Geology

Development of tectonic cyclothems in rift, pull-apart, and foreland basins: Sedimentary response to episodic tectonism

Terence C. Blair and William L. Bilodeau

Geology 1988;16;517-520
doi: 10.1130/0091-7613(1988)016<0517:DOTCIR>2.3.CO;2

Notes

Development of tectonic cyclothems in rift, pull-apart, and foreland basins: Sedimentary response to episodic tectonism

Terence C. Blair
Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309
William L. Bilodeau
971 Cook Street, Denver, Colorado 80206

ABSTRACT

The thickest part of asymmetric rift, pull-apart, and foreland basin fills commonly consists of large-scale (hundreds to thousands of metres thick), tectonically generated cyclothems of fine-grained marine, lacustrine, or longitudinal fluvial deposits and coarse-grained transverse braid-plain or alluvial-fan deposits. The appearance of coarse clastics in these basin fills is typically noted as the time of tectonically rejuvenated source-area uplift, based on the conceptual tie between relief and coarse grain size, and on the application of the Davis theory of landform development. We propose the opposite interpretation: that the commencement of fine-grained sedimentation above coarse-grained deposits in a tectonic cyclothem is the best indicator of renewed tectonic activity. This reinterpretation is more consistent with (1) modern examples, (2) the consideration of source-area and sedimentary-basin geomorphology, (3) the disparity between the reaction rates of the various environments to subsidence, (4) the disparity between the rates of tectonic uplift and erosion, and (5) the controls on clastic-wedge progradation. In our model, extensive coarse-grained clastic-wedge progradation is an indicator of tectonically quiescent phases.

INTRODUCTION

Rift, pull-apart, and foreland basin-fill sequences are typically asymmetric in cross-section geometry normal to their active margin (Fig. 1). This asymmetry results from the localization of tectonic activity, maximum subsidence, and sedimentation along one basin margin. Asymmetry in foreland basins is due to tectonic downflexure under the superimposed load of stacked thrust sheets (Beaumont, 1981), whereas asymmetry in rifts and pull-apart basins is the result of the development of half-graben structures. Half-grabens in rifts form due to block rotations along listric and planar-normal faults in zones of lithospheric attenuation (Wernicke and Burchfiel, 1982), and form in pull-apart basins due to the downward component of motion induced during strike-slip movements by extensional or compressional deformation along curving or en echelon fault segments (Mann et al., 1983).

The thickest part of all three basin-fill types commonly consists of large-scale (hundreds to thousands of metres thick), stacked cyclothems composed of relatively fine-grained marine, lacustrine, or longitudinal fluvial deposits and coarser grained (conglomeratic) transverse braid-plain or alluvial-fan deposits (Fig. 1; Table 1). The origin of these cyclothems almost invariably is attributed to pulsating active tectonic episodes separated by relatively quiescent periods. Cyclic climatic change is precluded because the known duration of these cyclothems (2.4 to 15 m.y.; Table 1) is 6 to 650 times longer than orbital-related climatic cycles, which have periodicities of 23 to 400 ka (Parrish and Barron, 1986). A eustatic origin is ruled out because many cyclothems consist entirely of continental deposits (Table 1). Although climatic change, eustasy, and autocyclic mechanisms may locally cause ambiguity (Beerbower, 1964), the temporal and spatial scales of these cyclothems and their restriction to the tectonically active basin margin are consistent with a pulsatory tectonic origin.

We present here a unifying conceptual model for the development of large-scale tectonic cyclothems in these diverse basin types. The onset of tectonic episodes in the basins is typically noted as the time when a phase of coarse-clastic deposition is initiated. We propose, on the basis of several lines of reasoning, that the opposite interpretation is the most likely.

COARSE-GRAINED DEPOSITS AS INDICATORS OF RENEWED TECTONIC ACTIVITY

The conceptual tie between coarse-grained sedimentation and tectonic activity is derived from the observed relation between gravel deposition and relief recognized by Playfair (1802, p. 381–382):

> It is a fact very generally observed that when the valleys among primitive mountains open into large plains, the gravel of those plains consists of stones, evidently derived from the mountains. The nearer any spot is to the mountains, the larger are the gravel stones. . . . The reason for this gradation is evident, the farther the stones have travelled, and the more rubbing they have endured, the smaller they grow . . . and the greater the quantity of that fine detritus. . . .

The correlation of a period of renewed coarse-grained sedimentation in a basin with an episode of tectonic uplift dates back at least to Barrell (1917), and is based on the idea of the rejuvenation of relief, a concept derived from the application of the "geographical cycle of landforms" theory of Davis (1899, p. 481–499):

> All the varied forms of the lands are dependent upon . . . structure, process, and time. In the

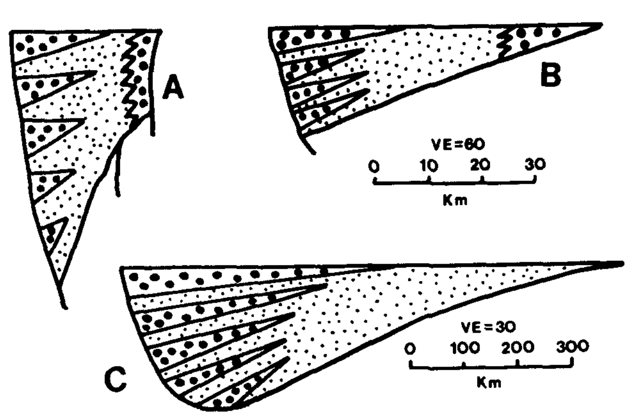

Figure 1. Schematic cross sections perpendicular to active margins of pull-apart (A), rift (B), and foreland (C) basins. Large-dot pattern depicts braid-plain and alluvial-fan deposits; small-dot pattern depicts fine-grained fluvial, lacustrine, and marine deposits. Upper scale is for A and B; lower scale is for C.

beginning, when the forces of deformation and uplift determine the structure and attitude of the region, the form of its surface is in sympathy with its internal arrangement, and its height depends on the amount of uplift it has suffered. . . . [E]ven the most resistant [rocks] yield under attack to the atmosphere, and their waste creeps and washes downhill as long as any hills remain; hence all forms, however high and however resistant, must be laid low, and thus destructive process gains rank equal to that of structure in determining the shape of a land-mass. . . . Like land-forms, the agencies that work upon them change their behaviour and their appearance with the passage of time. A young land-form has young streams of torrential activity, while an old form would have old streams of deliberate or feeble current. . . . [Load] rapidly increases in quantity and coarseness during youth. . . . [A]fter full maturity, load continually decreases in quantity and in coarseness of texture; and, during old age, the small load that is carried must be of very fine texture. . . . A land-mass, uplifted to a greater altitude than it had before, is at once more intensely attacked by the denuding processes in the new cycle thus initiated. . . .

The application of the Davis cycle theory of landform denudation to the origin of tectonic cyclothems is prevalent in the geological literature. The widespread use of this intuitively appealing theory, however, incorrectly implies that it and its corollaries have been rigorously and successfully tested at the spatial and temporal scale of the tectonic cyclothems.

FINE-GRAINED DEPOSITS AS INDICATORS OF RENEWED TECTONIC ACTIVITY

We propose that the onset of deposition of the finer grained part of a tectonic cyclothem is a more consistent and more logical indicator of the onset of renewed tectonic activity in rifts, pull-apart basins, and forelands, on the basis of (1) the consideration of the major changes in basin and source-area geomorphology dictated by the cyclothems; (2) modern examples; (3) the disparity between the rate of response to tectonic subsidence of the environments that produce the fine-grained units vs. those that produce the coarse-grained units; (4) the disparity between the rates of tectonic uplift and erosion; and (5) the unlikely event that a rapidly and widely dispersed coarse clastic wedge can form during active tectonic episodes.

The development of large-scale tectonic cyclothems near an active basin margin indicates that for extended periods of time (millions of years) marine, lacustrine, or longitudinal fluvial environments occupied that part of the basin, and that during alternate periods of similar duration, transverse braid plains or alluvial fans occurred there. A consequence of the traditional association of fan or braid-plain sedimentation to the period of active tectonic subsidence along the margin is the need for their displacement by marine, lacustrine, or low-gradient fluvial sedimentation during periods of tectonic quiescence. This interpretation requires basin alluviation, or a long-term rise in lake or sea level of hundreds of metres to deposit hundreds of metres of fine-grained sediment above the fans or braid plains, which constitute the highest depositional topography in the sedimentary basin. This scenario is geomorphologically inconsistent, because lakes, oceans, and low-gradient fluvial environments are maintained for long periods of time in the topographically lowest parts of the sedimentary basin. The inversion of the depositional topography indicated by the stratigraphic change in a tectonic cyclothem from fan or braid-plain deposition to lacustrine, marine, or low-gradient fluvial deposition is most easily developed by subsiding of the basin-margin bajada or braid plain to create a topographic depression.

The application of the Davis theory to the origin of tectonic cyclothems also implies that the uplifted source area is eliminated during tec-

TABLE 1. DATA FROM DESCRIBED TECTONIC CYCLOTHEM EXAMPLES

Reference	Age	Location	Basin type*	No. of cyclothems	Cyclothem compontents†	Average thickness (m)	Average Duration (m.y.)
Link (1982)	Miocene–Pliocene	S. California	PA	5	M/L to Fan/BP	1600	2.4
Hendrix and Ingersol (1987)	Oligocene	S. California	PA	4	F to Fan	525	?
Dutton (1982)	Pennsylvanian–Permian	NW Texas	PA-F?	7	M to BP/Fan	370	7
Heward (1978)	Upper Carboniferous	N. Spain	PA	2	F/L to Fan	260	?
Steel et al. (1977)	Devonian	S. Norway	PA	150	F/L to Fan	150	?
Smith and Hiscott (1984)	Precambrian–Cambrian	Newfoundland	PA-R?	3	F/L/M to Fan	725	?
Tiercelin (1987)	Pliocene–Recent	Ethiopia	R	1	L/F to Fan	300+	4
Vondra and Burggraf (1978)	Pliocene–Recent	Kenya	R	1	L/F to Fan	325	4
Cavazza (1985)	Miocene	N. New Mexico	R	4	L to Fan	700	4.5
Blair (1985, 1987b)	Jurassic–Cretaceous	SE Mexico	R	3	L/F to Fan	450	?
LeTourneau (1985)	Lower Jurassic	Connecticut	R	4(?)	L/F to Fan	175	?
Turner (1983)	Upper Triassic	South Africa	R	3	L/F to BP/Fan	120	?
Nadon and Middleton (1984)	Triassic	New Brunswick	R	4	L/F to Fan	850	?
Steel and Wilson (1975)	Permian–Triassic	Scotland	R	6	L/F to Fan	470	?
Deegan (1973)	Carboniferous	Scotland	R-PA?	3	M to Fan	475	?
Schluger (1973)	Upper Devonian	New Brunswick	R	3	F to BP/Fan	520	?
Wilson (1980)	Lower Devonian	Scotland	R	3	F to Fan	1000	?
Daily et al. (1980)	Lower Cambrian	S. Australia	R?	2	M to Fan	650	?
Hayward (1984)	Miocene	Turkey	F	1	M to Fan	1250	15
Van Houten (1974)	Oligocene–Miocene	Switzerland	F	2	M to Fan	2000+	12.5
Van Houten (1974)	Eocene–Pliocene	France–Spain	F	3	M to Fan	2000+	10 to 15
Van Houten (1974)	Eocene–Pliocene	Spain	F	3	M to Fan	3000	10 to 15
McLean and Jerzykiewiecz (1978)	Cretaceous–Tertiary	Alberta	F	3	F to BP	570	8
Flores and Pillmore (1987)	Cretaceous–Tertiary	Colorado–New Mexico	F	3	F to BP/Fan	165	7
Wiltschko and Dorr (1983); Schedl and Wiltschko (1984)	Cretaceous–Tertiary	Utah–Wyoming	F	4	F/M to BP/Fan	1600	8
Villien and Kligfield (1986)	Cretaceous–Tertiary	Utah	F	5	M/F to BP/Fan	2000	10
Mack and Rasmussen (1984)	Permian	W. Colorado	F	3	F to Fan	300	?
Casey (1980)	Pennsylvanian	N. New Mexico	F	2	M to Fan/BP	1200	10
Kingsley (1987)	Precambrian	South Africa	F	4	F to Fan	125	?

Note: Data obtained from text or estimated from figures in referenced manuscripts. Maximum thickness used where lateral variations occur.
* PA = pull-apart basin; R = rift basin; F = foreland basin.
† M = marine deposits; L = lacustrine deposits; F = fine-grained fluvial deposits; BP = braidplain deposits; Fan = fan deposits.

tonically quiescent phases. The fact that remnant highs and multiple tectonic cyclothems are found in many ancient basin fills attests to the existence of significant relief, even during quiescent periods. The total elimination of marginal uplifts is unlikely until a significant time after the mechanism producing the uplift and basin permanently ceases.

The occurrence of fluvial, lacustrine, or marine environments adjacent to the active fault margins instead of extensive braid plains or bajadas is documented in modern active basins, including the Bad Water playa and Amargosa River in southeastern Death Valley, California (Hunt and Mabey, 1966; Blair, 1987b); the Deep Springs Lake in Deep Springs Valley, California (Blair, 1987a); the Madison River in the Hebgen Lake basin in Montana (Alexander and Leeder, 1985, 1987; Leeder and Alexander, 1987); and the northwestern Red Sea and Gulf of Suez coast (Purser et al., 1987). The fact that low-gradient fluvial, lacustrine, or marine environments occupy the basin-margin depression indicates that they responded more quickly to tectonic subsidence than the fan or braid-plain environments. This disparity has been ascribed to different hydrologic controls on sedimentation in these environments (Blair, 1985, 1987a, 1987b); fan sedimentation has been infrequent because of the need for extremely intense, very low frequency rainfall in the small drainage basins from which coarse sediment is derived. Without sufficient time for these infrequent events, coarse-grained sedimentation is minimal, regardless of structural relief. Fluvial systems longitudinal to the tectonic grain react more quickly to subsidence because deposition in them results from water and sediment discharge gathered from drainage basins thousands to tens of thousands times larger than those of the fans, and because of the finer grain size involved. Lake sedimentation also commences more quickly than fan sedimentation, because lakes are maintained by discharge through the longitudinal rivers or from springs that commonly emanate from the freshly fractured basin margin adjacent to the tectonic depression. This disparity is significant, as demonstrated by the deposition of 350 m of lacustrine sediments at the basin margin in southeastern Death Valley during a time when only widely spaced, uncoalesced alluvial fans with radii of less than 1 km had been built (Hunt and Mabey, 1966; Blair, 1987b). Similar relations in ancient examples have been described by Steel et al. (1977) and Gloppen and Steel (1981) for the Devonian Hornelen pull-apart basin; by Beck and Vondra (1985a, 1985b) and Kvale and Beck (1985) for the active margin of the Cretaceous-Paleogene Rocky Mountain foreland basin; and by LeTourneau (1985) for the Jurassic Hartford rift basin. If active subsidence lowers the basin below sea level and there is a connection between the basin and the sea, the development of a marine embayment would be virtually instantaneous, in contrast to the relatively slow growth of alluvial fans. Examples of this response based on correlation of the age of superimposed thrusting with marine transgressions or with significant increases in ocean-floor depths have been described from ancient foreland-basin fills by Kauffman (1981), Hayward (1984), and Villien and Kligfield (1986).

The Davis cycle correlation of a coarse-clastic influx to the basin with a period of active tectonic uplift of the source area implies that alluvial-fan or braid-plain environments are able to quickly produce a widely dispersed clastic wedge across the basin, and that denudation rates of the rejuvenated uplifted block can keep pace with or exceed tectonic uplift. Schumm (1963) determined that the average tectonic uplift rates in modern orogenic belts are 8 times higher than the average denudation rates and are as much as 117 times higher in regions that receive <100 cm of annual precipitation. This disparity between tectonic and erosion (sedimentation) rates combined with active deepening of the depositional locus adjacent to the basin margin severely limits coarse-sediment bypass from the areas immediately adjacent to the active margin (Beck and Vondra, 1985a, 1985b; Blair, 1985, 1987a; Kvale and Beck, 1985; Bilodeau and Blair, 1986; Jordan et al., 1986; Alexander and Leeder, 1987; Purser et al., 1987). Only when basin subsidence greatly lessens or ceases can the rate of denudation in the source area exceed subsidence to produce a widely dispersed progradational clastic wedge.

One of the first geologists, or *the* first, to interpret the origin of tectonic cyclothems in a manner opposite to that produced by application of the Davis cycle theory was Davis himself (1898, p. 33–35), in an article on the Triassic formations of Connecticut:

> The coarser beds are to-day generally found near the margin of the formation, on the east or west; but sometimes pebbles or cobbles up to 6 or 8 inches in diameter are found near the medial axis of the lowland. . . . Such strata may be taken to indicate a more than ordinary activity of transporting forces in the middle of the depressed area, probably during a time of less rapid depression of the region than usual, and an encroachment of the coarser marginal deposits on the flatter surface of the finer sediments along the middle of the trough. On the other hand, fine-textured and evenly laminated shales sometimes occur close to the border of the lowland . . . and these must be taken to indicate periods when the tranquil middle waters reached over a broader area, probably because of an increase in the depth and breadth of submergence . . . caused by a gain of depression over deposition. . . .

This passage reveals that Davis did not consider the application of his geographic cycle theory appropriate for interpreting the origin of tectonic cyclothems, a lead largely ignored by or unknown to twentieth century geologists confronted with explaining similar phenomena.

CONCLUSIONS

Stacked, large-scale tectonic cyclothems form along the active margins of rift, pull-apart, and foreland basins as a consequence of alternating periods of active tectonic subsidence and relative tectonic quiescence. The onset of a new phase of tectonic activity is most likely indicated by initial lacustrine, marine, or relatively fine-grained fluvial sedimentation over the coarse-grained alluvial-fan or braid-plain deposits, on the basis of modern examples, changing depositional topography, the rates of response to tectonic subsidence of the fine-grain–depositing environments vs. the coarse-grain–depositing environments, the limitations of widespread dispersal of coarse sediment during active subsidence, and the persistence of relief in the source area.

REFERENCES CITED

Alexander, J., and Leeder, M.R., 1985, Tectonic control upon alluvial architecture: Fort Collins, Colorado, Third International Fluvial Sedimentology Conference, Abstracts Volume, p. 7.

——1987, Active tectonic control on alluvial architecture, *in* Ethridge, F.G., Flores, R.M., and Harvey, M.D., eds., Recent developments in fluvial sedimentology: Society of Economic Paleontologists and Mineralogists Special Publication 39, p. 243–252.

Barrell, J., 1917, Rhythms and the measurement of geologic time: Geological Society of America Bulletin, v. 28, p. 745–904.

Beaumont, C., 1981, Foreland basins: Royal Astronomical Society Geophysical Journal, v. 65, p. 291–329.

Beck, R.H., and Vondra, C.A., Jr., 1985a, Sedimentary-tectonic model for Laramide basement-thrusting: Timing of deformation: Geological Society of America Abstracts with Programs, v. 17, p. 521.

——1985b, Syntectonic sedimentation and Laramide basement thrusting, Rocky Mountain foreland, Wyoming, Utah, and Colorado: Society of Economic Paleontologists and Mineralogists Midyear Meeting Abstracts, v. 2, p. 9–10.

Beerbower, J.R., 1964, Cyclothems and cyclic depositional mechanisms in alluvial plain sedimentation, *in* Merriam, D.F., ed., Symposium on cyclic sedimentation: Kansas Geological Survey Bulletin 169, p. 31–42.

Bilodeau, W.L., and Blair, T.C., 1986, Tectonics and sedimentation: Timing of tectonic events using sedimentary rocks and facies: Geological Society of America Abstracts with Programs, v. 18, p. 542.

Blair, T.C., 1985, Sedimentological response to tectonism in nonmarine rift basins: A comparison of the Jurassic Todos Santos Formation, Chiapas, Mexico, with Quaternary deposits in Death Valley, California: Society of Economic Paleontologists and Mineralogists Mid-year Meeting Abstracts, v. 2, p. 11–12.

——1987a, Hydrologic and tectonic controls on alluvial fan/fan delta sedimentation and basin-axis fluvial-lacustrine sedimentation, southwestern United States, and their implications to the origin of cyclic fan-floodbasin megasequences, *in*

Proceedings, International symposium on fan deltas: Bergen, Norway, University of Bergen, Geological Institute, p. 121–122.
—— 1987b, Tectonic and hydrologic controls on cyclic alluvial-fan, fluvial, and lacustrine rift-basin sedimentation, Jurassic–lowermost Cretaceous Todos Santos Formation, Chiapas, Mexico: Journal of Sedimentary Petrology, v. 57, p. 845–862.
Casey, J.M., 1980, Depositional systems and paleogeographic evolution of the Taos Trough, northern New Mexico, *in* Fouch, T.D., and Magathan, E.R., eds., Paleozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Symposium 1, p. 181–196.
Cavazza, W., 1985, Sedimentation and tectonics in the central Espanola Basin, Rio Grande rift, New Mexico: Society of Economic Paleontologists and Mineralogists Mid-year Meeting Abstracts, v. 2, p. 16–17.
Daily, B., Moore, P.S., and Rust, B.R., 1980, Terrestrial-marine transition in the Cambrian rocks of Kangaroo Island, South Australia: Sedimentology, v. 27, p. 379–399.
Davis, W.M., 1898, The Triassic formations of Connecticut: U.S. Geological Survey Annual Report No. 18, part 2, p. 1–192.
—— 1899, The geographical cycle: Geographical Journal, v. 14, p. 481–504.
Deegan, C.E., 1973, Tectonic control of sedimentation at the margin of a Carboniferous depositional basin in Kirkudbrightshire: Scottish Journal of Geology, v. 9, p. 1–28.
Dutton, S.P., 1982, Pennsylvanian fan-delta and carbonate deposition, Mobeetie field, Texas panhandle: American Association of Petroleum Geologists Bulletin, v. 66, p. 389–407.
Flores, R.M., and Pillmore, C.L., 1987, Tectonic control on alluvial paleoarchitecture of the Cretaceous and Tertiary Raton Basin, Colorado and New Mexico, *in* Flores, R.M., Ethridge, F.G., and Harvey, M.D., eds., Recent developments in fluvial sedimentology: Society of Economic Paleontologists and Mineralogists Special Publication 39, p. 311–320.
Gloppen, T.G., and Steel, R.J., 1981, The deposits, internal structure, and geometry in six alluvial fan–fan delta bodies (Devonian—Norway)—A study in the significance of bedding sequence in conglomerates, *in* Ethridge, F.G., and Flores, R.M., eds., Recent and ancient nonmarine depositional environments: Models for exploration: Society of Economic Paleontologists and Mineralogists Special Publication 31, p. 49–69.
Hayward, A.B., 1984, Sedimentation and basin formation related to ophiolite nappe emplacement, Miocene, SW Turkey: Sedimentary Geology, v. 40, p. 105–129.
Hendrix, E.D., and Ingersoll, R.V., 1987, Tectonics and alluvial sedimentation of the upper Oligocene/lower Miocene Vasquez Formation, Soledad basin, southern California: Geological Society of America Bulletin, v. 98, p. 647–663.
Heward, A.P., 1978, Alluvial fan and lacustrine sediments from the Stephanian A and B (La Magdalena, Cinera-Matallana and Sabero) coalfields, northern Spain: Sedimentology, v. 25, p. 451–488.
Hunt, C.B., and Mabey, D.R., 1966, Stratigraphy and structure, Death Valley, California: U.S. Geological Survey Professional Paper 494-A, 162 p.
Jordan, T.E., Flemings, P.B., and Beer, J.A., 1986, Foreland basin indicators of thrust belt activity: Resolution and limitation, *in* Kleinspehn, K., and Paola, C., eds., New perspectives in basin analysis: Minneapolis, University of Minnesota, Symposium Abstracts Volume (unpaginated).
Kauffman, E.G., 1981, Interaction of tectonic, sedimentologic, and eustatic history of the Western Interior Cretaceous seaway of North America, *in* Steidtmann, J.R., ed., Sedimentary tectonics, principles and applications: Laramie, University of Wyoming, Annual Spring Meeting Abstracts Volume, p. 15.
Kingsley, C.S., 1987, Facies changes from fluvial conglomerate to braided sandstone of the Early Proterozoic Eldorado Formation, Welkom Goldfield, South Africa, *in* Flores, R.M., Ethridge, F.G., and Harvey, M.D., eds., Recent developments in fluvial sedimentology: Society of Economic Paleontologists and Mineralogists Special Publication 39, p. 359–370.
Kvale, E.P., and Beck, R.A., 1985, Thrust controlled sedimentation patterns of the earliest Cretaceous nonmarine sequence on the Montana–Idaho–Wyoming foreland basin: Geological Society of America Abstracts with Programs, v. 17, p. 636.
Leeder, M.R., and Alexander, J., 1987, The origin and tectonic significance of asymmetrical meander-belts: Sedimentology, v. 34, p. 217–226.
LeTourneau, P.M., 1985, Alluvial fan development in the Lower Jurassic Portland Formation, central Connecticut—Implications for tectonics and climate: U.S. Geological Survey Circular 946, p. 17–26.
Link, M.H., 1982, Stratigraphic nomenclature and age of Miocene strata, Ridge basin, southern California, *in* Crowell, J.C., and Link, M.H., eds., Geologic history of Ridge basin, southern California: Los Angleles, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 5–12.
Mack, G.H., and Rasmussen, K.A., 1984, Alluvial-fan sedimentation of the Cutler Formation (Permo-Pennsylvanian) near Gateway, Colorado: Geological Society of America Bulletin, v. 95, p. 109–116.
Mann, P., Hempton, M., Bradley, D., and Burke, K., 1983, Development of pull-apart basins: Journal of Geology, v. 91, p. 529–554.
McLean, J.R., and Jerzykiewicz, T., 1978, Cyclicity, tectonics, and coal: Some aspects of fluvial sedimentology in the Brazeau-Paskapoo Formations, Coal Valley area, Alberta, Canada, *in* Miall, A.D., ed., Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 441–468.
Nadon, G.C., and Middleton, G.V., 1984, Tectonic control on Triassic sedimentation in southern New Brunswick: Local and regional implications: Geology, v. 12, p. 619–622.
Parrish, J.T., and Barron, E.J., 1986, Paleoclimates and economic geology: Society of Economic Paleontologists and Mineralogists Short Course 18, 162 p.
Playfair, J., 1802, Illustrations of the Huttonian theory of the Earth: London, Cadell and Davis, 528 p. (reprinted by Dover Publications, New York, 1964).
Purser, B.H., Soliman, M., and M'Rabet, A., 1987, Carbonate, evaporite, and siliciclastic transitions in Quaternary rift sediments of the northwestern Red Sea: Sedimentary Geology, v. 53, p. 247–267.
Schedl, A., and Wiltschko, D.V., 1984, Sedimentological effects of a moving terrane: Journal of Geology, v. 92, p. 273–287.
Schluger, P.R., 1973, Stratigraphy and sedimentary environments of the Devonian Perry Formation, New Brunswick, Canada, and Maine, U.S.A.: Geological Society of America Bulletin, v. 84, p. 2533–2548.
Schumm, S.A., 1963, The disparity between present rates of denudation and orogeny: U.S. Geological Survey Professional Paper 454-H, 13 p.
Smith, S.A., and Hiscott, R.N., 1984, Latest Precambrian to Early Cambrian basin evolution, Fortune Bay, Newfoundland: Fault-bounded basin to platform: Canadian Journal of Earth Sciences, v. 21, p. 1379–1392.
Steel, R.J., and Wilson, A.C., 1975, Sedimentation and tectonism (?Permo-Triassic) on the margin of the North Minch basin, Lewis: Geological Society of London Journal, v. 131, p. 183–202.
Steel, R.J., Maehle, S., Nilsen, H., Roe, S.L., and Spinnangr, A., 1977, Coarsening-upward cycles in the alluvium of Hornelen basin (Devonian), Norway: Sedimentary response to tectonic events: Geological Society of America Bulletin, v. 88, p. 1124–1134.
Tiercelin, J.T., 1987, The Pliocene Hadar Formation, Afar depression of Ethiopia, *in* Frostick, L.E., Renault, R.W., Reid, I., and Tiercelin, J.J., eds., Sedimentation in the African rifts: Geological Society of London Special Publication 25, p. 221–240.
Turner, B.R., 1983, Braidplain deposition of the Upper Triassic Molteno Formation in the main Karoo (Gondwana) Basin, South Africa: Sedimentology, v. 30, p. 77–89.
Van Houten, F.B., 1974, Northern Alpine molasse and similar Cenozoic sequences in southern Europe, *in* Dott, R.H., Jr., and Shaver, R.H., eds., Modern and ancient geosynclinal sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 19, p. 260–273.
Villien, A., and Kligfield, R.M., 1986, Thrusting and synorogenic sedimentation in central Utah, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 281–307.
Vondra, C.F., and Burggraf, D.R., Jr., 1978, Fluvial facies of the Plio-Pleistocene Koobi Fora Formation, Karari Ridge, East Lake Turkana, Kenya, *in* Miall, A.D., ed., Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 511–529.
Wernicke, B., and Burchfiel, B.C., 1982, Modes of extensional tectonics: Journal of Structural Geology, v. 4, p. 105–115.
Wilson, A.C., 1980, The Devonian sedimentation and tectonism of a rapidly subsiding, semi-arid fluvial basin in the Midland Valley of Scotland: Scottish Journal of Geology, v. 16, p. 291–313.
Wiltschko, D.V., and Dorr, J.A., Jr., 1983, Timing of deformation in Overthrust belt and foreland of Idaho, Wyoming, and Utah: American Association of Petroleum Geologists Bulletin, v. 67, p. 1304–1322.

ACKNOWLEDGMENTS

We thank T. F. Lawton, J. G. McPherson, G. A. Smith, A. S. Cohen, and D. V. Wiltschko for helpful comments on an earlier version of the manuscript.

Manuscript received December 17, 1987
Manuscript accepted March 4, 1988