (*expansa* Zone) sequence is distinctive in the sequence's correlation: it is traceable from the thin-bedded cherty rocks in the deeper-water pelagic deposits to the thin black micrites and black shales in the shallow-water platform-facies deposits (Text-Fig. 8). The age between the *linguiformis* and early *triangularis* biozones is based mainly on conodonts from Yangdi. The upper (4th) sequence boundary is smooth without any relics of the shallow-water sediments; however, they are manifested in the platform margin and marginal-slope facies as carbonate breccias and debris-flows. The age of this boundary is inferred to be within the *expansa* Zone.

The 5th sequence is marked by transgression (Text-Fig. 8). Yet, there are features reflecting synsedimentary/penecontemporaneous subaerial-exposure at the top of this sequence, including solution-surfaces covered by shallow-water shales and lowstand-tract sediments on



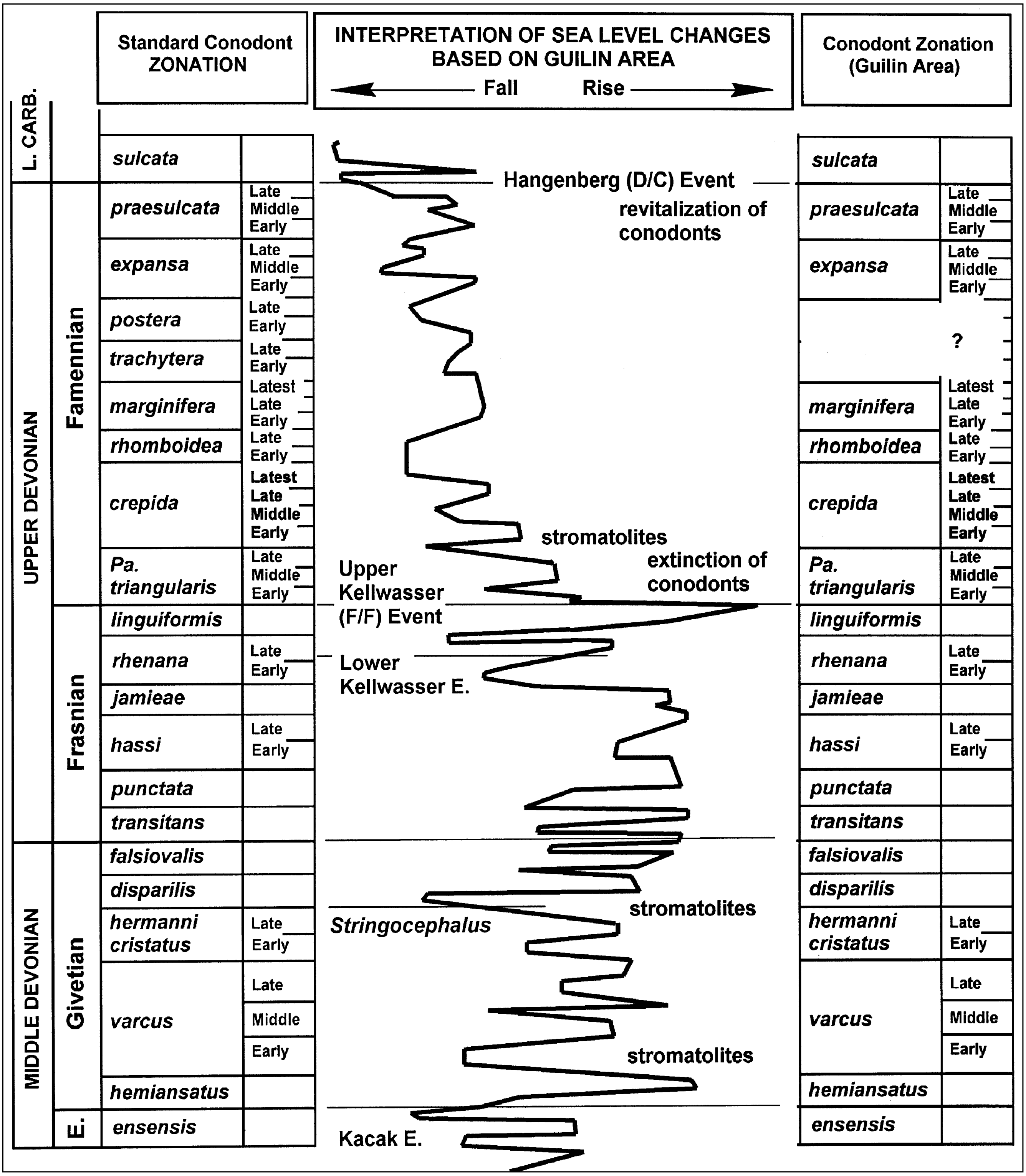
Text-Fig. 6.
Middle and Late Devonian paleogeography of south China and locations of three regions that are mentioned in this paper.

the proximal slope. The boundary is approximately dated to the middle/late *praesulcata* Zone.

Sequence boundaries recognized in the Devonian carbonate-platform complex at Guilin can be interpreted as type II (B2) boundaries, because there is no evidence of incised-valley fill, a progradational complex, a channel-levee complex, or a shelf margin wedge towards the foreslope. Exposure-erosion has been described in shallow-water platform-facies deposits, but they are difficult to identify in the ramp facies deposits of the foreslope facies. The Late Famennian exposure surface is a type I (B1) sequence boundary that shows massive brachiopod shelly fills, as well as allochthonous sediments transported from the margin to the steeply inclined foreslope. Sea-level fluctuations were interpreted from details of this sequence-stratigraphic pattern scaled by conodont biozonation (Text-Fig. 7). The Frasnian sea-level rise reached a relative high in the *punctata* Zone.

A subsequent facies is characterized by dark-colored siliceous rocks and forereef facies composed of carbonate bioclastic debris. Correlative platform sediments were covered by medium-bedded calcarenite. A transgression also occurred in the *hassi* Chronozone (Text-Fig. 7). Foreslope facies continued with siliceous rocks, but the platform interior was dominated by *Amphipora* floatstones with coral, brachiopod, and chaetetid or stromatoporoid biostromes. These accompanied a sea-level rise. In the *jamieae* Chronozone, there was a minor lowering of sea-level. Siltstone, silty shales and siliceous (cherty) rocks characterize the foreslope facies. In the platform interior a bed of yellow-green calcareous shale occurs, and it overlies an exposure-solution surface with a thin ferricrust. A lowstand wedge-shaped debris-flow occurs in the Liangshuijing section. Sea-level fell much lower during the early *rhenana* Chronozone, but it began to rise before the end of this zone. Thin-bedded breccias were deposited in inter-platform trough facies of the Yangdi section at this time. Thin-bedded argillaceous limestone rhythmically alternated with medium-bedded micrite in the foreslope, whereas *Amphipora* floatstone, bulbous and encrusting stromatoporoid limestone, and gastropod limestone are common in the platform interior. Maximum flooding, preceded by a brief eustatic minimum, took place in the *linguiformis* Chronozone (Text-Fig. 7). Another sea-level rise occurred over the Guilin carbonate platform (during the subsequent *triangularis* Zone), similar to that which characterized the latest *hemiansatus* Zone of the Givetian (Text-Fig. 7). The associated foreslope facies is characterized by siliceous (cherty) rocks and shales intercalated with black thin-bedded micrite and black shale. Stromatoporoids (mainly *Amphipora*), corals, brachiopods, gastropods and other benthic organisms suddenly disappeared close to the end of this zone.

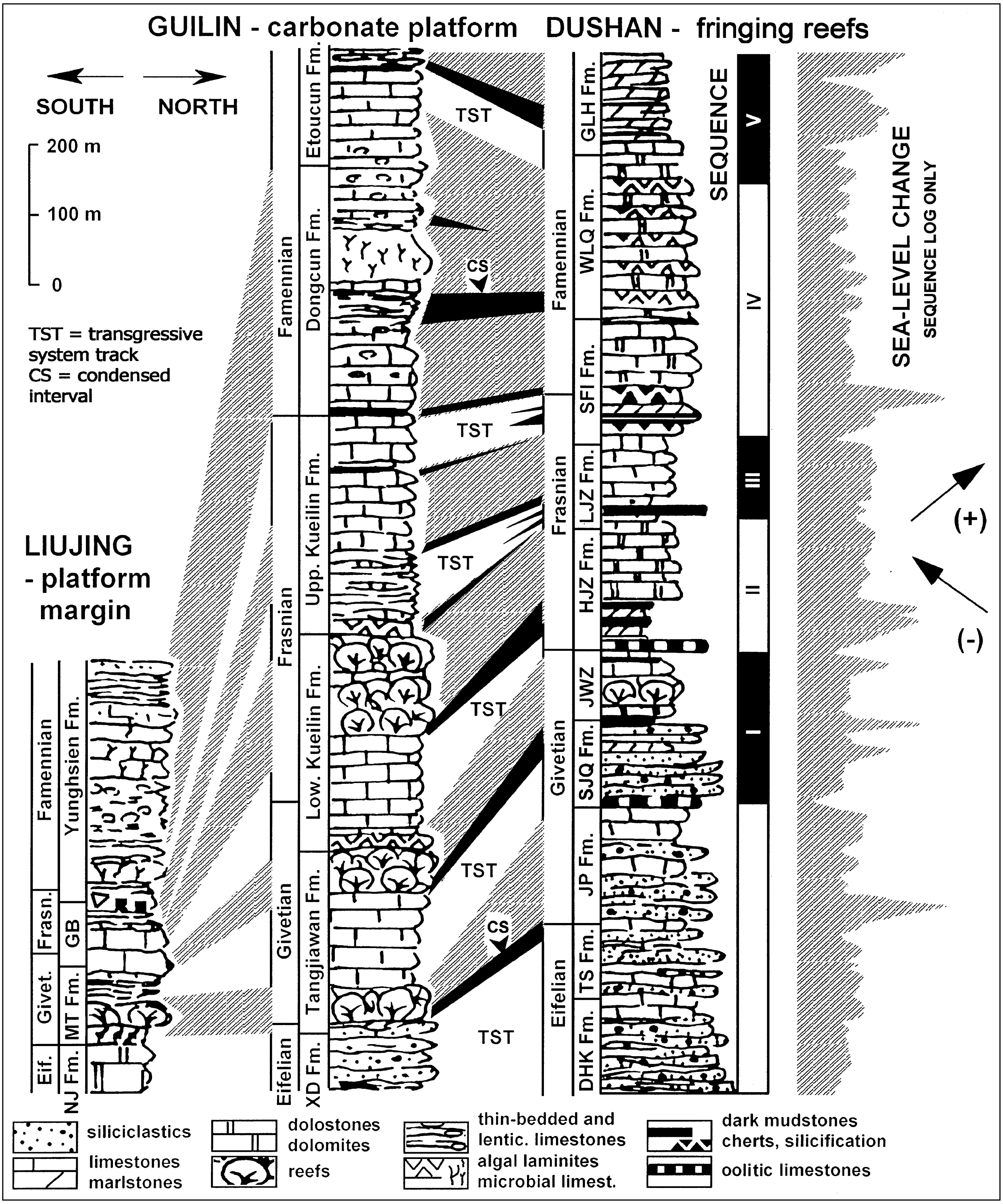
A rapid and extensive sea-level drop occurred in the late *triangularis* Chronozone (Text-Fig. 7). Sediments formed in the platform interior at this time mainly comprise light-gray fenestral-limestones that are intercalated with: dolomitic limestones; finely-crystalline dolomites with mud



Text-Fig. 7.
Middle and Late Devonian eustatic sea level curve at Guilin, South China.

cracks and fenestral fabrics; edgewise-conglomerate; and laminated limestones. Fossils are rare except for ostracodes. Lenticular-bedded lime mud was deposited on the foreslope and microbial/algal buildups grew at the platform margin. There was a sea-level offlap during the *crepida* Chronozone (Text-Fig. 7). Fenestral-limestones dominate the rocks of the platform interior, whereas algal/ microbial limestone, calcarenite and calcirudite, indicating a high-frequency eustatic fluctuation, characterize platform and platform-margin facies.

A major offlap subsequently occurred in the *rhomboidea* Chronozone, but an onlap accompanied by high-frequency eustatic fluctuations followed and continued to the *marginifera* Chronozone (Text-Fig. 7). However, the sea-level was generally shallow and intertidal sediments were mostly produced. The platform margins were covered by oolitic limestone, with calcarenite peloidal-limestone in their interiors; both of these sediment types show typical intertidal fabrics. During the *marginifera* Chronozone, another low sea-level phase began and progressed with



Text-Fig. 8.
Middle and Upper Devonian sequence-stratigraphic correlation and inferred sea-level change in south China.

continued offlap. Argillaceous-banded and lenticular-bedded lime mud characterized the foreslope facies at this time, whereas fenestral lime mud dominated the platform. Sea-level dropped to a minimum before the *expansa* Chronozone. The carbonate platform was mostly subaerially exposed so that the sediments of the *trachytera* and *postera* Biozones are absent. Associated lowstand debris-flows developed on the foreslope.

A partial sea-level rise appeared during the early *praesulcata* Chronozone, but another significant decrease started later in this zone (Text-Fig. 7). Storm-influenced debris-flow sediments accumulated in the foreslope facies, whereas a subaerial exposure-solution surface with undulating relief formed in the platform-margin facies. The top of the fenestral-limestone in the platform interior shows evidence of penecontemporaneous subaerial exposure.

At Dushan (Text-Figs. 6 and 8) mixed Devonian siliciclastic-carbonate lithofacies are assigned to five facies associations that record a broad range of depositional environments, from alluvial to deeper subtidal shelf. Facies-stacking patterns and correlations of individual surfaces across the nearshore part of the shelf suggest the following five distinct phases (Text-Fig. 8), are shown in Table 2.

Table 2.
Facies stacking patterns at Dushin (lowest to highest; Text-Fig. 8).

Phase	Sequence	Description
1	I	Mixed siliciclastic and carbonate sedimentation; progradation of ooid shoals (0.8 m), with top marked by subaerial exposure.
2	II	Progradation of perital and subtidal carbonate buildups; carbonaceous shale bed with flooding surface. Subsequent shallowing and aggradation, capped by oolitic and thin ferricrust.
3	II and III	Very shallow deposition with sea-level rise and ultimate offlap
4	IV	Retrogradational deposition of dolomite and laminated algal limestone with fenestral fabrics. Represents major sea-level drop throughout China.
5	V (latest Famennian)	Increased terrigeneous influx, progradational carbonates accompanying a sea-level rise.

Although conodont collections and data derived from them constraining even more exact correlations are not yet complete, it is important to note that nearshore siliciclastic wedges occur at similar relative stratigraphic levels in different places in south China's Upper Devonian succession. Furthermore, the pattern of sea-level changes in platform interiors and margins are similarly correlative across the region (Text-Fig. 8).

4. Famennian and Tournaisian Paleoclimates and Foraminiferan Biogeography

The composition of benthic foraminiferan assemblages is a very sensitive indicator of water temperature (SAIDOVA, 1975; MURRAY, 1987), and the study of benthic foraminifera dispersal patterns thus represents a very useful tool for deciphering past climatic oscillations (KALVODA, 1990). We suggest that the transgressive and regressive curve of JOHNSON et al. (1985) can be modified as newer information on Famennian and Tournaisian biota becomes available. Organism migration patterns provide a history of relative climatic change. This has been done to reconstruct Dinantian paleoclimates (RAYMOND et al., 1989; KALVODA, 1989). The lower Famennian is dominated by dark-colored muddy carbonate facies indicating a low oxygen (dysaerobic) environment. Siliceous organisms, e.g. radiolarians and sponges (NAZAROV & ORMISTON, 1985; MCGHEE, 1982), apparently flourished.

During the *P. expansa* Chronozone (late Famennian) transgressive biodetrital limestone facies reached their maximum distribution and covered wide areas of the broad, flooded shelves. This situation enabled widespread migration of typical late Famennian foraminifera (represented by diverse *Quasiendothyra*, which is reported in a wide belt from Alaska to Australia, KALVODA, 1986). This is compatible with the worldwide warming in the Strunian. The middle *praesulcata* Chronozone regression is perhaps the most characteristic event in the late Famennian. It can be traced worldwide, including the Rheinische Schiefergebirge, Belgium, Montagne Noire, Urals, China, Omolon, and North America (KALVODA, 1989), and it is more easily identifiable than the early *praesulcata* Chronozone anoxic event. This worldwide event correlates well with extended glaciation on South American continental precursors (STREEL, 1986). Data from many shelves show that the LE-LN fall sea level fall manifested a very significant glaciation peak occurring within a longer glaciation period (larger sea level lowering on continental margins of the world; Text-Fig. 9).

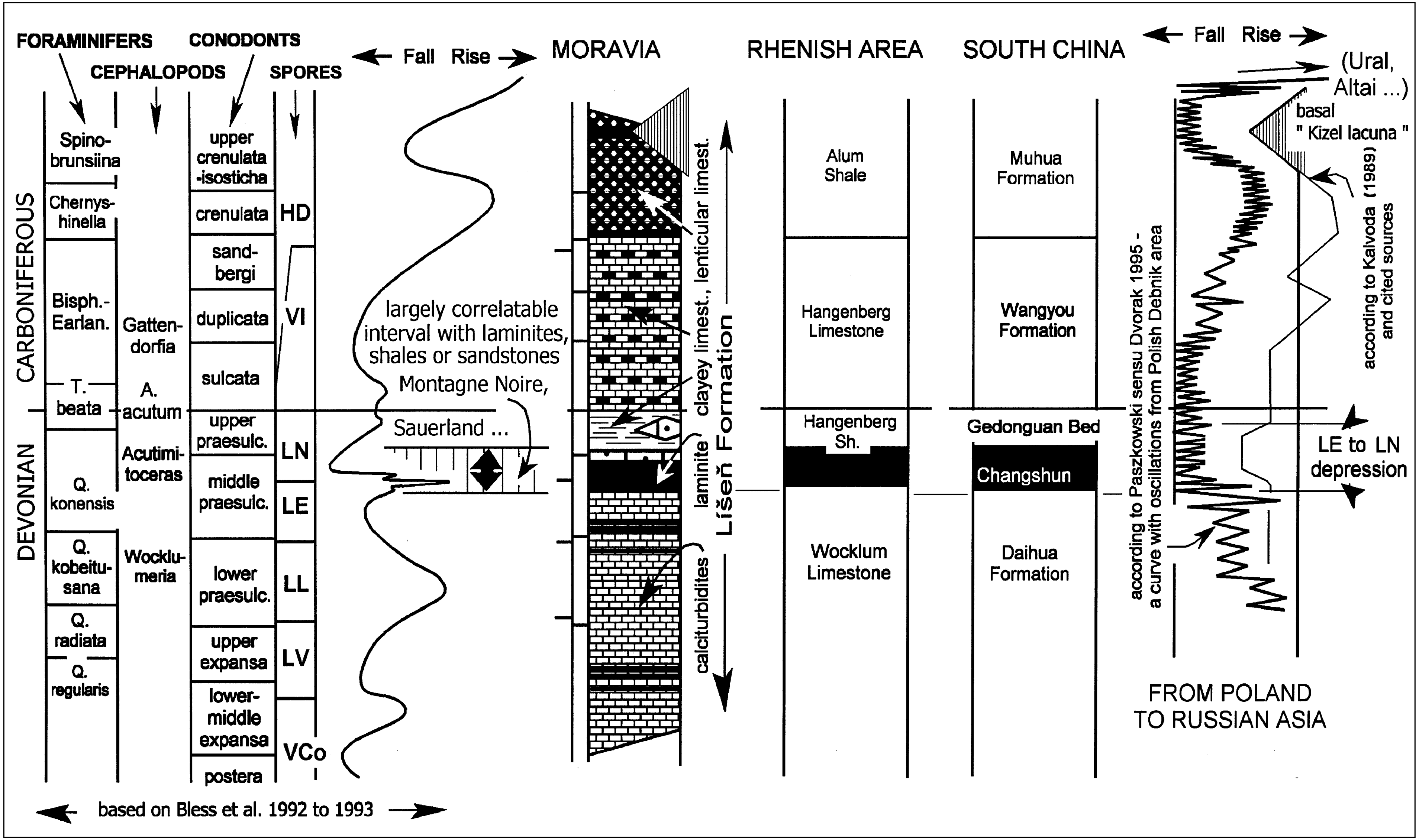
Another important event is the *sulcata* event (KALVODA & KUKAL, 1987). In Moravia, as in other parts of the world, *sulcata* Biozone sediments commonly unconformably overlie regressive facies of the *praesulcata* Biozone (KALVODA, 1986). In some places, the erosion that produced the unconformity also removed part or all of the *sulcata* Biozone record, and sediments of the *praesulcata* or *expansa* Biozones are overlain by sediments of the duplicata Biozone or even younger zones. Even though the sea-level at this time was in a relatively lowstand mode, the *sulcata-sandbergi* interval is transgressive in relation to the preceding middle and upper *praesulcata* regression (BLESS et al., 1993).

The *sulcata* event was marked by a considerable change in the character of carbonate sedimentation. During the *sulcata-sandbergi* interval muddy carbonate facies were widespread. They contain abundant radiolarians, thin-shelled ostracodes and primitive foraminifera. This situation resembles the early Famennian setting. Modeled water temperatures show that seas were generally warmer during the Famennian than during the Tournaisian (BRAND, 1993).

Restoration of high-diversity foraminiferan assemblages in the middle Tournaisian occurred mainly in the Paleotethyan Realm and is compatible with climatic warming in this realm. The middle Tournaisian transgression was worldwide. It is recognized in North America and Europe (KALVODA, 1989; BECKER, 1993), China (MUCHEZ et al., 1996), as well as Siberia's Omolon Massif (SIMAKOV et al., 1983). The middle-upper Tournaisian boundary is characterized by a considerable decline in foraminiferan diversity and the extinction of the *Chernyshinella* fauna. The onset of this interval, accompanied by the decline of this fauna, appears to be connected with the occurrence of time-specific euxinic black-shale facies along the southern European margin of Laurussia ("Calcschiste de Maurenne" in Belgium, and black shales in Moravia) and the development of widespread unconformities in North America, the Urals and in Siberia. In addition, facies with low-diversity faunas have been recognized both in Eastern and Western Europe and in North America (KALVODA, 1991).

A low diversity and widespread occurrence of calcareous foraminifera with inclusions of agglutinated grains characterize the foraminiferan fauna corresponding to the upper *crenulata-isosticha* and lower *G. typicus* Biozones. The occurrence of some taxa, such as *Paraendothyra* and *Latiendothyranopsis* in high paleo-latitude of the Siberian Realm and boundary regions (e.g., Tien Shan), as well as in North America, may be compatible with a high-latitude origin of the calcareous forms with agglutinated grains (caused by the availability of $CaCO_3$ in cold water) and migration to lower latitudes. At the middle-upper Tournaisian boundary this correlates with the reduced diversity of calcareous foraminifera. For comparison, there is a correspond-

Text-Fig. 9.
Significance of an additional sea level drop during the LE-LN (late Famennian) Palynozones that occurred within an overall sea level offlap in Famennian time.



ing minimal effect on small agglutinated foraminifera during anoxic events during the Mesozoic (BRASIER & YOUNG, 1988). The increased prevalence of shaley facies on the Tournaisian shelves evidently manifests a decline of carbonate sedimentation during a cooler climatic episode.

In the upper Tournaisian there is a transgression and widespread migration of the Paleotethyan biotic elements in the Siberian and North American Realms. This represents the Tournaisian warming climax (KALVODA, 1989). This conclusion is supported by the coral faunas (FEDOROWSKI, 1981). The upper part of the *G. typicus* Biozone is characterized by diversification and widespread occurrence of "upper Kizel fauna" (especially by loeblichiids), which is typical of the Kizel Cycle of LIPINA (1963) in the Paleotethyan Realm. This fauna is relatively scarce in the Siberian Realm. There is a massive migration of the Paleotethyan foraminifera fauna, which can be traced into the Kolyma region and the Omolon Massif (YUFEREV, 1973; SHILO et al., 1984) areas in Siberia.

An important aspect of the development of and changes within foraminiferan biogeography compatible with the global eustatic curve is a certain periodicity of climatic oscillations. Thus the faunal patterns in the upper parts of the stages (i.e., upper Frasnian, uppermost Famennian, upper Tournaisian) suggest the acme of climatic amelioration connected with the widespread migration of Paleotethyan tropical and subtropical organisms to the higher latitudes. This was followed by climatic deterioration at stage boundaries resulting in the immigration of taxa to the Paleotethys area from higher latitudes. The lower parts of the stages are characterized by evidence of further cooling that resulted even in the decline or retreat of the Paleotethyan fauna from high latitudes. It is partly supported by data of STREEL (1986) that most glacigenic sediments of South America correspond in age to the uppermost Famennian, Tournaisian and Visean. This agrees well with lower Visean tillites recently reported from Niger (LANG et al., 1991). Additional support comes from the data of BRUCKSCHEN & VEIZER (1994), who report that both oxygen and strontium isotopic curves show cyclic 4^{th}-order fluctuations with a periodicity of 10^6 years that are superimposed on the 3^{rd}-order (10^7 years) trends. Concurrently, both curves correlate with smaller scale sea level changes. Since ice-volume fluctuation is the only presently-known mechanism that could have produced such sea-level changes, the 4^{th} order $\delta^{18}O$ oscillations appear to reflect combined ice-mass and temperature effects.

5. Conclusions

While there is not direct support for early Famennian glaciation, in our opinion the sedimentological data (especially the geographical contraction of the carbonate sedimentation belt; HECKEL & WITZKE, 1979) and paleontological data (e.g., the great impact on the stenothermal fauna), together with evidence of a worldwide regression recognized at the Frasnian-Famennian boundary (GOODFELLOW et al., 1988; HLADIL et al., 1991) can all be construed as manifesting the effects of glaciation (BUGGISCH, 1991).

The middle Famennian is dominated by regression. The widespread occurrence of evaporites is reported from Montana (SANDBERG et al., 1983), and from the Pripyat Depression and the Dnieper-Donetz Basin (MANUKALOVA-GREBENJUK, 1974; AVKHIMOVICH & DEMIDENKO, 1985). The middle Famennian sea-level lowstand, traced both in the western part of Laurussia (JOHNSON et al., 1985) and in Moravia (KALVODA, 1987), in Poland (MATYJA, 1993) as well as in Eastern Europe (accompanied by the widespread evaporite occurrence), seems to be compatible with another glacial event.

The correlation of Gondwanan glaciation to North American marine cycles (HECKEL, 1977) during Carboniferous time is well-established (VEEVERS & POWELL, 1987). We submit that with increasing evidence for significant glaciation in the Late Devonian of South America, its effects in more temperate contemporary depositional systems must be studied. Several avenues of analysis are required, including:

1) timing of karstification and phreatic zone brecciation of various Late Devonian and earlier carbonates;
2) deposition of evaporites;
3) clastic wedge progradation;
4) black shales as sequential replacement lithologies for Frasnian carbonate banks; and
5) the timing of Famennian hiatuses in the framework of a recently corrected timescale.

Also, further study of this time interval on a global basis (e.g., ferruginous oolites in Libya) is required.

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