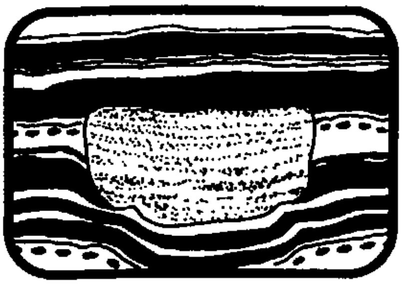

The Compaction of Floodplain Sediments: Timing, Magnitude and Implications

G.C. Nadon
Department of Geological Sciences
Ohio University
Athens, Ohio 45701
United States

D.R. Issler
Geological Survey of Canada
3303 33rd Street N.W.
Calgary, Alberta T2L 2A7

SUMMARY

Backstripping techniques for basin and stratigraphic analyses assume that the original porosity of the sediments is known within reasonable limits. Erroneous original porosity assumptions lead to serious errors in stratigraphic sections with a significant proportion of fine-grained material. The present algorithms, which assume initial porosities of between 50% and 70% for muds and 40% to 50% for sands, are only applicable to sediments that were never subaerially exposed. Outcrop data from floodplain deposits show that the differential compaction between sandstones and mudstones that should be present if those assumptions were correct does not exist. Modern floodplain silts and clays below the liquid limit, *i.e.*, that behave as plastics, have porosities that vary from 34% to 39%, and sands have 27-35% porosity. Sections decompacted using the marine shale and sandstone porosity values overestimate the original thickness of floodplain strata by as much as 31%. These errors mean that the estimates of total basin subsidence in regions, such as proximal foreland basins, are seriously overestimated. The subtle inflections in burial history curves, sometimes used to infer either eustatic or tectonic sea-level fluctuations in these basins, are noise rather than signal.

RÉSUMÉ

Les techniques de reconstitution par délitage des unités lithologiques utilisées dans les analyses sédimentologiques ou stratigraphiques de bassin reposent sur l'hypothèse que la porosité initiale des couches sédimentaires est connue avec une précision raisonnable. Les erreurs d'estimation de la porosité initiale entraînent d'importantes erreurs d'évaluation de l'épaisseur des colonnes stratigraphiques qui comportent une proportion significative de dépôts à grains fins. Les algorithmes utilisées présentement et où il est présumé que la fourchette des valeurs de porosité initiale varie entre 50 % et 70 % pour les boues et entre 40 % à 50 % pour les sables, ne sont valides que pour les sédiments n'ayant jamais été exposés à l'air. Les données provenant d'affleurements de sédiments de plaine d'inondation indiquent que la compaction différentielle entre les couches de grès et de pélites, calculée selon ces hypothèses ne se vérifie pas. Les limons et les argiles des plaines d'inondation actuelles, situés sous la surface de l'eau, c.-à-d. qui se compor-tent comme des matériaux plastiques, montrent des valeurs de porosité allant de 34 % à 39 %, et des sables dont la porosité varient de 27 % à 35 %. Cela signifie que l'utilisation des valeurs de porosité usuelles lors de reconstitutions sédimentologiques et stratigraphiques, entraînent des surévaluations de l'épaisseur initiale des couches de la plaine d'inondation pouvant atteindre 31 %. Ces erreurs signifient que les estimations de subsidence glo-bale des bassins des régions, telles les bassins de sédimentation d'avant-pays, sont considérablement surévaluées. Les faibles inflexions observés dans la courbe de l'histoire d'enfouissement de bassins sédimentaires, et à partir desquelles on se base parfois pour déduire l'existence de fluctuations eustatiques ou tectoniques pas-sées du niveau de la mer, correspondent à un bruit de fond plutôt qu'à un signal.

INTRODUCTION

Geologists and geophysicists have long understood and discussed the various implications of sediment compaction (Sorby, 1908; Athy, 1930; Baldwin, 1971; Angevine *et al.*,1990). For example, sedimentologists interested in either detailed facies architecture (*e.g.*, Baldwin, 1971; Anderson, 1990) or patterns of sediment dispersal (*e.g.*, Miall, 1981) must quantify the amount of compaction in order to reconstruct the initial geometry of the sediment packages at all scales. Structural geologists and geophysicists modelling basin formation and deformation (*e.g.*, Bond and Kominz, 1984; Steckler *et al.*, 1988; Steckler, 1990) decompact the basin fill to remove the effects of sediment loading in order to reconstruct rates of basin subsidence at discrete points through time.

Numerical backstripping algorithms were developed to restore original sediment thicknesses in order to show the relative magnitude and timing of subsidence associated with both sedimentary and tectonic events in the North Sea basin (Sclater and Christie, 1980). The explicit assumptions in the technique are that 1) the volume of sediment remains constant (*i.e.*, no dissolution), 2) the reduction of porosity with depth is solely the result of mechanical compaction, 3) there is an exponential decrease in compaction with depth, 4) the original porosity of the sediment is known, and 5) strata of similar lithology exhibit the same compaction behavior. Sclater and Christie (1980) used well log porosity data from the North Sea to generate a series of best-fit exponential curves that were lithology dependent. These curves were then used to incrementally decompact the sedimentary column in each well until the various facies at the surface reached a predetermined "original" porosity. The original porosity values assigned to the four lithofacies of interest to Sclater and Christie (1980), *i.e.*, shale (63%), sandstone (49%), shaley sand (56%), and chalk (70%), were based on their data and those of previous workers (Athy, 1930; Hedberg, 1936; Baldwin, 1971; Perrier and Quiblier, 1974).

These initial porosity estimates have been reduced by subsequent workers (*e.g.*, Angevine *et al.*, 1990). Two additional important assumptions, one explicit and one implicit, remain open to question, however. The assumption that porosity decreases exponentially with depth is treated elsewhere (Issler, 1992). This paper deals with the problems inherent in the implicit assumption that floodplain sediments have the same compaction factor as marine units of similar lithology.

GSC Contribution No. 1996423

The compaction data commonly cited for terrestrial environments are derived from sediments from deep, permanent lakes that were never subaerially exposed (Meade, 1966). The assumption that lithologically similar marine and floodplain deposits follow the same compaction behavior may be justified, but it is not obvious that fluvial and floodplain sediments will behave in a similar manner. The abundance of paleosol data now available show that floodplain deposits were repeatedly inundated and desiccated on a variety of time scales, hence the term floodplain. Exposure causes the muds and sands to partly-to-fully dewater and therefore compact at the surface (*e.g.,* Bown and Kraus, 1987; Kraus, 1992; Wright, 1992; Kraus and Bown, 1993). This fact was noted by the earlier workers (Athy, 1930; Hedberg, 1936) but apparently was not incorporated into subsequent compaction algorithms.

If floodplain pre-burial compaction can be demonstrated, the assumptions used in the most common decompaction algorithms will yield significant errors in original unit thicknesses. This paper presents two lines of evidence from ancient floodplains, augmented by data from modern floodplains, to show that a substantial portion of the compaction of floodplain muds occurs within a few tens of centimetres of the surface. Because floodplain mudstones and sandstones compact far less than their marine counterparts they exhibit virtually no differential compaction with burial.

EVIDENCE FROM THE STRATIGRAPHIC RECORD

Two lines of evidence from the Cretaceous of southwestern Alberta (Fig. 1), dinosaur tracks and facies architecture,

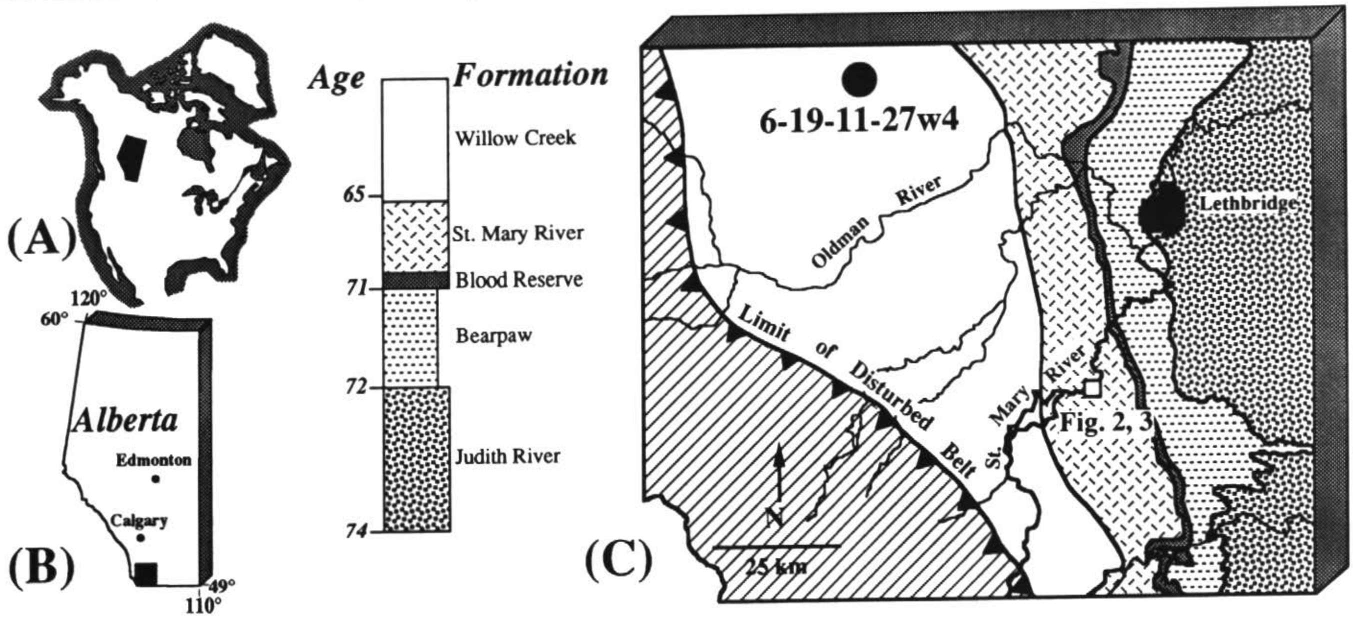

Figure 1 *Location map of the St. Mary River Formation (Upper Cretaceous) in southwestern Alberta. Locations of the photos in Figures 2 and 3 are designated by the white square. The well used in backstripping the St. Mary River Formation is shown by the black circle.*

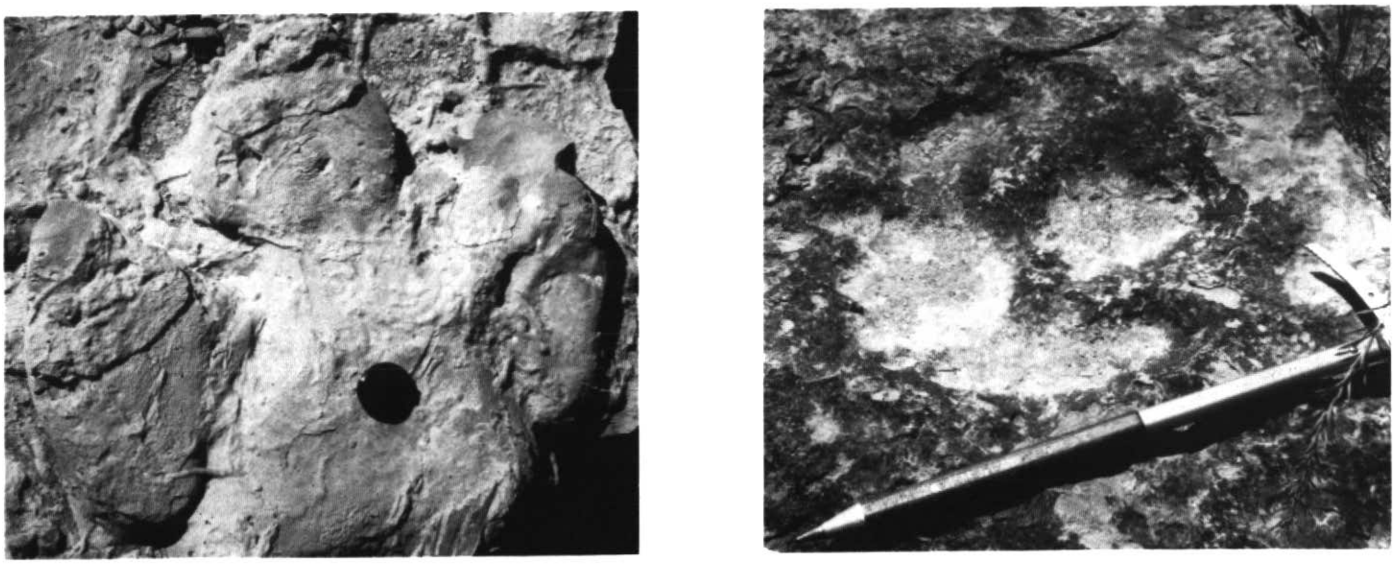

Figure 2 *Photographs of hadrosaur tracks, probably Edmontosaurus, from the St. Mary River Formation. Fig 2a* (**left**) *is a mould from the base of a crevasse splay sandstone showing that the foot penetrated a floodplain mudstone only 0.05 m. Figure 2b* (**right**) *shows an impression left on the top of a crevasse splay sandstone. Such shallow tracks are indicative of a significant floodplain compaction prior to burial.*

demonstrate that the compaction of floodplain mudstones upon burial is minimal. Vertebrate tracks reflect more than just the mechanisms of locomotion (*e.g.*, Gillette and Lockley, 1989); they also record the substrate response to an imposed load. This sediment response can be used to refine paleoenvironmental interpretations (*e.g.*, Lockley, 1987) and to infer information on the porosity of the substrates that the animals walked over. Qualitatively, tracks can be viewed as paleopenetrometers that performed compaction tests on ancient floodplains (Allen, 1989).

Adult dinosaurs have left a large number of tracks in the floodplain mudstones of the St. Mary River Formation (Currie *et al.*, 1991; Nadon, 1993). The tracks, preserved as sandstone casts in the floodplain mudstones, range from 0.001 m to 0.8 m, with most in the range of 0.05 m to 0.15 m. The numerous shallow tracks that show well-preserved features (Fig. 2) (Currie *et al.*, 1991; Nadon, 1993) are a key element for this study. Adult hadrosaurs, for example, weighed approximately 3500-4000 kg and had feet with surface areas ranging from approximately 1400-1500 cm^2 (*e.g.*, Currie *et al.*, 1991, fig. 3). Therefore, assuming that the entire base of foot impacted the surface vertically, each step of this bipedal animal produced a force of 2.3-2.9 $kg \cdot cm^{-2}$. Sediments that have an unconfined compressive strength of two to four are described as having a very stiff consistency (McCarthy, 1993). The shallow depth of penetration for many of the tracks in the St. Mary River Formation indicates that the mud at the surface in the Cretaceous was very stiff. In addition, the preservation of footprint geometry after burial can only occur if there is little or no postburial differential compaction between the mudstone and the overlying sandstone. Both lines of evidence suggest minimal differences in porosity between the two lithologies prior to burial. In other words, the mud was largely dewatered prior to the dinosaurs walking on these floodplains.

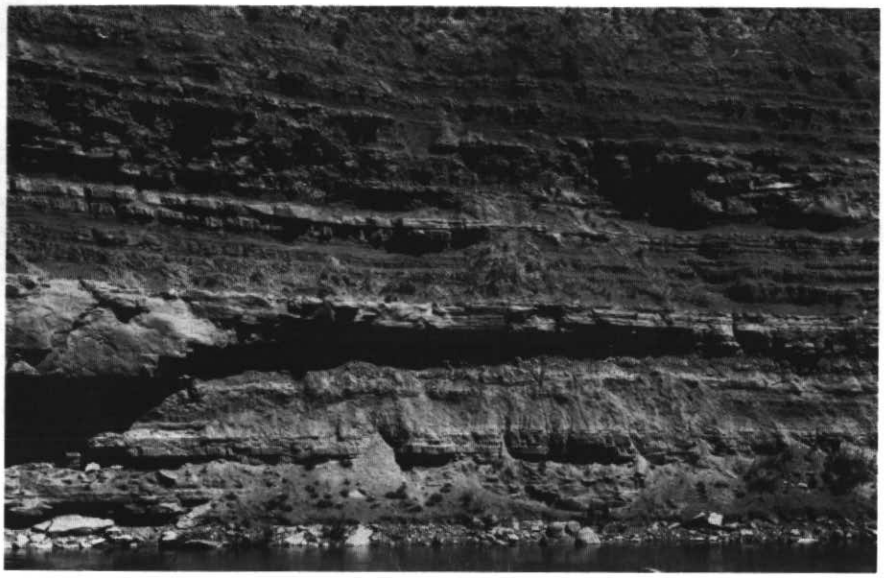

Figure 3 *A typical channel sandstone lens within the St. Mary River Formation of southwestern Alberta. Note the lack of deformation of the sandstones on the margins of the lens and the horizontal nature of beds surrounding the sandstone lens even though maximum burial depth has exceeded 2000 m. This geometry is only possible if there is no significant differential compaction between the floodplain mudstones and sandstones.*

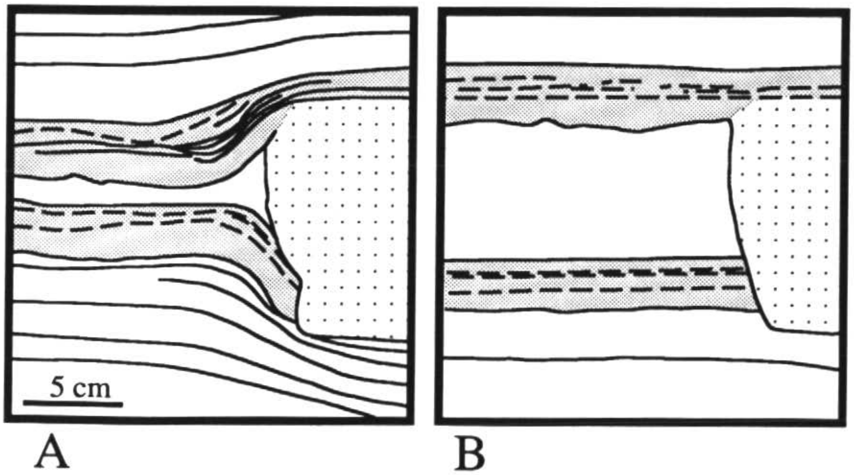

Figure 4 *The lateral facies relationships at the margin of a sandstone lens and adjacent mudstones in a marine deposit.* (**A**) *illustrates the effects of large differences in initial sediment porosity between sands and muds on differential compaction, and* (**B**) *shows the original depositional configuration after decompaction. After Baldwin (1971).*

The second indication of early floodplain compaction is the geometry of the fluvial channel sandstones within the St. Mary River Formation (Fig. 3). The channels, which represent deposition in a mud-dominated fluvial system (Nadon, 1994), occur as sandstone lenses composed of upper fine-grained to medium-grained sandstone. The lenses are commonly flat topped and are surrounded by interbedded mudstones and sandstones representing a range of floodplain deposits from ponds and marshes to crevasse splays. The sandstone/mudstone ratio of the St. Mary River Formation is approximately 1:1.

A difference in initial porosity among the various floodplain sediments will result in some evidence of differential compaction of the mudstones around the sandstones (*e.g.*, Fig. 4) (Baldwin, 1971). However, Figure 3 shows that the adjacent floodplain sediments compacted at very nearly the same rate and to the same degree as the channel sandstones. This could only happen by reduction of mudstone porosity to values close to those of the sandstones, through subaerial mudstone exposure prior to burial. Furthermore, the geometry of the channel sandstone bodies within the St. Mary River Formation is by no means anomalous (Nadon, 1994). Photographs and line drawings in papers dealing with similar sedimentary deposits (Table 1) all show no evidence of differential compaction around the margins of similar sandstone lenses.

EVIDENCE FROM MODERN FLOODPLAINS

There is an abundance of data on the porosity of modern floodplain sediments, usually expressed as void ratios, and obtained in programs to understand groundwater flow and soil mechanics. Anderson (1990) suggested that the variation in mud porosity on modern floodplains is dependent on several factors including mineralogy, grain size, and sorting. Despite the variations in floodplain facies as well as depositional and post-depositional processes, a compilation of data collected by the Bureau of Reclamation (1960) and 1983 (Austin, pers. comm., 1995) from 17 states in the United States shows a relatively small range in porosity (Table 2). These porosity ranges, from 33.8% to 39.4% (average 36.5%) for clay and silty soils below the liquid limit (*i.e.*, the Atterberg limit above which a soil-water mixture changes from a plastic to a liquid state; Kehew, 1995) and 27% to 34.6% (average 30.8%) in sandy soils, are all substantially lower than the assumptions made in decompaction algorithms.

DISCUSSION

The largest sources of error in decompacting sedimentary sequences probably rest with the assumptions that porosity decreases solely by mechanical compaction and with the measurement of porosity. The effects of grain shape, composition and diagenesis on porosity distribution through time make the assumption of mechanical compaction for sandstones a particularly poor assumption at any depth (Houseknecht, 1987; Pittman and Larese, 1991). The same is true for mudstones after burial to more than 2700 m (Powers, 1967) where fundamental chemical changes may occur. Porosity measurements from wireline logs vary, depending on the tool, but commonly overestimate porosity relative to sample density due to the presence of fractures and the caving of weakly lithified sediments (*e.g.*, Rhodehamel, 1977). The initial assumption of an exponential decrease in porosity with depth made by Athy (1930) is, in itself, fraught with problems (Issler, 1992). However, erroneous assumptions of original porosity compound these errors.

The data from modern floodplains (Table 2) indicate that the previous porosity assumptions overestimate the initial porosity of floodplain sediments by 13.5-27% for mudstones and 9-18% for sandstones. The small (5.7%) difference in average porosity between the sandy and silty modern floodplain sediments is consistent with the lack of compaction observed in dinosaur tracks as noted, and around the sandstone lenses within the St. Mary River Formation.

To illustrate the differences these revised initial porosity estimates make on decompaction of foreland basin fluvial sediments, the St. Mary River Formation in well 6-19-11-27W4 (Fig. 1) was

Table 1 A sample of sedimentary units similar to the St. Mary River Formation that likewise show no evidence of differential compaction between the sandstones and mudstones (from Nadon, 1994).

Age	Formation	Source
Foreland Basins		
Permian	Beaufort Group	Stear (1983)
Lower Cretaceous	Gething Fm.	Stott (1973)
Upper Cretaceous	St. Mary River Fm.	Nadon (1994)
Upper Cretaceous	Two Medicine Fm.	Lorenz and Gavin (1984)
Upper Cretaceous	Lenticular Sst. and Shale Fm.	Shuster and Steidtmann (1987)
Eocene	Kuldana Fm.	Wells (1983)
Eocene	Willwood Fm.	Kraus and Middleton (1987)
Miocene	Catissent Sandstone	Marzo *et al.* (1988)
Lower Miocene	Luna Fm.	Nichols (1987)
Lower Miocene	Uncastillo Fm.	Turner (1992)
Grabens		
Devonian	Kapp Kjeldsen Fm.	Moody-Stuart (1966)
Carboniferous	Cumberland Group	Rust *et al.* (1984)
Pennsylvanian	Boss Point Sandstone	Plint and Browne (1994)
Pennsylvanian	Waddens Cove Fm.	Gibling and Rust (1990)
Permian–Pennsylvanian	Cutler Fm.	Eberth and Miall (1991)
Jurassic	Porto Novo	Hill (1989)
Jurassic	Ness Fm.	Dreyer (1990)
Middle Jurassic	Saltwick Fm.	Dreyer (1990)
Upper Jurassic/Lower Cretaceous	Galve Fm.	Diaz *et al.* (1984)
Other Basins		
Carboniferous	Cliffon Fm.	Rust and Legun (1983)
Jurassic	Scalby Fm.	Nami and Leeder (1978)

Table 2 Data on the porosity of modern floodplain mudstones compiled from the Bureau of Reclamation (1961).

Lithology		Number	Minimum Porosity	Maximum Porosity	Mean Values
Silts and Clays					
(Liquid Limit <50)					
Primarily inorganic silts	M1*	61	37.89%	39.39%	
Primarily inorganic clays	Cl	261	35.48%	36.31%	
		Ave.	**35.72%**	**37.34%**	**36.52%**
(Liquid Limit >50)					
Primarily inorganic silts	Mh	9	50.74%	55.95%	
Primarily inorganic clays	Ch	61	43.18%	45.65%	
		Ave.	**46.96%**	**50.80%**	**48.88%**
Sands					
Clean Sand – well graded	Sw	20	27.01%	27.01%	
Clean Sand – poorly graded	Sp	62	31.97%	34.64%	
Silty Sands	Sm	153	31.51%	33.33%	
Clayey sands	Sc	88	31.97%	32.89%	
		Ave.	**30.10%**	**31.59%**	**30.85%**

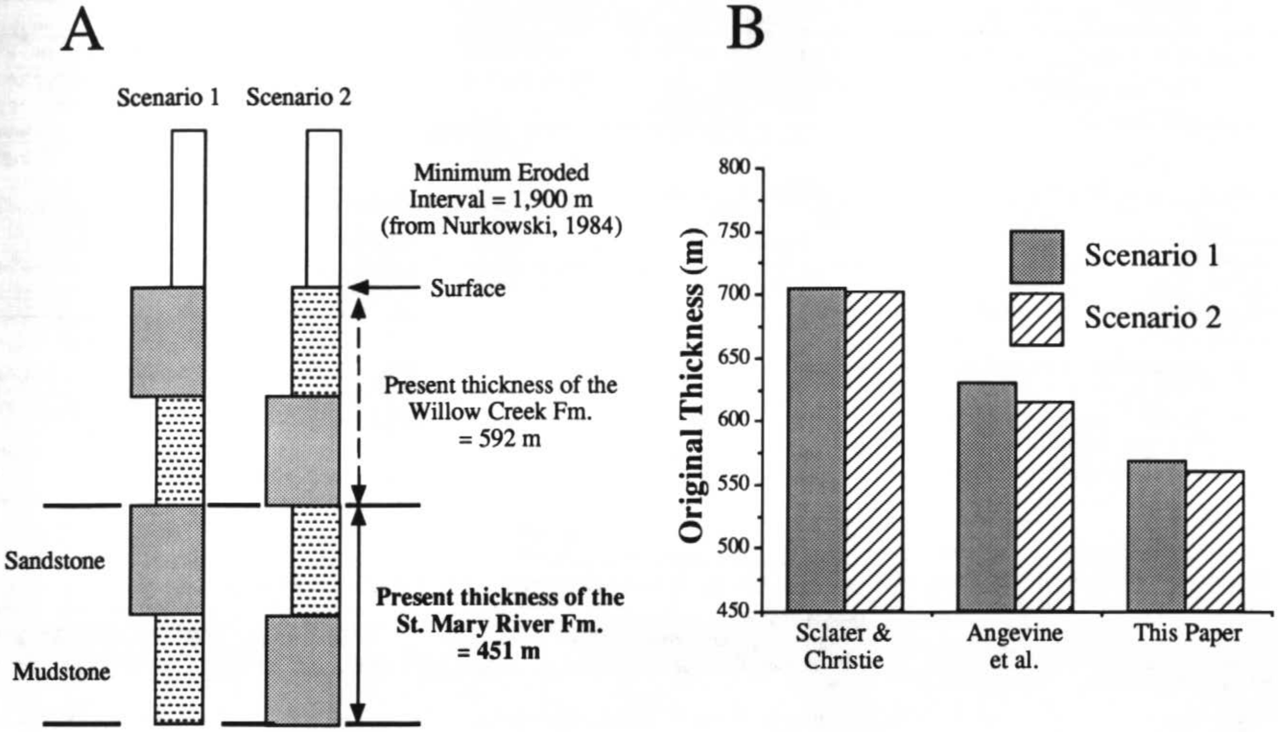

Figure 5 *The results of decompaction of the St. Mary River Formation in well 6-19-11-27W4. The location is shown in Figure 1.* (**A**) *The sediments were divided into two equal units, one of sandstone and one of mudstone.* (**B**) *The restored initial thickness for each algorithm depends slightly on which lithology is chosen to overlie the other. In both scenarios the assumed initial porosity values of Sclater and Christie (1980) and Angevine* et al. *(1990) result in overestimates of original thicknesses of 137-141 m and 55-62 m, respectively.*

decompacted using the iterative spreadsheet method of Angevine *et al.* (1990) and the initial porosity estimates of Sclater and Christie (1980), Angevine *et al.* (1990), and Table 2. The unit was divided into equal thicknesses of mudstone and sandstone based on the sand/mudstone ratios of the surface exposures (Nadon, 1994). Burial depths in the well were compensated for Tertiary uplift and erosion by using the minimum estimate of 1.9 km obtained from coal rank studies (Nurkowski, 1984). This estimate is consistent with values obtained by converting sonic measurements into porosity values in the underlying marine Bearpaw Formation (Magara, 1976) and calculating the burial depths needed to produce such values based on the constants of both Sclater and Christie (1980) and Angevine *et al.* (1990). These calculations suggest 2-5 km of erosion in the area. The original depositional thickness of the St. Mary River Formation in the 6-19 well, which is presently approximately 451 m thick, varies from 701-705 m (Sclater and Christie, 1980) to 615-630 m (Angevine *et al.*, 1990) to 560-568 m (this study) depending on the partitioning of the sediments within the section, *i.e.*, the base of the section can be assigned values for either mudstone or sandstone (Fig. 5).

The errors in decompaction, which are dependent on the amount of fluvial material in the section under study, have implications for modelling floodplain sediments. The increasingly sophisticated models for alluvial stratigraphy (*e.g.*, Mackey and Bridge, 1995) and the backstripping of basin sediments (*e.g.*, Lankreijer *et al.*, 1995) are all affected by the assumptions inherent in sediment compaction. The magnitude of the error involved in backstripping, on the order of tens to hundreds of metres within individual formations, results in a significant overestimation of total subsidence for basins dominated by fluvial sedimentation. Consequently, the use of decompaction curves to demonstrate spatial variations of subsidence or sea level between wells within a basin, or to estimate the effects of secondary parameters, such as intraplate stress that requires a resolution of a few tens of metres (*e.g.*, Kooi and Cloetingh, 1989; Lankreijer *et al.*, 1995), clearly cannot produce meaningful results using the original porosity assumptions of Sclater and Christie (1980).

CONCLUSIONS

Rates and magnitudes of subsidence calculated for basins containing fluvial sediments are overestimated. The magnitude of the error depends on the ratio between marine and fluvial sediments, the facies partitioning within the fluvial deposits, and the thickness of the units considered in the decompaction algorithm. The lack of differential compaction in fluvial deposits demonstrates that backstripping routines should employ the more realistic initial porosity values obtained from modern floodplains to prevent overestimates of original thicknesses. In light of these findings, the estimates of total subsidence and rates of subsidence for basins that contain fluvial sediments should be re-evaluated.

ACKNOWLEDGMENTS

This paper stems from ideas generated by a talk given by David Powley. We wish to thank David Powley and J. Bahr for discussions and help in locating data sources and Bill Austin of the Bureau of Reclamation, Denver, Colorado for his assistance in providing the 1982 soil porosity data. D. Sack and H.F. Wang provided valuable reviews of an earlier draft of this manuscript. Dave Morrow, Lloyd Snowdon, Dale Leckie, John Bloch, and John Bridge provided useful reviews of the present manuscript.

REFERENCES

Allen, J.R.L., 1989, Fossil vertebrate tracks and indenter mechanics: Geological Society of London, Journal, v. 146, p. 600-602.

Anderson, S.H., 1990, Compaction of alluvial overbank mudstones: American Association of Petroleum Geologists, Bulletin, Abstracts, p. 599.

Angevine, C.L., Heller, P.L. and Paola, C., 1990, Quantitative sedimentary basin modeling: American Association of Petroleum Geologists, Continuing Education Course, Note Series No. 32, 133 p.

Athy, L.F., 1930, Density, porosity, and compaction of sedimentary rocks: American Association of Petroleum Geologists, Bulletin, v. 14, p. 1-24.

Baldwin, B., 1971, Ways of deciphering compacted sediments: Journal of Sedimentary Petrology, v. 41, p. 293-301.

Bond, G.C. and Kominz, M.A., 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: implications for subsidence mechanisms, age of breakup, and crustal thinning: Geological Society of America, Bulletin, v. 95, p. 155-173.

Bown, T.M. and Kraus, M.J., 1987, Integration of channel and floodplain suites, I. Developmental sequence and lateral relations of alluvial paleosols: Journal of Sedimentary Petrology, v. 57, p. 587-601.

Bureau of Reclamation, 1960, The design of small dams: US Government Printing Office, 611 p.

Currie, P.J., Nadon, G.C. and Lockley, M.G., 1991, Dinosaur footprints with skin impressions from the Cretaceous of Alberta and Colorado: Canadian Journal of Earth Sciences, v. 28, p. 102-115.

Diaz, M., Yebenews, A., Goy, A. and Sanz, J.L., 1984, Landscapes inhabited by Upper Jurassic/Lower Cretaceous Archosaurs (Galve. Teruel, Spain), *in* Reif, W.-E. and Westphal, F., eds., Third Symposium on Mesozoic Terrestrial Ecosystems Short Papers, Tübingen, p. 67-72.

Dreyer, T., 1990, Sand body dimensions and infill sequence of stable, humid climate delta plain channels, *in* Buller, A.T., Berg, E., Hjelmeland, O., Kleppe, J., Torsæter, O. and Aasem, J.O., eds., North Sea Oil and Gas Reservoirs II, p. 337-351.

Eberth, D.A. and Miall, A.D., 1991, Stratigraphy, sedimentology, and evolution of a vertebrate-bearing, braided to anastomosed fluvial system, Cutler Formation (Permian-Pennsylvanian) north-central New Mexico: Sedimentary Geology, v. 72, p. 225-252.

Gibling M.R. and Rust, B.R., 1990, Ribbon sandstones in the Pennsylvanian Waddens Cove Formation, Sydney Basin, Atlantic Canada: the influence of siliceous duricrusts on channel-body geometry: Sedimentology, v. 37, p. 45-65.

Gillette, D.D. and Lockley, M.G., 1989, Dinosaur Tracks and Traces: Cambridge University Press, New York, 454 p.

Hedberg, H. D., 1936, Gravitational compaction of clays and shales: American Journal of Science, Fifth Series, v. 31, p. 241-287.

Hill, G., 1989, Distal alluvial fan sediments from the Upper Jurassic of Portugal: controls on their cyclicity and channel formation: Geological Society of London, Journal, v. 146, p. 539-555.

Houseknecht, D.W., 1987, Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones: American Association of Petroleum Geologists, Bulletin, v. 71, p. 633-642.

Issler, D.A., 1992, A new approach to shale compaction and stratigraphic restoration, Beaufort-Mackenzie basin and Mackenzie Corridor, northern Canada. American Association of Petroleum Geologists, Bulletin, v. 76, p. 1170-1189.

Kehew, A.E., 1995, Geology for Engineers and Environmental Scientists, 2nd Edition, Prentice Hall, New Jersey, 574 p.

Kooi, H. and Cloetingh, S., 1989, Intraplate stresses and the tectono-stratigraphic evolution of the North Sea, *in* Tankard, A.J. and Balkwill, H.R., eds., Extensional Tectonics and Stratigraphy of the North Atlantic Margins: American Association of Petroleum Geologists, Memoir 46, p. 541-558.

Kraus, M.J., 1992, Mesozoic and Tertiary paleosols, *in* Martini, I.P. and Chesworth, W., eds., Weathering, Soils & Paleosols: Elsevier, New York, p. 525-542.

Kraus, M.J. and Bown, T.M., 1993, Palaeosols and sandbody prediction in alluvial sequences, *in* North, C.P. and Prosser, D.J., eds., Characterization of Fluvial and Aeolian Reservoirs: Geological Society of London, Special Publication 73, p. 23-31.

Kraus, M.J. and Middleton, L.T., 1987, Contrasting architecture of two alluvial suites in different structural settings, *in* Ethridge, F.G., Flores, R.M. and Harvey, M.D., eds., Recent Developments in Fluvial Sedimentology: SEPM, Special Publication 39, p. 253-262.

Lankreijer, A., Kovác, M., Cloetingh, S., Pitonák, P., Hloska, M. and Biermann, C., 1995, Quantitative subsidence analysis and forward modeling of the Vienna and Danube basins: thin-skinned versus thick-skinned extension: Tectonophysics, v. 252, p. 433-451.

Lockley, M.G., 1987, Dinosaur trackways and their importance in paleoenvironmental reconstruction, *in* Czerkas, S. and Olsen E.C., eds., Dinosaurs Past and Present: Los Angeles County Museum, p. 81-95.

Lorenz, J.C. and Gavin, W., 1984, Geology of the Two Medicine Formation and the sedimentology of a dinosaur nesting ground, *in* McBane, J.D. and Garrison, P.B., eds., Northwest Montana and Adjacent Canada: Montana Geological Society, 1984 Field Conference and Symposium, p. 175-186.

Mackey, S.D. and Bridge, J.S., 1995, Three-dimensional model of alluvial stratigraphy: theory and application: Journal of Sedimentary Research, v. B65, p. 7-31.

Magara, K., 1976, Thickness of removed sedimentary rocks, paleopore pressure, and paleotemperature, southwestern part of Western Canada Basin: American Association of Petroleum Geologists, Bulletin, v. 60, p. 554-565.

Marzo, M., Nijman, W. and Puidefabregas, C., 1988, Architecture of the Castissent fluvial sheet sandstones, Eocene, South Pyrenees, Spain: Sedimentology, v. 35, p. 719-738.

McCarthy, D.F., 1993, Essentials of Soil Mechanics and Foundations, Basic Geotechnics, 4th Edition, Prentice-Hall, New Jersey, 618 p.

Meade, R.H., 1966, Factors influencing the early stages of the compaction of clays and sands – review: Journal of Sedimentary Petrology, v. 36, p. 1085-1101.

Miall, A.D., 1981, Alluvial sedimentary basins: tectonic setting and basin architecture, *in* A.D. Miall, ed., Sedimentation and Tectonics in Alluvial Basins: Geological Association of Canada, Special Paper 23, p. 1-33.

Moody-Stuart, M., 1966, High- and low-sinuosity stream deposits, with examples from the Devonian of Spitsbergen: Journal of Sedimentary Petrology, v. 36, p. 1102-1117.

Nadon, G.C., 1993, The association of anastomosed fluvial deposits and dinosaur tracks, eggs, and nests: implications for the interpretation of floodplain environments and a possible survival strategy for ornithopods: Palaios, v. 8, p. 31-44.

Nadon, G.C., 1994, The genesis and recognition of anastomosed fluvial deposits: Data from the St. Mary River Formation, southwestern Alberta, Canada: Journal of Sedimentary Research, v. B64, p. 451-463.

Nami, M. and Leeder, M.R., 1978, Changing channel morphology and magnitude in the Scalby Formation (M. Jurassic) of Yorkshire, England, *in* Miall, A.D., ed., Fluvial Sedimen-tology: Canadian Society of Petroleum Geologists, Memoir 5, p. 431-440.

Nichols, G.J., 1987, Structural control on fluvial distributary systems – the Luna system, northern Spain, *in* Ethridge, F.G., Flores, R.M. and Harvey, M.D., eds., Recent Developments in Fluvial Sedimentology: SEPM, Special Publication 39, p. 269-277.

Nurkowski, J.R., 1984, Coal quality, coal rank variation and its relation to reconstructed overburden, Upper Cretaceous and Tertiary Plains coals, Alberta, Canada: American Association of Petroleum Geologists, Bulletin, v. 68, p. 285-295.

Perrier, R. and Quiblier, J., 1974, Thickness changes in sedimentary layers during compaction history; methods for quantitative evaluation: American Association of Petroleum Geologists, Bulletin, v. 58, p. 507-520.

Pittman, E.D. and Larese, R.E., 1991, Compaction of lithic sands: experimental results and applications: American Association of Petroleum Geologists, Bulletin, v. 75, p. 1279-1299.

Plint, A.G. and Browne, G.H., 1994, Tectonic event stratigraphy in a fluvio-lacustrine, strike-slip setting: the Boss Point Formation (Westphalian A), Cumberland Basin, Maritime Canada: Journal of Sedimentary Research, v. B64, p. 341-364.

Powers, M.C., 1967, Fluid release mechanisms in compacting marine mudrocks and their importance in oil exploration: American Association of Petroleum Geologists, Bulletin, v. 51, p. 1240-1254.

Rhodehamel, E.C., 1977, Sandstone porosities, *in* P.A. Scholle, ed., Geological studies on the COST No. B-2 well, US Mid-Atlantic outer continental shelf area: United States Geological Survey, Circular 750, p. 23-31.

Rust, B.R. and Legun, A.S., 1983, Modern anastomosing fluvial deposits in arid central Australia, and a Carboniferous analogue in New Brunswick, Canada, *in* Collinson, J.D. and Lewin, J., eds., Modern and Ancient Fluvial Systems: International Association of Sedimentologists, Special Publication 6, p. 385-392.

Rust, B.R., Gibling, M.R. and Legun, A.S., 1984, Coal deposition in an anastomosing-fluvial system: the Pennsylvanian Cumberland Group south of Joggins, Nova Scotia, Canada, *in* Rahmani, R.A. and Flores, R.M., eds., Sedimentology of Coal and Coal-bearing Sequences: International Association of Sedimentologists, Special Publication 7, p. 105-120.

Sclater J.G. and Christie, P.A.F., 1980, Continental stretching: an explanation of the post-mid-Cretaceous subsidence of the central North Sea basin: Journal of Geophysical Research, Part B, v. 85, p. 3711-3739.

Shuster, M.W. and Steidtmann, J.R., 1987, Fluvial-sandstone architecture and thrust-induced subsidence, northern Green River Basin, Wyoming, *in* Ethridge, F.G., Flores, R.M. and Harvey, M.D., eds., Recent Developments in Fluvial Sedimentology: SEPM, Special Publication 39, p. 279-285.

Sorby, H.C., 1908, On the application of quantitative methods to the study of the structure and history of rocks: Geological Society of London, Quarterly Journal, v. 64, p. 171-233.

Stear, W.M., 1983, Morphological characteristics of ephemeral stream channel and overbank splay sandstone bodies in the Permian Lower Beaufort Group, Karoo Basin, South Africa, *in* Collinson, J.D. and Lewin, J., eds., Modern and Ancient Fluvial Systems: International Association of Sedimentologists, Special Publication 6, p. 405-420.

Steckler, M.S., 1990, The role of the thermal-mechanical structure of the lithosphere in the formation of sedimentary basins, *in* Cross, T., ed., Quantitative Dynamic Stratigraphy: Prentice Hall, New York, p. 89-112.

Steckler, M.S., Watts, A.B. and Thorne, J.A., 1988, Subsidence and basin modeling at the US Atlantic passive margin, *in* Sheridan, R.E. and Grow, J.A., eds., The Atlantic continental margin, US: Geological Society of America, The Geology of North America, v. I-2, p. 399-416.

Stott, D.F., 1973, Lower Cretaceous Bullhead Group between Bullmoose Mountain and Tetsa River, Rocky Mountain Foothills, northeastern British Columbia: Geological Survey of Canada, Bulletin 219, 228 p.

Turner, J.P., 1992, Evolving alluvial stratigraphy and thrust front development in the West Jaca piggyback basin, Spanish Pyrenees: Geological Society of London, Journal, v. 149, p. 51-63.

Wells, N.A., 1983, Transient streams in sand-poor redbeds: Early-Middle Eocene Kuldana Formation of northern Pakistan, *in* Collinson, J.D. and Lewin, J., eds., Modern and Ancient Fluvial Systems: International Association of Sedimentologists, Special Publication 6, p. 393-403.

Wright, V.P., 1992, Paleopedology: stratigraphic relationships and empirical models, *in* Martini, I.P. and Chesworth, W., eds., Weathering, Soils & Paleosols: Elsevier, New York, p. 475-499.

Accepted as revised 21 March 1997