Flysch to molasse transition in peripheral foreland basins: The role of the passive margin versus slab breakoff

H. D. Sinclair
School of Earth Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

ABSTRACT

The initiation of continental collision and the inception of peripheral foreland basins occur by the deformation and flexure, respectively, of the inherited passive margin of the foreland plate. During progressive plate convergence, peripheral foreland basins develop from an underfilled flysch stage to a filled or overfilled molasse stage. Classically, this flysch to molasse transition is interpreted as recording the migration of the thrust wedge and foreland basin over the hinge line of the inherited passive margin. It is demonstrated that during the development of the North Alpine foreland basin neither inherited paleobathymetry nor changing lithospheric strength of the underthrust European passive margin played a significant role in the flysch to molasse transition.

Sediment supply from the Alps increased at least 30% from the time of flysch to molasse deposition. At about the same time as the flysch to molasse transition (mid-Oligocene), the inner parts of the mountain belt experienced accelerated exhumation, uplift of high-pressure metamorphic rocks, lower lithospheric melting, and the onset of major backthrusting, all of which have been linked via a model of slab breakoff. A further consequence of the model is isostatic surface uplift and erosion. It is proposed that slab breakoff may have been responsible for the increased sediment supply that resulted in the flysch to molasse transition in the North Alpine foreland basin, and that this provides an alternative to the passive margin model.

INTRODUCTION

The collision of two continental plates is initiated by the overthrusting of the leading edge of one plate on to the outer passive margin of the other. The toe of the deforming thrust wedge is fully submarine, and the preceding turbiditic trench fill is classically termed flysch, and represents the early stage of peripheral foreland basin sedimentation (Allen et al., 1991). As the foreland basin becomes filled with sediment, so the depositional environments in the basin become shallow marine and continental; these sediments are classically termed molasse.

The flysch to molasse transition in peripheral foreland basins has been interpreted as recording the passage of the thrust wedge over the passive margin of the underthrust plate (Dewey, 1982; Allen et al., 1986; Stockmal et al., 1986; Stockmal and Beaumont, 1987; Watts, 1992). The influence of the passive margin is threefold: First, the stretched continental lithosphere seaward of the hingeline is likely to be mechanically weaker, generating a deep and narrow flexural depression. Second, the inherited paleobathymetry of the passive margin initiates the foreland basin in a deep-water setting. Third, the emergence of the thrust wedge above sea level results in accelerated erosion and sediment supply to the basin.

The Swiss Alps of Europe (Fig. 1) is one of the most cited mountain belts used to demonstrate the relationship between the inherited passive margin and the subsequent foreland basin development. This study questions the influence of the passive margin as a primary control on the flysch to molasse transition in the North Alpine foreland basin by analyzing the stratigraphic evidence for both the paleobathymetric hole and the mechanical weakening of the plate. Flysch and molasse sedimentation is compared in terms of sediment supply from the mountain belt. These data are then compared to the tectonic and thermal history of the Alps, leading to an alternative hypothesis for the flysch to molasse transition.

NORTH ALPINE FORELAND BASIN DEVELOPMENT

The Alpine orogeny commenced in middle Cretaceous time with the southward subduction of Tethyan oceanic crust. North-south convergence of the European and African continents resulted in the collision of the Adrian microplate into the southern margin of Europe in about Paleocene time (Dewey et al., 1989). The shortened European passive margin succession is now preserved within the folded and thrusted Helvetic zone of the Alps and its autochton (Trümpy, 1980). Initiation of the North Alpine foreland basin is recorded by the first evidence of orogenically derived sediments on the distal southern margin of the European plate. These oldest flysch deposits are exposed in eastern Switzerland within a thrust sheet of the southern Helvetic Alps called the Sardona thrust unit (Fig. 2) and are represented by turbidites of early Eocene age (Lihou, 1996). The underfilled flysch stage of the North Alpine foreland basin continued until middle Oligocene time when the basin became filled with shallow marine and continental sedi-

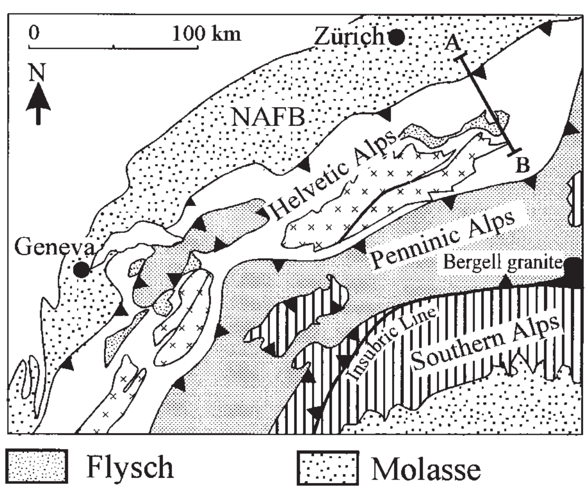

Figure 1. Geological map of Swiss Alps showing North Alpine foreland basin (NAFB). Section A–B is line for the chronostratigraphic reconstruction in Figure 2, modified from Sinclair (1997).

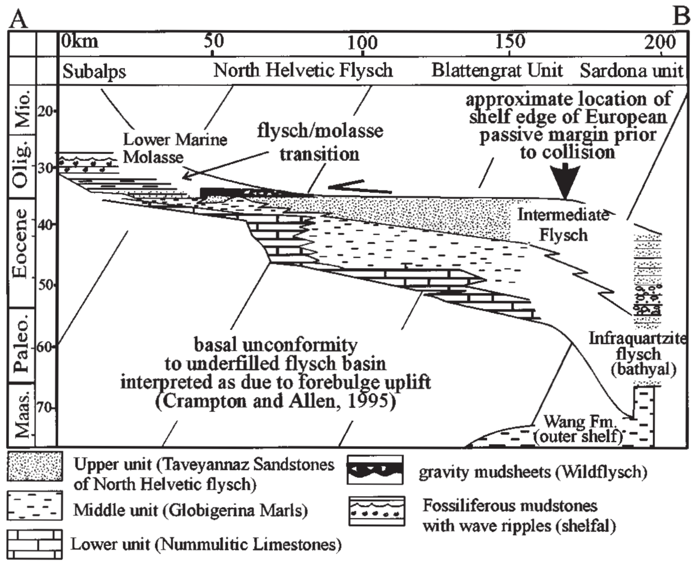

Figure 2. Palinspastically restored chronostratigraphic diagram for underfilled stage of North Alpine foreland basin modified from Sinclair (1997). For line of reconstruction, see A–B, Figure 1. Names across top refer to structural units within which succession below name is located.

ments (Sinclair and Allen, 1992). The subsequent filled or overfilled molasse stage in the development of the North Alpine foreland basin was characterized by continued but slower migration of the basin over the craton, and by a sedimentological infill dominated by shallow marine and continental sediments (Matter et al., 1980; Homewood et al., 1986; Sinclair, 1997).

EVIDENCE FOR A PALEOBATHYMETRIC HOLE

The oldest, orogenically derived flysch sediments of the Sardona thrust unit conformably overlie the Upper Cretaceous Globotruncana Marl (Fig. 2), which accumulated in an outermost shelf to slope setting (Lihou, 1996). By middle Eocene time, the thrust wedge–foreland basin system had migrated northward over the passive margin, as recorded in the stratigraphy of the Blattengrat thrust sheet (Fig. 2; Lihou, 1995). The underfilled trinity (Sinclair, 1997) unconformably overlies Cretaceous calcareous mudstones (Wang Formation) which accumulated in the passive margin shelf-slope environment. Overlying the unconformity, the lower unit of the trinity is represented by transgressive shallow-marine nummulite-rich limestones which are in turn overlain by hemipelagic marls recording bathyal water depths (Herb, 1988; Lihou, 1995). The uppermost deposits of the trinity are sandstone turbidites, which are part of the classical flysch sequences of the Alps (Trümpy, 1980). The geometry and sedimentary characteristics of the basal unconformity have been interpreted to record forebulge uplift of the European passive margin (Crampton and Allen, 1995). Localized pockets of middle to upper Eocene, iron-rich sandstone and breccia, which are interpreted as a continental fissure filling unit, infill the paleokarst surface of the unconformity (Trümpy, 1980; Herb, 1988; Crampton and Allen, 1995). Forward modeling of the uplift and erosion that generated this unconformity suggests that the southward transition from unconformity to conformity (Blattengrat to Sardona units) coincides with the continental margin–shelf break (Crampton and Allen, 1995). The flexural basin containing the underfilled trinity, bound at its base by the unconformity, migrated north-northwestward for at least 100 km over the subaerially exposed European passive margin for a period of ~20 m.y. (Sinclair, 1997). Therefore, this stage of flysch sedimentation cannot record the infilling of an inherited paleobathymatric hole, but the water depths into which the trinity accumulated were wholly generated by flexural subsidence.

EVIDENCE FOR MECHANICAL WEAKENING

Stratigraphic studies have established that the shelf edge of the European margin prior to foreland basin development was located ~100 km south of the position of termination of flysch sedimentation (see above). The restored cross-sectional geometry of the molasse foreland basin at 17 Ma, which developed ~50 km northwestward (cratonward) of the earlier underfilled basin, indicates an effective elastic thickness of 10 ± 5 km (Sinclair et al., 1991). Similarly, Schlunegger et al. (1997) indicate a Te of 10–15 km during deposition of the Lower Freshwater Molasse (25 Ma). Watts's (1992) model for bimodal strength of passive margins and its control on the flysch to molasse transition in foreland basins uses an increase in elastic thickness of >50 km; any increase in elastic thickness under the North Alpine foreland basin from flysch to molasse cannot have been greater than 15 km. To summarize, it appears that neither the inherited paleobathymetry nor varying flexural rigidity of the passive margin are likely to have played a role in the flysch to molasse transition in the Alps.

EXHUMATION AND SEDIMENT SUPPLY

Sinclair and Allen (1992) recognized that the underfilled to filled transition was linked to increased exhumation rates in the Alpine mountain belt; such exhumation may be tectonic or erosional in origin. Differentiation of these mechanisms of exhumation may be indirectly evaluated by looking for evidence of variations in sediment supply from the mountain belt to the foreland basin using reconstructed sediment volumes.

Basin-parallel transport of sediment results in both an influx and outflux of material within a given portion of a basin over long time intervals. Therefore, the following comparison of flysch to molasse sediment volumes necessarily assumes that the influx to outflux ratio in the portion of the basin analyzed remained approximately constant. Volumes of sediment are calculated (Table 1) allowing for compaction, and are then divided by

TABLE 1. DATA USED TO CALCULATE SEDIMENT DISCHARGE FOR FLYSCH AND MOLASSE STAGES IN THE EVOLUTION OF A 180 km ALONG-STRIKE DISTANCE OF THE SWISS NORTH ALPINE FORELAND BASIN

Stage	Duration* (m.y.)	Depth of burial† (km)	Burial compaction§ (%)	Decompacted volume (km^3)	Sediment supply (km^3/my)	Sediment discharge** (Mt/yr)	Denudation†† (mm/yr)
Flysch	10	10	60	10080	1008	2.1672	-
Molasse	19	2	20	24303	1279	2.8138	0.074

*Age dates from Taveyannaz sandstones from Fischer and Villa (1989) and for the molasse from Berger (1992).

†From Rahn et al. (1994).

§Assuming 50:50 mudstone sandstone ratio for flysch and 0:100 for molasse and compaction curves from Allen and Allen (1990).

**Assuming sandstone density of 2200 kg m^{-3} and mudstone of 2100 kg m^{-3}.

††Assuming present-day drainage basin area.

the duration of accumulation to enable time-averaged sediment supply rates to be estimated and compared between times of flysch and molasse deposition. The starting hypothesis is that molasse sedimentation rates are higher than those of flysch. Therefore, the flysch sediment supply rates are calculated as maximum values, and molasse as minimum values, thus pushing the error bars to yield least difference values between the two sets of data.

The volume of flysch sediments deposited during the early development of the North Alpine foreland basin uses palinspastic restorations of the underfilled basin (Sinclair, 1997). Maximum observed thicknesses for the Taveyannaz Sandstones of the North Helvetic Flysch in Switzerland are 240 m (Sinclair, 1992), which decompacts to 384 m (Table 1). The cross-sectional length of the basin from the northward termination under the Helvetic nappes (Pfiffner et al., 1990) to southward termination against the paleothrust front was up to 46 km (Sinclair, 1997). The slightly older South Helvetic flysch was no thicker than 200 m (320 m decompacted), and when linked to the southernmost deposits of the Taveyannaz Sandstones, had a cross-sectional length of no greater than 120 km. To give a maximum value for the dimensions of the basin, the cross-sectional area was based on two rectangles representing the North Helvetic and South Helvetic basins. Given that the Glarus Alps expose the maximum thicknesses of North Helvetic flysch sediments, this cross-sectional geometry was projected across Switzerland to yield an upper limit. The maximum value for sediment supply during the period of flysch sedimentation was ~2.17 Mt yr^{-1} (Table 1).

The molasse sediments are well preserved and documented, constrained by a large number of wells (Rigassi, 1977); these data were converted into a contoured isopach map for the same along-strike distance as that studied in the flysch sediments. Volumetric calculations used a trapezoidal approximation. The minimum sediment supply during molasse times was ~2.81 Mt yr^{-1} (Table 1), representing a 30% increase compared to the time of flysch deposition.

Assuming that the surface area of the northern slope of the Alpine mountain belt during the time of molasse deposition was similar to that of today (~80 km wide), then the sediment supply of ~2.81 Mt yr^{-1} translates to a sediment yield of 195 t yr^{-1} km^{-2} which, assuming an average rock density of 2650 kg m^{-3}, equates to a denudation rate of 0.074 mm yr^{-1}. Exhumation rates in the Alps at this time from fission-track data ranged from 0.1 to 0.6 mm yr^{-1} , depending on location relative to major structures such as the Insubric line (Hurford et al., 1989).

CONTROLS ON THE FLYSCH TO MOLASSE TRANSITION

In the Alpine case, the transition from an underfilled flysch foreland basin to a filled molasse foreland basin is characterized by two major changes in the nature of the thrust wedge–foreland basin system approximately in middle Oligocene times (1) increased exhumation and initiation of major backthrusting in the core of the mountain belt (Sinclair and Allen, 1992) linked to an associated increase in sediment supply to the basin (see above), (2) reduction in the rate of thrust-front propagation (Sinclair and Allen, 1992) and an associated slowing down in the rate of basin migration across the foreland (Sinclair, 1997). These changes could be explained by internal thickening of the thrust wedge caused by the buttress effect of the passive margin, leading to subaerial emergence of the wedge. However, without evidence to support this mechanism, an alternative explanation is considered.

There are three candidate mechanisms that could bring about such a change in the behavior of the thrust wedge–foreland basin system without invoking the influence of the passive margin: (1) a climatic change leading to increased erosion rates and sediment supply, (2) change in the mechanical properties of the thrust wedge, leading to internal thickening and uplift, or (3) isostatic uplift induced by the mechanical detachment of high-density material at the root of the mountain belt. Local climatic change was tentatively proposed as a control by Sinclair and Allen (1992), although primarily in response to increased relief and maximum peak elevations, i.e., as a response rather than a cause. Climatically, western Europe is thought to have cooled from sub-tropical to warm temperate from Eocene into Oligocene times (Frakes, 1979), but any interpretation of how this may have effected denudation rates would be speculative due to the complex link between climate and denudation (Summerfield, 1991). Changes in the mechanical properties of a thrust wedge, such as an increase in the resistance to shear on the basal detachment of the wedge or a decrease in the mechanical strength of the wedge, could lead to accelerated surface uplift, and hence erosional downcutting (Dahlen and Suppe, 1988). However, we currently have no evidence to suggest that such mechanical changes took place in the Alpine thrust wedge.

Von Blankenburg and Davies (1995) proposed a model for syncollisional magmatism and tectonics in the Alps that invokes detachment of the subducted oceanic lithosphere from the less dense underthrust continental lithosphere during collision (Fig. 3). The detached lithosphere is replaced by upwelling asthenospheric mantle, which leads to heating and partial melting of the lower boundary of the over-riding lithospheric mantle and resultant magmatism. The removal of the load of the subducting slab also generates rapid isostatic uplift, which is most likely to lead to accelerated erosion.

The slab-breakoff model predicts the rapid exhumation of high-pressure rocks, intrusion of magmas above the line of slab breakoff, and accelerated surface uplift of the mountain belt. High-pressure metamorphic rocks derived from subduction of the Penninic ocean indicate that subduction stopped ca. 40 Ma, followed by rapid uplift from 40 to 35 Ma (Von Blankenberg and Davies, 1995). Granitic and basaltic intrusion ages aligned along the Insubric backthrust (Fig. 1) show a pronounced and sharp maximum between 33 and 29 Ma. Fission-track data indicate accelerated exhumation of the Sesia zone between 33 and 25 Ma in the hanging wall of the Insubric backthrust (Hurford et al., 1989, 1991). The transition from the underfilled flysch to the filled or overfilled molasse stage in the North

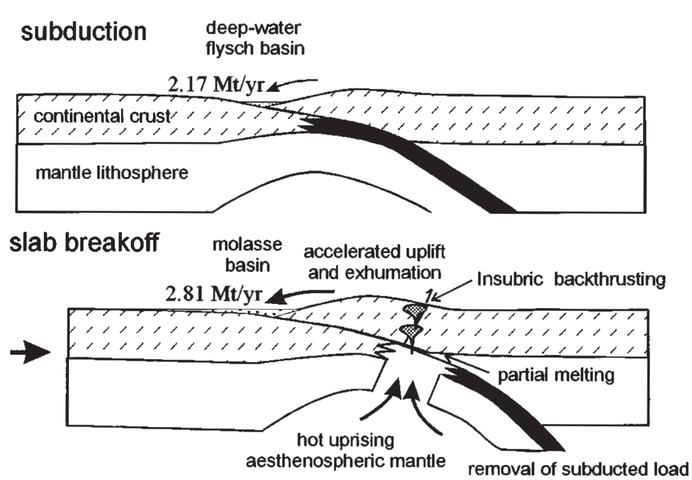

Figure 3. Model of slab breakoff as applied to European Alps. Removal of slab causes buoyant isostatic surface uplift, uplift of high pressure metamorphic rocks, partial melting of the overriding slab, and back-thrusting (modified from Davies and von Blanckenburg, 1994). Arrows indicate maximum (flysch) and minimum (molasse) sediment discharge values (labelled) from mountain belt to basin during two stages in the basin's evolution.

Alpine foreland basin took place during the upper Rupelian (33–30 Ma).

In conclusion, the similarity in the timing of events related to slab breakoff and the filling of the North Alpine foreland basin from flysch to molasse suggest a possible link. The prediction of accelerated isostatic uplift by the slab breakoff model, and the evidence for increased exhumation and sediment yield from the mountain belt further strengthen the link. Consequently, the slab breakoff model is viewed as a more likely control on the filling of the North Alpine foreland basin than the relatively unconstrained linkage that has classically been proposed between the depositional filling and the inherited passive margin.

ACKNOWLEDGMENTS

Thanks to Philip Allen (Dublin) for early comments, and to Rudy Slingerland (Pennsylvania State University) and Mike Williams (Galway) for constructive reviews.

REFERENCES CITED

Allen, P. A., Homewood, P. W., and Williams, G. D., 1986, Foreland basins: An introduction, *in* Allen, P. A., and Homewood, P., eds., Foreland basins: International Association of Sedimentologists Special Publication, v. 8, p. 3–12.

Allen, P. A., Crampton, S. L., and Sinclair, H. D., 1991, The inception and early evolution of the North Alpine Foreland Basin, Switzerland: Basin Research, v. 3, p. 143–163.

Allen, P. A., and Allen, J. R., 1990, Basin analysis: Principles and products: Oxford, United Kingdom, Blackwell Scientific Press, 451 p.

Berger, J.-P., 1992, Correlative chart of the European Oligocene and Miocene: Application to the Swiss Molasse Basin: Eclogae Geologicae Helveticae, v. 85, p. 573–609.

Crampton, S. L., and Allen, P. A., 1995, Recognition of forebulge unconformities associated with early stage foreland basin development: Example from the North Alpine foreland basin: American Association of Petroleum Geologists Bulletin, v. 79, p. 1495–1514.

Dahlen, F. A., and Suppe, J., 1988, Mechanics, growth, and erosion of mountain belts, *in* Clark, S. P., Jr., Burchfiel, B. C., and Suppe, J., eds., Processes in continental lithospheric deformation: Geological Society of America Special Paper 218, p. 161–178.

Davies, J. H., and von Blanckenburg, F., 1994, Slab breakoff: A model of lithospheric detachment and its test in the magmatism and deformation of collisional orogens: Earth and Planetary Science Letters, v. 129, p. 85–102.

Dewey, J. F., 1982, Plate tectonics and the evolution of the British Isles: Geological Society of London Journal, v. 139, p. 371–414.

Dewey, J. F., Helman, M. L., Turco, E., Hutton, D. H. W., and Knott, S. D., 1989, Kinematics of the western Mediterranean, *in* Coward, M. P., Dietrich, D., and Park, R. G., eds., Alpine Tectonics: Geological Society of London Special Publication, v. 45, p. 265–283.

Fischer, H., and Villa, I. M., 1989, Erste K/Ar- und ^{40}Ar/^{39}Ar-Hornblende-Mineralalter des Taveyannaz Sandsteins: Schweizerische Mineralogische und Petrographische Annual Meeting Abstracts, p. 42.

Frakes, L. A., 1979, Climate change through geological time: Amsterdam, Elsevier, 310 p.

Herb, R., 1988, Eocaene paläogeographie und paläotektonik des Helvetikums: Eclogae Geologicae Helveticae, v. 81, p. 611–657.

Homewood, P. W., Allen, P. A., and Williams, G. D., 1986, Dynamics of the molasse basin in western Switzerland, *in* Allen, P. A., and Homewood, P., eds., Foreland basins: International Association of Sedimentologists Special Publication, v. 8, p. 119–217.

Hurford, A. J., Flisch, M., and Jäger, E., 1989, Unravelling the thermo-tectonic evolution of the Alps: A contribution from fission-track analysis and mica-dating, *in* Coward, M. P., Dietrich, D., and Park, R. G., eds., Alpine tectonics: Geological Society of London Special Publication, v. 45, p. 369–398.

Hurford, A. J., Hunziker, J. C., and Stöckhert, B., 1991, Constraints on the late thermotectonic evolution of the western Alps: Evidence for episodic rapid uplift: Tectonics, v. 10, p. 758–769.

Lihou, J. C., 1995, A new look at the Blattengrat unit of eastern Switzerland: Early Tertiary foreland basin sediments from the south Helvetic realm: Eclogae Geologicae Helveticae, v. 88/1, p. 91–114.

Lihou, J. C., 1996, Stratigraphy and sedimentology of the Sardona unit, Glarus Alps: Upper Cretaceous/middle Eocene deep-marine flysch sediments from the Ultrahelvetic realm: Eclogae Geologicae Helveticae, v. 89, p. 721–752.

Matter, A., Homewood, P. W., Caron, C., Van Stuijvenberg, J., Weidmann, M., and Winkler, W., 1980, Flysch and molasse of central and western Switzerland, *in* Trümpy, R., ed., Geology of Switzerland, a guide book: Schweiz Geologica Kommissione, p. 261–293.

Pfiffner, O. A., Frei, W., Vlalsek, P., Stäuble, M., Levato, L., Dubois, L., Schmid, S. M., and Smithson, S. B., 1990, Crustal shortening in the Alpine orogen: Results from deep seismic reflection profiling in the Eastern Swiss Alps. Line NFP 12-east: Tectonics, v. 9, p. 1327–1355.

Rahn, M., Mullis, J., Erdelbrock, K., and Frey, M., 1994, Very low-grade metamorphism of the Taveyanne greywacke, Glarus Alps, Switzerland: Journal of Metamorphic Geology, v. 12, p. 625–641.

Rigassi, D., 1977, Subdivision et datation de la molasse "d'eau douce inferieure" du Plateau Suisse: Terreaux du Temple, Geneva, Paleolab. News, v. 1.

Schlunegger, T., Jordan, T. E., and Klaper, E., 1997, Controls of erosional denudation in the orogen on foreland basin evolution: The Oligocene central Swiss Molasse Basin as an example: Tectonics (in press).

Sinclair, H. D., 1992, Turbidite sedimentation during Alpine thrusting: The Taveyannaz Sandstones of eastern Switzerland: Sedimentology, v. 39, p. 837–856.

Sinclair, H. D., 1997, Tectonostratigraphic model of underfilled peripheral foreland basins: An Alpine perspective: Geological Society of America Bulletin, v. 109, p. 323–347.

Sinclair, H. D., Coakley, B. J., Allen, P. A., and Watts, A. B., 1991, Simulation of foreland basin stratigraphy using a diffusion model of mountain belt uplift and erosion: An example from the central Alps, Switzerland: Tectonics, v. 10, p. 599–620.

Sinclair, H. D., and Allen, P. A., 1992, Vertical versus horizontal motions in the Alpine orogenic wedge: Stratigraphic response in the foreland basin: Basin Research, v. 4, p. 215–232.

Stockmal, G. S., and Beaumont, C., 1987, Geodynamic models of convergent margin tectonics: The Southern Canadian cordillera and the Swiss Alps, *in* Beaumont, C., and Tankard, A. J., eds., Sedimentary basins and basin–forming mechanisms: Canadian Society of Petroleum Geologists Memoir 12, p. 93–411.

Stockmal, G., Beaumont, C., and Boutilier, R., 1986, Geodynamic models of convergent margin tectonics: Transition from rifted margin to overthrust belt and consequences for foreland basin development: American Association of Petroleum Geologists Bulletin, v. 70, p. 181–190.

Summerfield, M. A., 1991, Global geomorphology: An introduction to the study of landforms: New York, Longman Scientific and Technical, 537 p.

Trümpy, R., 1980, Geology of Switzerland, a guide book. Part A: An outline of the geology of Switzerland: Basel, Wepf, 104 p.

Watts, A. B., 1992, The effective elastic thickness of the lithosphere and the evolution of foreland basins: Basin Research, v. 4, p. 169–178.

Manuscript received May 27, 1997
Revised manuscript received September 8, 1997
Manuscript accepted September 22, 1997