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See table of contents

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Article abstract

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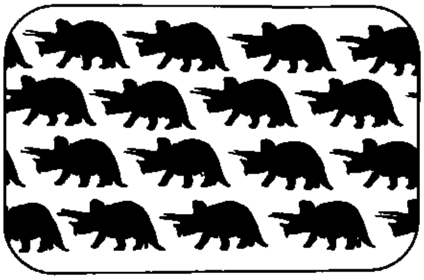

Western Interior Cretaceous

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Summary
Cretaceous North America was divided throughout most of the period by the Western Interior seaway, which connected temperate waters to the developing Arctic Ocean and tropical waters of the opening Atlantic. Vast quantities of terrigenous clastic sediments, fed into the seaway from the Cordillera, accumulated in shallow waters during two, major, marine cycles of sedimentation. Widely distributed, rapidly evolving, invertebrate stocks and a reliable radiometric time-scale combine to produce an exceptionally refined stratigraphic system. Marginal-marine sand complexes, some of which have been used to establish model patterns of deltaic and interdeltaic sedimentation, record local and regional tectonic movements.

Sommaire
Durant presque tout le Crétacé, l'Amérique du Nord était coupée par la mer de l'Intérieur ouest qui reliait les eaux de l'Océan Arctique en voie de développement, à celles de l'Océan Atlantique. De grandes quantités de sédiments clastiques terrigènes provenant de la Cordillère se sont accumulées dans les eaux peu profondes durant deux cycles majeurs de sédimentation marine. Des groupes d'invertébrés très répandus et d'évolution rapide, ainsi qu'une échelle de temps radiométrique fiable nous offrent un système stratigraphique exceptionnellement raffiné. Des complexes de sables marins marginaux, dont quelques uns ont servi pour établir des modèles de sédimentation deltaique et interdeltaique, se sont accumulés en réponse à des mouvements tectoniques locaux et régionaux.

General

A wealth of new information on the Cretaceous System in the Western Interior of North America has emanated recently from federal, provincial, and state geological surveys, and from museums, universities, and allied institutions in Canada and the United States. Moreover, a renewed interest in the system has been shown of late by the oil and mineral industries in both countries. The desirability of bringing together geologists from these various concerns so that they might increase understanding of a subject of common interest was recognized some years ago by the Geological Association of Canada. It led that body to sponsor a symposium on "The Cretaceous System in the Western Interior of North America" at its annual meeting held in May, 1973, at the University of Saskatchewan in Saskatoon. The proceedings of the symposium are to be released shortly as Geological Association of Canada Special Paper 13. A review of selected aspects of Western Interior Cretaceous geology in the light of a few correspondingly selected contributions to the symposium and its proceedings seems appropriate and timely.

Rocks of the Cretaceous System are widely distributed throughout the continental Western Interior. Although partly buried beneath Tertiary and Quaternary deposits, they can be traced with negligible break in continuity from the valley of the Mackenzie River to that of the Rio Grande and from the valley of the Mississippi River to the Rocky Mountain front. Together with the Tertiary deposits, they form the bed-rock foundation of the Great Plains.

The Western Interior is by far the largest North American Cretaceous 'province'. Its thick sequences of terrigenous clastic sediments represent the products of sedimentation in a differentially subsiding trough, asymmetrical in cross-section, which ran the length of the continent and separated the rugged, tectonically restless Nevadan-Columbian mountains of the Cordillera from the topographically subdued platform of the Stable Interior. For most of the Cretaceous Period (nearly 40 million years) the trough was covered by a vast strait, commonly called the Rocky Mountain or (preferably) the Western Interior seaway, which resulted from the confluence in late Early Cretaceous time of a sea rapidly transgressive by way of the District of Mackenzie and the Canadian prairie provinces and a sea slowly transgressive from the Gulf Coast through the four-corner states. Between 5,000 and 10,000 feet of terrigenous clastic sediments were deposited over much of the Western Interior before withdrawal of the seas towards the close of the Cretaceous Period. Most of the Cretaceous sediments in the Western Interior are marine, therefore, but they are usually underlain and overlain by non-marine sediments which accumulated before the marine transgression and after the regression. Moreover, the increasing strength of pulsatory tectonic movements, premonitory of the Laramide revolution, led to huge wedges of the coarser grades of continental clastic sediments being shed into the seaway during Late Cretaceous time. These are important components of the western sequences and, together with the wedges of marine shales with which they are intertongued, they form the clastic-wedge associations for which the Western Interior basin is justly famous.

The general distribution of Cretaceous rocks in the Western Interior has been known for well over a century, but as K. M. Waage of Yale University has pointed out in a valuable paper filling a long-acknowledged gap in the history of North American geology, it was much later before the basic sedimentary structure of large-scale, intertonguing, marine and non-marine deposits was unravelled through the efforts of the United States and Canadian Geological Surveys. This solution of the intertonguing pattern led to the first clear understanding of facies relationships in North American stratigraphy.

Spatial and Temporal Considerations

The weighty evidence that now has accumulated in support of proximity of the North American and European plates during the Cretaceous Period invites re-examination of the differences and similarities between the Cretaceous deposits of North America and those of northern Europe. In terms of the sequence of facies recognizable in the Upper Cretaceous Series, this now has been done by J. M. Hancock of the University of London. Hancock points out that, although the sequences in northern Europe are thin compared to those in the Western Interior, they contain rocks of similar facies. But whereas the age and distribution of the facies in the Western Interior points to two, complete, transgressive-regressive cycles of sedimentation (the Greenhorn and Niobrara cycles of Hattin, 1966 and Kauffman, 1969), similar facies in Europe generally are so disposed as to appear to mark a single transgression. Regressive sequences are rare in Europe, where times of regression in the Western Interior are marked either by breaks in the sequences (a whole stage may be missing) or by severely condensed sequences. Hancock finds an explanation for many of the dissimilarities between Europe and North America in the contrasted physiographic frameworks and climates of the two continents. Whereas in North America the vast Cordillera, repeatedly revived by proto-Laramide movements, was available for erosion, in Europe there was only a number of relatively small, insular, oldland massifs and, as these became submerged beneath the expanding Cretaceous sea, clastic sedimentation decreased. Moreover, the climate of the Western Interior well may have been conducive to greater erosion of the flanking landmasses. After Cenomanian time the climate of Britain and northern France probably was arid, so that the total amount of detritus contributed to the seas was extremely small. Hancock finds support for this facet of his argument by pointing out that, in central Europe where the fossil floras indicate a more humid and seasonal climate, thicknesses of detrital sediments are considerably greater than in northwestern Europe.

R. Couillard and E. Irving of the EMR Earth Physics Branch, on the basis of palaeomagnetic observations from scattered localities within the continent, have concluded that the magnetic north pole in Cretaceous times lay just west of present-day Alaska (lat. 68°N; long. 185°W), with the latitudes of the northern and western parts of the continent about 10° higher than at present, those of the eastern parts about 10° lower. The Western Interior seaway, therefore, must have had a NNE–SSW alignment. Such an orientation for the continent helps to explain some differences and similarities in faunas. For example, Douglas and Sliter (1966) pointed to the similarities of foraminiferal faunas in the Gulf Coast and Atlantic Coastal Plain Cretaceous 'provinces', and both these provinces must have lain within a fairly narrow zone straddling the 30° parallel of latitude.

Couillard and Irving go on to point out that a world-wide compilation of palaeomagnetic data from continental Cretaceous rocks shows that from 109 to 82 m.y. ago the geomagnetic field was predominantly of normal polarity – the Cretaceous Normal Polarity Interval – and that this is represented in the ocean floors by the Cretaceous 'Quiet Zone', the limits of which have been determined independently by Larson and Pitman (1972) as 111.5 to 84.5 m.y. ago. The boundaries of this interval are useful stratigraphic markers. Couillard and Irving stress that the Cretaceous Normal Polarity Interval was also a time of change in the rates and patterns of plate movements. They attribute the correlation of plate activity and behaviour of the core-generated geomagnetic field to a sudden increase in the number of volcanic sources deep within the mantle (Morgan-type plumes) about 110 m.y. ago. It has already been suggested (Pitman and Hayes, 1973) that the rapid sea-floor spreading and uplift of new ridges that took place during the Cretaceous Normal Polarity Interval caused the oceans to spill on to the continents, creating the mid-Cretaceous (Cenomanian) transgression. Pitman and Hayes consider that, about 85 m.y. ago, the ridges subsided and the shallow epicontinental seas, such as that forming the Western Interior strait, began to empty back into the ocean basins. They believe that the regression was of greater magnitude than the transgression and speculate that it triggered the faunal changes marking the Cretaceous-Tertiary transition.

Whereas Couillard and Irving concern themselves with the implications for the Western Interior of certain world-wide Cretaceous events, G. D. Williams and C. R. Stelck of the University of Alberta have considered the implications of changes in North American Cretaceous geography. Their review is timely, because concepts of Western Interior palaeogeography have changed markedly in less than a decade. Due partly to an inadequate knowledge of the Cretaceous System in the northern parts of Canada, the notion was prevalent some years ago that, shortly after confluence of the northern and southern seas to form the Western Interior seaway, the northern arm receded and left the Western Interior of the United States and the southern parts of the Canadian prairie provinces covered by a vast extension of the Gulf of Mexico. Gill and Cobban (1966, p. A43-A45) presented a palaeogeographical map of North America in late Campanian time showing the seaway open to the north and with a connection through southern Ellesmere Island and Baffin Bay to western Greenland. The connection with Greenland was postulated to provide a migration route between the Western Interior and the Nugussuaq and Svartenhuk Peninsulas of western Greenland from which Birkelund (1965) described ammonites (particularly scaphites) closely similar to Turonian to Maestrichtian species described from the northern Western Interior. Jeletzky (1971a,b) also has been a strong proponent of the seaway being open to the north with a link to western Greenland until near the close of the Cretaceous Period. The idea of a migration route between the Western Interior and western Greenland is not new – Teichert postulated one in 1939 – but its precise position was, and remains, unknown in detail. Drawing freely on the palaeogeographic reconstructions of others (for example, Jeletzky, 1971a, b) and cognizant of the recent studies of the Cretaceous System in the Sverdrup Basin and other parts of Arctic Canada, Williams and Stelck hypothesize that the connection with western Greenland lay through eastern Manitoba, western Ontario, Hudson Bay, Hudson Strait, and Davis Strait for most of Late Cretaceous time. They favour the Western Interior seaway openly connected with a northern ocean through early Maestrichtian time, and the Hudson Bay–Davis Strait seaway also openly connected with the northern ocean through Baffin Bay and Ellesmere Island for much of Campanian and Maestrichtian time. Although, by their own admission, Williams and Stelck's suggestion is speculative, extension of an arm of the Western Interior seaway from Manitoba through Hudson Bay and beyond will appeal to students of the Cretaceous System in the Interior Plains of Canada, many of whom long have been troubled by a tendency to assume that the eastern margin of the Western Interior seaway lay only a short distance east of the erosional edge of the Manitoba escarpment. Most of the Manitoba sediments offer not the slightest hint of near-shore deposition, and some of them compare most closely with beds of mid-basinal facies in eastern Colorado, western Kansas, and other parts of the United States.

An important step towards refining the Cretaceous time-scale has been taken by J. D. Obradovich and W. A. Cobban of the USGS, who integrate radiometric ages obtained from bentonites (altered volcanic ashes) using the K/Ar chronometer with some of the 60 (mainly) molluscan zones now recognized in the Upper Cretaceous Series of the Western Interior. They offer absolute ages for 14 of these zones and, on the bases of correlation of the faunal zones of the Western Interior with those of the European type sections and of available radiometric data, they suggest ages for all the stage boundaries of the Upper Cretaceous Series. Ideally, of course, the absolute time-scale should be based on the European type sections in France, Switzerland, and The Netherlands, but there interlayered volcanics, which provide minerals suitable for dating, are virtually absent from these sections, and three-quarters of the ages obtained are based on glauconite (Casey, 1964, Table I), a mineral of questionable reliability for age determinations. By contrast, it is quite possible that during the Cretaceous every Rocky Mountain province and state had its volcanic centres that underwent repeated, explosive eruption and spread ashes over the flanking interior seaway. These became intercalated, as isochronous markers, with a nearly continuous pile of marine deposits containing the remains of many rapidly evolving ammonite and bivalve stocks. They were altered to bentonite and today yield such minerals as biotite and sanidine which may be used for reliable age determinations. The Obradovich–Cobban study should contribute substantially to establishing the Western Interior as the region upon which the Late Cretaceous time-scale logically will be based.

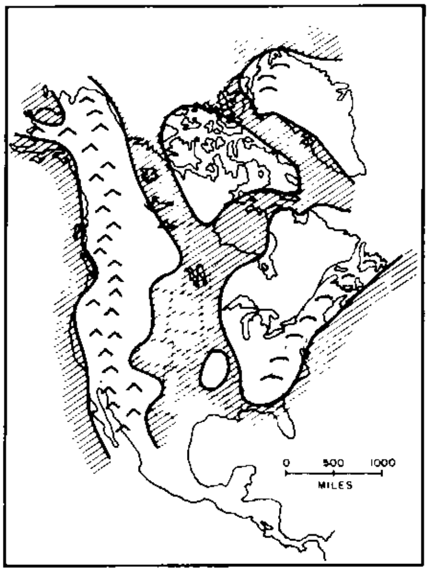

Figure 1
Distribution of the Late Cretaceous mid-Campanian seas in North America. Note the proposed extension of the Western Interior seaway to Western Greenland through Hudson Bay, Hudson Strait, Davis Strait, and Baffin Bay (After Williams and Stelck, 1974).

Biostratigraphy

Mollusca. The Cretaceous basin of the Western Interior is an outstanding centre for biostratigraphical studies. As Kauffman (1969) has noted, the epicontinental sea that covered it (3,000 miles long and 900 miles wide at maximum flooding) provided a major thoroughfare for the migrations of boreal and warm-water faunas. The basin as a whole is noted for its excellent exposures of marine sedimentary rocks, lateral persistence of formations and members, clearly documented cyclicity of sequence, abundance and diversity of fossils, wide geographic distribution and rapid evolutionary development of many molluscan stocks, and completeness of the sedimentary and faunal record of marine history. The most refined and reliable zonal schemes are overwhelmingly dominated by molluscs, particularly ammonites (see, for example, Gill and Cobban *in* McGookey, 1972; Jeletzky, 1968), with nearly 60 zones identifiable in the Upper Cretaceous Series, 27 of them in Campanian and Maestrichtian rocks alone. The zones are of 0.12 to 0.5 m.y. duration (Kauffman, 1969). The biostratigraphic system is one of the most detailed in the world, and it has been largely developed within the last 20 years. Yet by using population systematics, developing and integrating zonal schemes based on a wide variety of fossil groups, and refining the absolute time-scale (the new Obradovich-Cobban time-scale being a step in that direction), Kauffman and Kent (1968) and Kauffman (1970, 1972) foresee a more sophisticated and reliable biostratigraphic system – 'a new biostratigraphy' – that will improve the current system by a factor of approximately one-third.

E. G. Kauffman of the U.S. National Museum has been a vigorous proponent of a greater role for bivalves in Cretaceous biostratigraphy, and in his latest paper he argues convincingly and forcefully for his cause. Pointing out that the benthonic bivalves are common constituents of most Western Interior biotas; that large, closely spaced populations of many lineages are to be found in the marine sequences, allowing detailed evolutionary studies; that evolutionary rates in many bivalve lineages equal those of ammonites and far exceed those of foraminifers; and that bivalves achieved wide, rapid, biogeographic and environmental dispersal, he claims that bivalves should be important zonal elements for widespread correlation and should figure prominently in his 'new biostratigraphy'. Biostratigraphers long have had the notion that the nektonic ammonites should have achieved a much wider geographic dispersal than the benthonic (commonly sessile) bivalves. It is upon this question of dispersal that Kauffman focusses much of his attention, building a thesis rooted in neontology. His study of the modern counterparts of Cretaceous bivalves has revealed that the following factors among others offset a general lack of adult mobility and lead to wide, rapid, geographical spread: large egg yield; long-lived, planktonic, larval stages, which may be extended if high-stress environments are imposed or suitable substrates for settling are not encountered; and broad, environmental tolerance at the late neanic and ephebic stages. Kauffman argues that the success of the inoceramid and ostreid bivalves in Western Interior biostratigraphy should provide an impetus for further research on bivalves. These families are exceptionally reliable for intercontinental and interregional correlation. Between 70 and 80 per cent of the species and subspecies of the Western Interior and Gulf Coast are shared with Europe as far east as Russia, and in both continents they remain in consistent stratigraphic succession. By contrast, the Western Interior ammonites are more endemic, with less than 10 per cent common to both continents. About 50 per cent of inoceramid zones are common to both the Cretaceous rocks of the Caribbean and Western Interior regions, but there are no common ammonite zones. These bivalves, therefore, seem to have been able to transgress without much difficulty the boundary between the Cretaceous Tropical and Temperate climatic zones.

Kauffman's study is strongly palaeobiological and illustrates the kind of study that more palaeontologists undoubtedly will undertake in search of better understanding of the Western Interior biostratigraphic system.

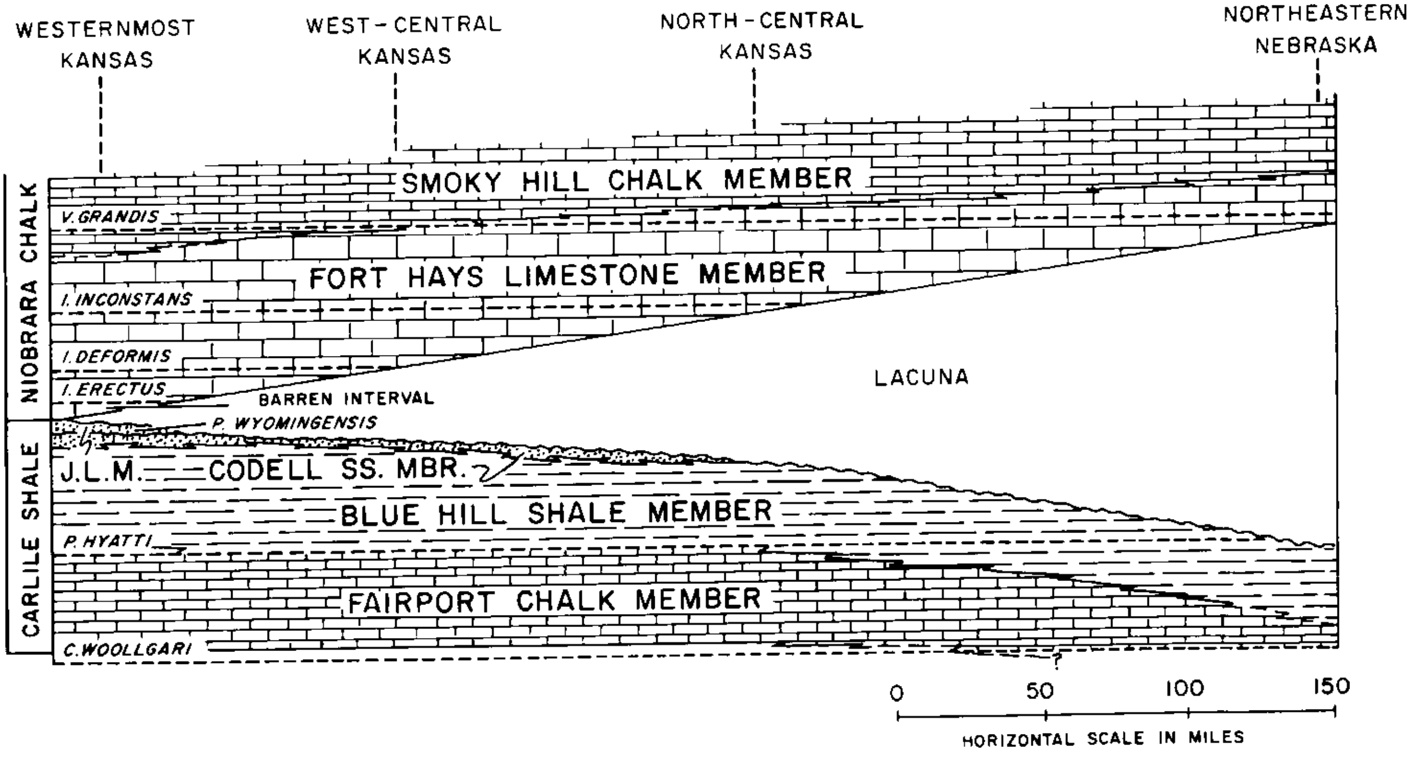

Figure 2
The Carlile-Niobrara unconformity in Kansas and Nebraska. Note (i) the expansion of the lacuna (time of erosion and non-deposition) northeastwards into Nebraska, indicated by the progressive elimination in that direction of the higher zones of the Carlile Shale (by erosion) and of the lower zones of the Niobrara Chalk (by overlap); and (ii) the southwestward diachronic rise of the Fairport-Blue Hill and Blue Hill-Codell contacts, and the northeastward diachronic rise of the Fort Hays-Smoky Hill contact. Explanation of abbreviations: J.L.M. = Juana Lopez Member, a calcarenite member of the uppermost Carlile widely traceable through northwestern New Mexico and southwestern Colorado, the attenuated eastern edge of which reaches westmost Kansas. Generic names: C = Collignoniceras; P = Prionocyclus; I = Inoceramus; V = Volviceramus (After Hattin, 1974).

An impressive illustration of the detailed stratigraphic resolution that is possible by applying molluscan zonal schemes has been provided by D. E. Hattin of Indiana University. Along a 400-mile line of section running from western Kansas to northeastern Nebraska, Hattin recognizes six ammonite and bivalve zones in some 30 feet of beds that include the disconformable contact between the Carlile and overlying Niobrara Formations. The ammonite zones, based on collignoniceratid species, are confined to the Carlile Formation, and they are correlative with the lower bivalve zones. The bivalve zones are all founded upon inoceramid species and are distributed through both formations. Three members are recognized in the Carlile Formation – the lower Fairport Chalk, middle Blue Hill Shale, and upper Codell Sandstone – and two in the lower part of the Niobrara Formation – the basal Fort Hays Limestone and succeeding Smoky Hill Chalk. By placing his various sequences in the zonal framework, Hattin demonstrates that, north-eastwards from westernmost Kansas, the uppermost beds of the Carlile Formation become older, the basal beds of the Niobrara Formation younger. The Codell Sandstone and the upper Blue Hill Shale are bevelled by erosion, and the Fort Hays Limestone displays strong internal overlap and external overstep with respect to the Codell and Blue Hill Members. At least five ammonite or bivalve zones recognized in other parts of the Western Interior are missing at the disconformity in western Kansas, and as many as eight are missing in northeastern Nebraska. In other words, the magnitude of the lacuna marked by the plane of disconformity becomes progressively greater northeastwards. The biostratigraphic analysis, moreover, allows Hattin to recognize a westward diachronic rise in the Fairport–Blue Hill contact, to assume one for the Blue Hill–Codell contact, and to recognize an eastward diachronic rise in the Fort Hays–Smoky Hill contact. The Carlile beds represent the prograding deposits of the regressive sea that marked the end of the first, major, marine cycle of sedimentation in the Western Interior (the Greenhorn Cycle of Hattin, 1966); the Niobrara beds represent the overlapping deposits of the transgressive sea that launched the second, major, marine cycle (the Niobrara Cycle of Kauffman, 1967, 1969). Theoretically, each facies within such cycles should be diachronous, transecting progressively younger time planes in the directions of regression and transgression (see the model of Kauffman, 1967). Hattin's findings pointing to broadly westward regression of the Carlile sea and eastward transgression of the Niobrara sea fit the cyclic model ideally. More generally, his convincing demonstration of interrelated facies variation, diachronism, and unconformity in a transgressive-regressive couplet would be appropriately included in future textbooks on stratigraphic principles.

Foraminifera. Just as molluscan biostratigraphy has been dominated by the once-mobile ammonites and yet the benthonic bivalves may have at least comparable biostratigraphic potential, so foraminiferal biostratigraphy has been dominated by the pelagic groups, and the potential of the more numerous, varied, benthonic groups has not yet been fully realized. D. L. Eicher of the University of Colorado has begun to fill a critical void by describing the sequence of foraminiferal faunas (benthonic and pelagic) in some of the type and reference sections in the Western Interior of the United States (see Eicher, 1960, 1965, 1966, 1967; Eicher and Worstell, 1970), thereby providing a yardstick against which the faunas in the Canadian portion of the basin, described over the last twenty years, can be measured. Eicher has concentrated mainly on faunas of Albian to Turonian age. In an extension of this work, M. P. Frush and Eicher now have described the faunas of two successive assemblage zones in facies-equivalent carbonate and shaly sequences of Cenomanian and Turonian age from the Big Bend region of Texas and Mexico. They dispute a previous suggestion that the eastern limy sequence represents a shoal-water facies of the western shaly sequence, arguing that the depth of water under which the eastern facies accumulated was as great or greater than that in which the western facies accumulated because the limy sequence contains a greater abundance and diversity of keeled planktonic species. The Frush and Eicher paper refocusses attention on the contentious issue of water depths within the Western Interior seaway, particularly in the axial zone of the basin when the sediments of the Greenhorn and Niobrara Limestones and equivalents were deposited. Kauffman (1969) concluded that the limestones originated on a broad, elevated platform in the axial zone at depths of 100 to 200 feet – a few hundred feet shallower than the depths at which the calcareous and non-calcareous muds of the basin flanks were deposited. In sharp contrast, Eicher (1969), using the evidence provided by the planktonic foraminifers and that of the inferred palaeoslope transgressed by the sea, concluded that Greenhorn water depths probably were between 1,500 and a maximum of 2,000 feet. Powell (1965) proposed a bathymetric model similar to Kauffman's for the Big Bend region. Asquith (1970) proposed essentially the Eicher model for deposition of the younger Niobrara Limestone in the Wind River basin of Wyoming. Not surprisingly, Frush and Eicher argue for deposition of their limy sequences at the Big Bend in water depths in excess of 1600 feet, and they do so on the basis of both the planktonic and benthonic assemblages.

Frush and Eicher stress the similarity of the foraminiferal distribution spectrum at the Big Bend to that of coeval deposits in Colorado and adjacent states insofar as there is a notable dearth of benthonic species in beds of late Cenomanian age. Eicher and Worstell (1970), discounting the possibilities of widely fluctuating temperatures or salinities, or of lack of nutrients, suggested stagnation, and as a consequence anaerobic bottom conditions, as an explanation. They attributed these conditions to sluggish circulation or to the presence of a sill. Now recognizing the extent of the zone devoid of benthonic species (at least 600 miles through the American Great Plains to the Rio Grande), Frush and Eicher conclude that the explanation must lie in widespread oceanographic conditions and suggest inhospitable bottom conditions resulting from a layer of oxygen-depleted water. They bolster their argument by citing examples of oxygen-minimum layers in modern seas and oceans, particularly the Arabian Sea, and the effect of these on modern foraminiferal distribution.

Palynology. The mushrooming literature of the last decade or more attests to the growing importance of palynology in Cretaceous biostratigraphy. Invertebrate fossils tend to be poorly represented in continental deposits, and therefore a significant role for palynology lies in stratigraphic analysis of the fluvio-lacustrine and marginal-marine sediments that mark the base and top of most complete Cretaceous sequences (see, for example, Kosanke and Cross, 1970). Moreover, because palynomorphs are found in both continental and marine deposits, they should figure prominently in unravelling the facies equivalency of the interleaved marine and non-marine wedges in the Upper Cretaceous Series. In wider context, palynologic studies are shedding new light on plant provincialism, continental relationships, and contemporary climatic and geographic conditions. Two papers illustrate some of these points.

G. Norris, D. M. Jarzen, and B. V. Awai-Thorne of the University of Toronto have summarized the 'Evolution of the Cretaceous terrestrial palyno-flora in western Canada', stressing as some of the main features: the domination of pre-middle Albian floras by gymnosperms and pteridophytes; the appearance of the first undoubted angiosperms in middle Albian time; the introduction of more elaborate, distinctive types of pollen in Cenomanian and in Turonian-Santonian times, when some forms of the important genus *Aquilapollenites* also made their appearance; and the marked diversification of the angiosperms in Campanian-Maestrichtian time. The *Aquilapollenites* flora is strongly represented in the Campanian-Maestrichtian assemblages. This flora is widespread in the Cordillera and in Siberia, suggesting land connections across or around the developing Arctic Ocean. Norris and his co-workers use the stratigraphically sensitive dinoflagellates, associated with the spores and pollen, to date important changes in the palynologic assemblages. Although a valuable compilation, the title of the paper may be somewhat misleading: strictly speaking, the paper deals with the succession of palynological suites in two, complementary, cored-borehole sections in southern Alberta.

C. Singh of the Research Council of Alberta has taken up in more detail the biostratigraphic significance of the appearance and diversification of angiosperm pollen in Albian and Cenomanian times. He has studied early angiosperm pollen from the Peace River country and other parts of Alberta, compared them to pollen described from correlative beds in other parts of North America, and concludes that five main stages can be recognized in the diversification of the angiosperm pollen within the continent. Singh dates these stages as carefully as possible in Alberta by using the associated megaflora, and mega- and microfauna. The angiosperms seem to have spread rapidly westward from Europe at the time of most rapid separation of the European and North American plates: the earliest reticulate monosulcate species appear in late Barremian beds in England, Aptian beds in the eastern United States, and middle Albian beds in Alberta and other parts of the Western Interior. The European Normapolles genera made their initial appearance in middle Cenomanian beds in the eastern United States, but their westward migration probably was checked by the expanded Rocky Mountain seaway. They reached Manitoba in late Turonian time and subsequently spread across the region of the present Great Plains.

Vertebrates. The dramatic extinction of the dinosaurs at the end of the Cretaceous Period is one of the best known but curious features of the fossil record. It tends to obscure the fact that many other groups of reptiles (although reduced in kind and number) survived the Cretaceous-Tertiary transition – a fact that, in turn, makes it more difficult to explain the selective elimination of the dinosaurs. In seeking reasons for the dinosaurs' demise, reliable documentation of reptilian changes across the Cretaceous-Tertiary boundary is clearly important, and to this end, D. A. Russell of the National Museum of Natural Science in Ottawa has made a semi-quantitative study of the various stocks with special reference to the Western Interior. His work shows that the apparent climax of reptilian diversity during Campanian time and the decline during Maestrichtian time reflect a bias in sampling; that extinctions coinciding with the Cretaceous-Tertiary transition occurred suddenly in both continental and marine realms (the duration best evaluated in the marine record); and that reptilian diversity in North America in earliest Tertiary time was about half that of latest Cretaceous time at the familial level, considerably less at lower taxonomic levels.

If D. A. Russell's paper emphasizes that the end of the Cretaceous Period was not truly the end of the 'Age of Reptiles', so a new contribution by L. S. Russell of the Royal Ontario Museum just as strongly underscores that the Paleocene Epoch was not truly the beginning of the 'Age of Mammals'. L. S. Russell has prepared a valuable synthesis of the Cretaceous, mammalian, faunal succession in western North America. Although the collection of Cretaceous mammals began with the work of the notorious rivals O. C. Marsh and E. D. Cope more than a century ago, Russell points out that it is the discoveries of the last decade that have provided the basis for a mammalian chronology. In an extension of the widely adopted scheme for post-Cretaceous rocks, Russell recognizes five stages based on certain geological formations and defined by mammalian faunas in the Cretaceous System of western North

America: the Paluxian (Albian), Aquilan (early Campanian), Judithian (middle Campanian), Edmontonian (late Campanian–early Maestrichtian), and Lancian (Maestrichtian); and he comments on the distinctive mammalian faunas that define them. The Aquilan to Lancian sequence is almost continuous, but there is a great gap between the Paluxian and Aquilan corresponding to the time of greatest marine inundation of the Western Interior. As Russell implies, the gap is critical, because if mammalian faunas of post-Paluxian–pre-Aquilan age can be found, they will be the key to the evolution of Jurassic-like assemblages into those that prefigured the remarkable mammalian radiation of Tertiary time. Although Russell's scheme offers a refinement of the Campanian Stage, in all likelihood his mammalian-stage terminology will be critized by those who have already fought hard and successfully to eliminate such North American stage names as 'Montanan' and to adopt entirely the international nomenclature.

Sands: Their Origins and Conditions of Deposition

Sedimentologists seeking to identify the sources and establish the modes of transportation and conditions of deposition of the vast quantity of terrigenous clastic sediment in the Western Interior basin have concentrated on the sands. They have been drawn particularly to the complex associations of non-marine, marginal-marine, and marine sands which, together with finer-grained sediments, accumulated mainly about the times of the initial advance and final retreat of the Western Interior seas but also between times in the thick tongues of detritus shed into the seaway as a result of tectonic revival of the western mountains. A few recent papers illustrate the contribution that sedimentological studies have made to deciphering the geographical and historical evolution of the Western Interior basin.

Partly because of post-Cretaceous cover, partly because of overlap within the Cretaceous series, and partly because of indifferent exposure, there are few areas where the basal sandy sequence deposited along the eastern margin of the seaway, can be examined, analysed, and interpreted. One such area is mid-Kansas, where the sequence consists of the late Albian to early Cenomanian Cheyenne, Kiowa, and Dakota Formations. In a comprehensive study, P. C. Franks of the University of Akron, Ohio, has used such factors as geometry of the sedimentary bodies, grain-size distribution, primary and secondary sedimentary structures, distribution and kind of fossils (including ichnofossils), and even diagenetic changes to reconstruct a series of depositional environments ranging from alluvial plain and estuarine (Cheyenne), through open marine (Kiowa), and back again to deltaic coastal plain (Dakota). His work confirms that the basal sandy sequence in Kansas was deposited adjacent to, and within, the waters of the Western Interior seaway as they underwent a minor transgressive-regressive fluctuation during the overall expansionary phase of the Greenhorn Cycle.

Most of the Cretaceous sediment in the Western Interior basin gives evidence of having been derived from the western mountains, and comparatively little from the Canadian Precambrian Shield and overlying Paleozoic rocks of the American mid-continent. Sediment of cratonic derivation is to be expected, however, along the eastern depositional margin of the basin, and Franks points to its presence in Kansas. Using heavy minerals as a guide, he concludes that not only the craton but also the central Appalachian Mountains were sources of some Kiowa and Dakota detritus. It is moot, however, whether the material was transported directly from the Appalachians to Kansas in Albian-Cenomanian time, or whether it was then merely recycled from the Permian rocks that now lie beneath the Cretaceous cover.

On the other side of the Western Interior basin and at the other end of the Cretaceous column, deltaic and interdeltaic complexes that formed in the wake of the final marine withdrawal have been contrasted by R. J. Weimer and C. B. Land of the Colorado School of Mines. They see the well-known Maestrichtian formation sequence in the western Denver basin as a record of sedimentation in a high-constructive delta. Prodelta shales and siltstones (Pierre Formation) are overlain by delta-front sandstones (Fox Hills Formation), delta-plain sandstones, claystones, and coals (Laramie Formation), and finally by braided channel conglomerates (Arapahoe Formation). Deposition of the pro-delta, delta-front, and delta-plain sediments was influenced by penecontemporaneous (growth) faulting, which locally caused increases in thickness of up to 200 feet. Posthumous movement on other deep-seated faults is believed to have exerted some control on water-depths. It is notable that growth faults have played an important role in trapping petroleum in the Gulf Coast region, and thus their recognition in the Upper Cretaceous rocks of the Rocky Mountain region has important implications for petroleum exploration (Weimer, 1973).

Farther north, in southwestern Wyoming, the time-equivalent sequence on the east flank of the Rock Springs uplift is interpreted by Weimer and Land as a product of sedimentation in a broad, regional embayment between major deltaic centres. Off-shore, shallow-water shales of the Lewis Formation are found to intertongue with, and be overlain by, littoral sandstones of the Fox Hills Formation which accumulated as barrier-islands and in tidal-rivers. These sandstones in turn intertongue with, and are overlain by, mudstones, thin coals, and lenticular sandstones of the Lance Formation which were deposited in lagoons, swamps, and small stream channels (Land, 1972).

Although Weimer and Land describe two distinctly different, yet related, patterns of sedimentation that, in their general characteristics, probably prevailed in the Rocky Mountain region near the close of Cretaceous times, they themselves caution against their reconstructions being used indiscriminately as models for other deltaic and interdeltaic complexes. As models, they may serve only for the analysis of high-constructive, deep-water deltas and interdeltaic embayments of high tidal energy. It should be borne in mind that both the Colorado and Wyoming sequences were influenced by immediately adjacent oldlands undergoing contemporary uplift in response to early Laramide tectonism.

The use of heavy minerals in determining the provenance and direction of transportation of Campanian to Paleocene sediments in Alberta and western Saskatchewan is the subject of an enlightening contribution by R. A. Rahmani and J. F. Lerbekmo of the University of Alberta. They divide the lithostratigraphic sequences into three 'slices' – the Belly River (Campanian), Edmonton (largely Maestrichtian) and Paskapoo (Maestrichtian-Paleocene), each including, and named after, an important group or formation in Alberta. By subjecting their heavy-mineral data to Q-mode factor analysis, they are able to recognize ten heavy-mineral associations, which form the bases for delineating ten heavy-mineral provinces. When mapped these provinces mostly take the form of linear belts parallel or subparallel to the principal structural elements of the flanking Cordillera. The distribution patterns of the heavy-mineral suites suggest that detritus was transported by a dominantly southeastward-flowing river system with a subordinate eastward- to northeastward-flowing one in the extreme south of the area of study. The kinds of heavy minerals, and, to a lesser extent, of light minerals, lead Rahmani and Lerbekmo to derive the detritus from sedimentary, plutonic, volcanic, and high- and low-grade metamorphic rocks, and to identify the probable sources as the Omineca Geanticline and, later, the Laramide uplift. Hornblende is a particularly common constituent of certain sandstones in the eastern part of the plains region, and previous workers (Chi, 1966; Lerbekmo, 1963, 1964) suggested that the distribution best could be explained by deriving the hornblende from Precambrian rocks of the Canadian Shield. Rahmani and Lerbekmo now have dated the hornblende radiometrically and found it to be 114 to 155 m.y. old (Late Jurassic–Late Cretaceous). Being of such an age, it could only reasonably have been derived from the intrusive rocks of the Omineca Geanticline in north-central British Columbia and southern Yukon Territory which were emplaced during the Columbian orogeny and are of compatible age. Clearly, therefore, the intrusive bodies of the northern Omineca uplift had been unroofed and were being eroded by Campanian time. Rahmani and Lerbekmo relate changes in the composition of the heavy-mineral suites and distribution of the heavy-mineral provinces with time to the waning pulses of the Columbian orogeny and early pulses of the Laramide orogeny. They suggest that these tectonic movements resulted more in shifts of the drainage system within the source area than in uplift and erosion to produce different kinds of source rocks. Others who have studied the mineralogy of the younger Cretaceous rocks of the southern Canadian Great Plains, working more locally and using less sophisticated methods than Rahmani and Lerbekmo, have suggested similar kinds of source rocks. Envisioning streams flowing more or less at right angles to the grain of the Cordillera, however, they tended to seek sources for the detritus to the west and southwest of the sites of deposition (for example, Byers, 1969; McLean, 1971). The important conclusions of Rahmani and Lerbekmo will require re-examination of some of the sources hitherto proposed.

Whereas considerable attention has been paid to the stratigraphy and sedimentology of the vast deltaic complexes that grew seawards from the western mountains at various times during the Cretaceous Period, the geographic positions of these complexes usually have been assumed to be adventitious and random. This C. R. Stelck of the University of Alberta points out in a thought-provoking paper on basement control of these deltaic wedges in

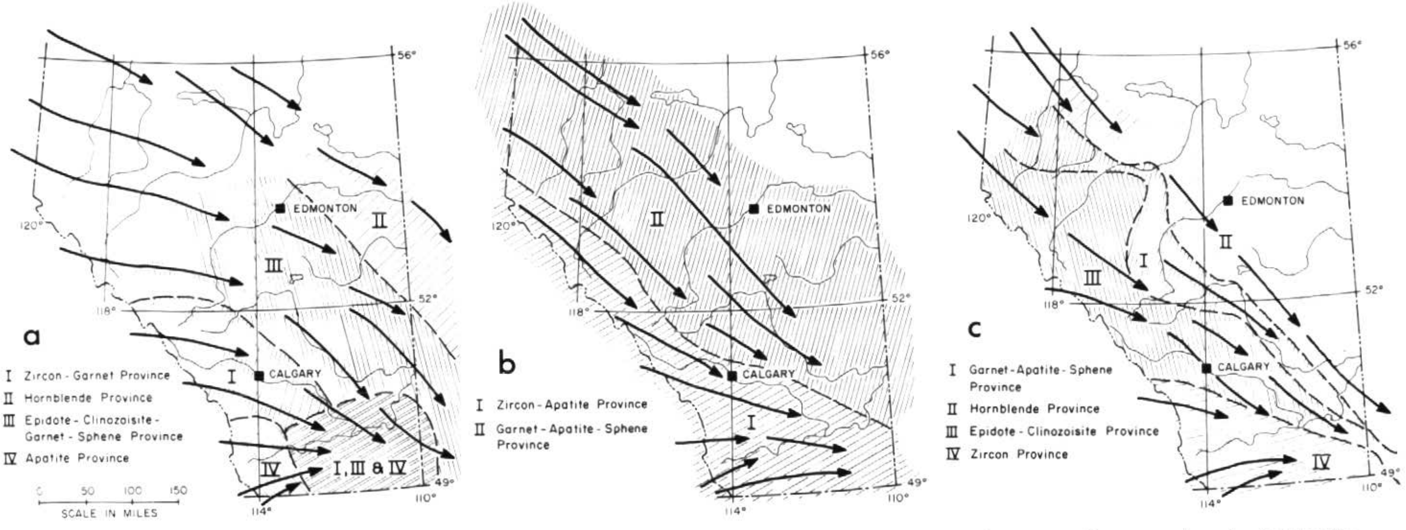

Figure 3
Heavy-mineral provinces (Roman numerals) and dispersal directions for some Upper Cretaceous and Paleocene beds in Alberta and western Saskatchewan: a, Belly River Group and equivalent beds; b, Edmonton Group and equivalent beds; c, Paskapoo Formation and equivalent beds (After Rahmani and Lerbekmo, 1974).

western Canada. Finding a possible mechanism for the upward movement of large blocks of the Precambrian basement in the ideas of Burwash and Kupricka (1969, 1970, 1973), and noting the evidence of Robinson, Charlesworth, and Ellis (1969) for basement influence on sedimentary patterns at least as late as Santonian time, Stelck develops a thesis of isostatic control of the basement arches and basins of western Canada and examines the behaviour of these structures during Cretaceous sedimentation. He concludes that the arches, particularly the Peace River and Sweetgrass arches, exerted subtle control on the geographic disposition of the coarser-grained sediment wedges. Among the more obvious signs of control, Stelck cites the restriction of the Dunvegan delta to the Keg River basin, north of the Peace River Arch, and of the early Edmonton delta to the West Alberta basin, south of the Peace River Arch and northwest of the Sweetgrass Arch. He considers that the margins of the Keg River and West Alberta basins against the Peace River Arch were sites of strong winnowing; hence the arch tends to be outlined by coarser, cleaner, clastic sediments. At times these clean sands spread over part of the arch itself, as for example when the McMurray Sand was deposited. Reasserting itself, the arch later provided a measure of control for the migration and accumulation of the large quantities of heavy oil that produced the Athabasca oil sands.

If Stelck's arguments be accepted, the Canadian Western Interior comes more into line with the Western Interior of the United States, where for some time the movements of local arches and basins have been known to have influenced Cretaceous sedimentation. The evidence of basement control of sites of deposition leads Stelck to wonder if there might not have been similar control of the source areas of the coarser clastic sediments in British Columbia. Such might explain some of the compositional and distributional changes found by Rahmani and Lerbekmo in the heavy-mineral suites.

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