Back folds in the core of the Himalayan orogen: An alternative interpretation

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ABSTRACT

The hanging wall of the South Tibetan detachment system in the central Nepal Himalaya is characterized by regional-scale, northeast-verging folds, classically interpreted as gravity-induced structures developed during down-to-the-north extensional shearing along the detachment system. New structural observations and balanced cross sections of the Tethyan sedimentary sequence in the Kali Gandaki area and new U-Pb geochronology support an alternative interpretation. The northeast-verging folds developed before ductile extensional shearing along the detachment system, thereby recording some of the earliest contraction of this part of the orogen. We propose a new model in which the northeast-verging folds of the Kali Gandaki area represent the northern part of a late Eocene to Oligocene contractional fan structure.

INTRODUCTION

This paper focuses on a regional-scale fold system in the central Nepal Himalaya. The folds have a northward vergence, opposite to the main south-verging structures across most of the Himalaya, and are preserved in the hanging wall of the South Tibetan detachment system, a major Miocene extensional fault zone (Burchfiel et al., 1992). Segments of the detachment system were active at ca. 20 Ma, coeval with southeast-verging contractional structures associated with the Main Central thrust at deeper structural levels (e.g., Hodges et al., 1996). At that time, the Greater Himalayan metamorphic sequence between the South Tibetan detachment system and the Main Central thrust was intruded by leucogranitic rocks and subjected to high-temperature metamorphism (Deniel et al., 1987; Pêcher, 1989; Vannay and Hodges, 1996). Considerable emphasis has been placed on the timing of extension along the South Tibetan detachment system and contraction along the Main Central thrust (Hubbard and Harrison, 1988; Burchfiel et al., 1992; Hodges et al., 1996). Despite recent structural studies in the Ladakh-Zanskar Himalaya in northwest India (Searle et al., 1997 and references therein), few studies in the Nepal Himalaya have focused directly on the relationship between the South Tibetan detachment system and the fold structures in its hanging wall.

Since the pioneering work of French researchers in the Dhaulagiri-Annapurna range of central Nepal (Bordet et al., 1971; Caby et al., 1983), the northeast-verging folds elsewhere in the Himalayan orogen have been classically interpreted as the result of gravity-induced sliding along the South Tibetan detachment system (Burchfiel et al., 1992). More recently, Brown and Nazarchuk (1993) questioned this interpretation for central Nepal. As an alternative, they speculated that the northeast-verging folds could result from an early period of compression and crustal thickening (see also Bordet et al., 1971, p. 266).

Newly obtained field data are used in reevaluating both the extensional gravity-induced sliding model current in the literature and the compressional alternative suggested by Brown and Nazarchuk (1993). The geometric and kinematic constraints from cross sections constructed through the Kali Gandaki valley of central Nepal are briefly described, and the timing relationships between these northeast-verging folds and the extensional detachment fault system are presented (see also Godin et al., 1999). New U-Pb data indicate that regional metamorphism affected the Greater Himalayan metamorphic sequence during the Oligocene. A new, testable compressional model for the generation of the northeast-verging folds is proposed.

GEOLOGIC SETTING

From south to north, the Kali Gandaki valley in central Nepal (Fig. 1) comprises three important tectonostratigraphic units: (1) the Lesser Himalayan sedimentary sequence, composed of Precambrian to Mesozoic low-grade metasedimentary rocks; (2) the Greater Himalayan metamorphic sequence, composed of highly sheared kyanite- and sillimanite-bearing gneisses intruded by variably deformed Miocene leucogranites; and (3) the Tethyan sedimentary sequence, a nearly continuous, 10-km-thick early Paleozoic to early Tertiary sedimentary pile, representing the Indian continental margin of the Tethys ocean (Bordet et al., 1971; Colchen et al., 1981; Gradstein et al., 1992).

Previous workers have identified two main north-dipping tectonic boundaries in the Kali Gandaki area: (1) the Main Central thrust, which is a Miocene crustal-scale plastic-brittle shear zone along which the Greater Himalayan metamorphic sequence was emplaced southward over the Lesser Himalayan sedimentary sequence (Colchen et al., 1981); and (2) the Annapurna detachment, which is defined as a plastic-brittle normal fault juxtaposing the Tethyan sedimentary sequence in the hanging wall against the Greater Himalayan metamorphic sequence in the footwall (Caby et al., 1983; Brown and Nazarchuk, 1993). The Annapurna detachment has been correlated by Brown and Nazarchuk (1993) with the South Tibetan detachment system described by Burchfiel et al. (1992) and is correlative with the Deurali detachment described farther east in the Annapurna range, where multi-stage extensional faulting has been observed (Hodges et al., 1996).

The Tethyan sedimentary sequence in the Kali Gandaki area has undergone five stages in its structural evolution (Godin et al., 1999) that are represented by the following: (1) southwest-verging isoclinal folds (F1), (2) northeast-verging, tight, megascopic folds (F2); (3) transposition of F1 and F2 into the extensional north-dipping Annapurna detachment (Brown and Nazarchuk, 1993) and related high-strain zone (Dt; Godin et al., 1999); (4) postmetamorphic, southwest-verging kink folds (F3) and related crenulation cleavages produced by renewed contraction; and (5) east-west extension in the southern part of the Tibetan Plateau (Molnar and Tapponnier, 1978), which initiated movement along north-striking normal faults related to the Thakkhola graben system in the northern Kali Gandaki valley.

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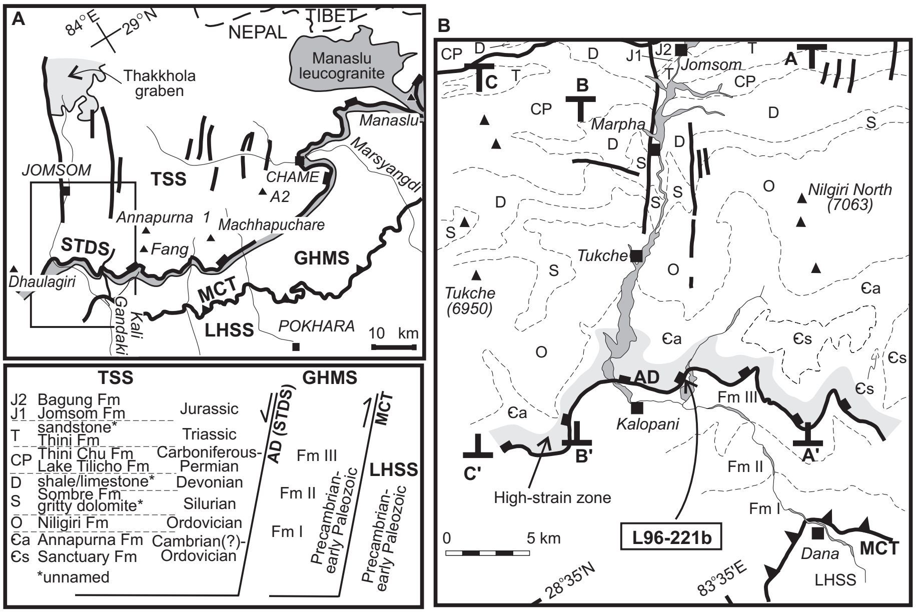

Figure 1. A: Geologic map of central Nepal simplified and modified after Colchen et al. (1981). B: Geologic map of upper Kali Gandaki valley, modified from Bordet et al. (1971), Colchen et al. (1981), and Godin et al. (1999). AD—Annapurna detachment, GHMS—Greater Himalayan metamorphic sequence, LHSS—Lesser Himalayan sedimentary sequence, MCT—Main Central thrust, STDS—South Tibetan detachment system, TSS—Tethyan sedimentary sequence; A–A', B–B', and C–C' locate section lines of Figure 2.

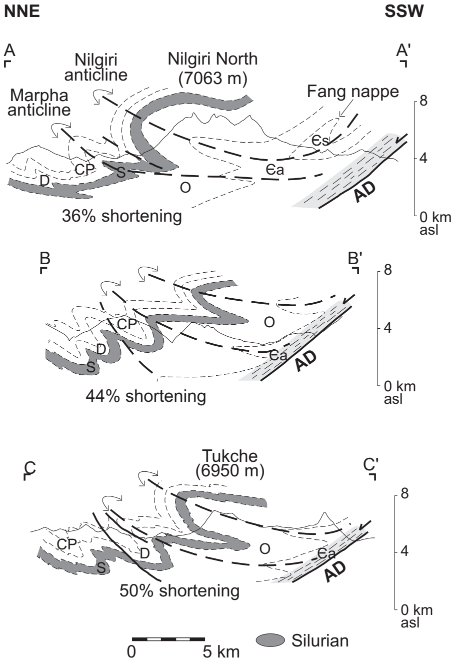

Figure 2. Three geologic cross sections of upper Kali Gandaki valley, showing northeast-verging second-generation folds preserved in hanging wall of Annapurna detachment. Visible on section A–A', Fang nappe is a first-generation southwest-verging fold, refolded by F2 Nilgiri anticline. Abbreviations as in Figure 1, and asl = above sea level.

In the Annapurna sector, the spectacular F2 folds are well exposed, especially on the west face of the Nilgiri peaks where Ordovician limestones are folded in a kilometer-scale overturned antiform (Bordet et al., 1971) (Fig. 2). The gravity-induced sliding model generally accepted for these folds has also been applied to folds adjacent to extensional faults in the Austroalpine nappes of Switzerland (Froitzheim, 1992) and within the Indus suture zone of northwest Pakistan (Burg et al., 1996). In these two studies, folds were attributed to ductile horizontal extension of originally steep layering or anisotropy during vertical shortening of a gravitationally unstable orogenic system, based on three principal assumptions: (1) folding is restricted to a ductile layer, (2) folds are localized and associated with extensional structures, and (3) the layering or anisotropy was steeply dipping before initiation of normal faulting (Froitzheim, 1992).

FOLD GEOMETRY AND RESTORATION

In the Annapurna area, F2 folds have interlimb angles of 20º to 55º (average 35º). The fold hinge zones are typically subangular to subrounded. Analysis of cross sections and field photographs indicates that the folds generally belong to class 1B to 1C of Ramsay (1967), intermediate between ideal parallel and ideal similar folds. F2 folds are typically moderately inclined to overturned, with shallow southwest-dipping axial surfaces and gently (~12º) east-southeast–plunging axes, with a penetrative axial-plane cleavage (S2). The general vergence of the fold train is toward the northeast in the lower structural levels, becoming progressively more upright at higher levels. F2 folds have been observed by the authors in reconnaissance studies as far north as Lo Monthang, 75 km from the Annapurna detachment.

Three northeast-trending balanced cross sections (Fig. 2), 22 to 27 km long, have been constructed, with the Annapurna detachment as the southern limit. The lack of geophysical data in central Nepal precludes geologic extrapolation below sea level. Although the total stratigraphic thickness of the Cambrian(?) to Lower Cretaceous Tethyan sedimentary sequence in the Kali Gandaki valley averages 11 km, the three sections only show up to 6 km of stratigraphic thickness, from Cambrian(?) to Carboniferous-Permian strata.

In the prominent northeast-verging F2 fold system, the southernmost and geometrically highest fold is the Nilgiri anticline, whose axis can be traced for more than 300 km, from the Gyirong and Manang areas in the east (Fuchs et al., 1988; Burchfiel et al., 1992) to the Tarap Khola area in the Dolpo region to the west (Fuchs, 1977). The axial-plane cleavages of these folds are cut and progressively transposed by the high-strain zone associated with the Annapurna detachment (Godin et al., 1999). The amount of layer-parallel shortening by folding of the Silurian strata increases westward from 36% to 50% as the Annapurna detachment cuts up section (Fig. 2).

To help quantify the amount of vertical and horizontal deformation that affected the rocks of central Nepal, two end-member restoration models are presented (Fig. 3). Model 1 attributes the F2 folding entirely to drag along the Annapurna detachment. Model 2 assumes that the F2 folds were produced during an early contractional event, but were subsequently affected by ductile strain associated with the detachment.

A geometric construction to restore folding associated with extensional faulting in the Kohistan arc of northwest Pakistan was used by Burg et al. (1996). Their method assumes a marker unit that retains its original length and thickness and attributes folding entirely to drag along the detachment fault. The construction can be applied to the Kali Gandaki sections by using the Silurian horizon as a marker. Each section is pinned at the northeastern end, and it is assumed that the layering was initially parallel to the enveloping surface of the F2 folds. Furthermore, the bed-length restoration assumes that the layers were tilted down to the north prior to sliding and folding along the Annapurna detachment. Simple geometrical unfolding of the F2 folds provides minimum estimates for horizontal and vertical shortening of the Silurian rocks by the F2 folds of 44% ± 8% and 37% ± 3%, respectively, yielding a minimum fault displacement of 10 km and a minimum throw of 6.4 km (Fig. 3A). However, our field evidence indicates that these geometrical constraints are not the appropriate boundary conditions. The F2 folds are deflected and transposed by a high-strain zone associated with the Annapurna detachment (Godin et al., 1999). Accordingly, the F2 fold system may have been generated prior to ductile normal faulting. Furthermore, as noted above, the F2 folds extend well to the

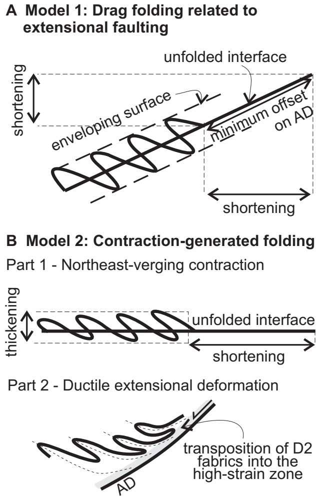

Figure 3. Two end-member models for restoration of second-generation northeast-verging folds of central Nepal. A: Drag folding related to extensional faulting along Annapurna detachment (from Burg et al., 1996). B: Contraction-generated folding prior to movement along Annapurna detachment. AD—Annapurna detachment.

north of the Annapurna detachment. We therefore suggest that the F2 folds formed during a pre-detachment compressional event and that bedding was nearly horizontal prior to folding (Fig. 3B). Restoring these folds to a prefaulting orientation undoes the rotational effect that the Annapurna detachment had on the axial surfaces. Applying the above restoration method yields minimum estimates of 43% ± 7% horizontal shortening and ~150% vertical thickening. This deformation would increase the original 10-km stratigraphic thickness of the Tethyan sedimentary sequence to 25 km, in agreement with the erosion and/or exhumation calculated for the footwall rocks of the detachment (Vannay and Hodges, 1996).

TIMING

Detailed structural mapping has demonstrated that the stratigraphy and the D1 and D2 structures affecting the Tethyan sedimentary sequence are cut and completely transposed into the ductile high-strain zone associated with the Annapurna detachment (Godin et al., 1999) and, as noted, that the northeast-verging F2 folds may predate the main ductile extensional shearing associated with the Annapurna detachment. In this light, it is significant that emplacement of the ca. 22 Ma Manaslu granite to the east postdates northeast-verging folds (Guillot et al., 1993, 1994). Given that the earliest movement on the Main Central thrust in the central Nepal Himalaya occurred at ca. 22.5 Ma (Hodges et al., 1996), the northeast-verging folds appear to predate both extensional deformation associated with the high-strain zone of the Annapurna detachment and contractional deformation along the Main Central thrust.

An obvious test of our hypothesis would be the presence of a pre-Miocene thermal anomaly associated with crustal thickening induced by the contractional event. Several early Oligocene magmatic and metamorphic ages have been obtained from the Greater Himalayan metamorphic sequence (36–30 Ma; Coleman, 1996; Hodges et al., 1996; Vannay and Hodges, 1996). However there are no unequivocal constraints on potential pre-Miocene kyanite-grade metamorphism. We have obtained a new U-Pb lower-intercept age of 35 ± 3 Ma for monazite and zircon extracted from a kyanite-bearing leucosome from the immediate footwall of the Annapurna detachment (Fig. 4)[1]. We interpret this age to be the time of magmatic crystallization of the leucosome during kyanite-grade metamorphism. We consider this age to be a first firm indication of Oligocene metamorphism affecting the Greater Himalayan metamorphic sequence, consequently requiring crustal thickening at higher structural levels. The monazite and zircon array is produced by a mixture of inherited monazite and zircon with a ca. 35 Ma magmatic component produced during crystallization in the kyanite + melt stability field of an anatectic melt. The upper-intercept age of 460 ± 11 Ma is interpreted as inheritance from immediately adjacent and structurally lower Formation III augen gneiss of early Ordovician age (Le Fort et al., 1986).

ALTERNATIVE DYNAMIC MODEL

We propose a testable alternative model to explain the presence of northeast-verging folds in the hanging wall of the Annapurna detachment (Fig. 5), wherein they developed as part of a compressional fan structure prior to ductile normal faulting on the Annapurna detachment. Such a fan structure fits available data and is predicted by numerical and mechanical orogenic models as a response to lithospheric underthrusting (Malavieille, 1984; Willet et al., 1993).

We envisage that the first stage of evolution of the Tethyan sedimentary sequence in the Kali Gandaki area corresponds to southward-directed folding during initial underthrusting of the Indian plate under its continental shelf deposits, represented by southwest-verging isoclinal folds such as the Fang nappe (Bordet et al., 1971). Although timing of this stage is not well constrained in the Nepal Himalaya, it has been inferred that the earliest deformation affecting the Tethyan sedimentary sequence may be early to middle Eocene (Hodges et al., 1996; Vannay and Hodges, 1996), similar to age constraints obtained for the earliest deformation in the Ladakh-Zanskar area (Searle et al., 1988). Stage 2 corresponds to the growth of a fan structure through continued underthrusting, with northeast-verging folds developed on the northern side of the fan axis. Crustal thickening should result in an Eohimalayan high-temperature, high-pressure metamorphic event, such as that recorded in the Greater Himalayan metamorphic sequence (Vannay and Hodges, 1996). Stage 3 marks the activation of the Miocene southwest-verging Main Central thrust system, with coeval development of the extensional South Tibetan de-

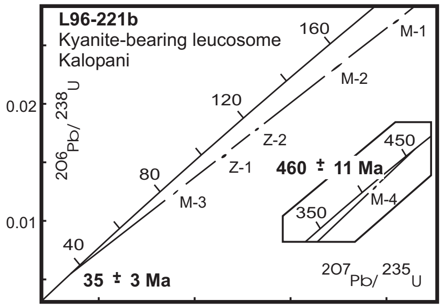

Figure 4. U-Pb concordia diagram for kyanite-bearing leucosome (L96-221b) sampled in immediate footwall of Annapurna detachment, near Kalopani (see Fig. 1 for location). All monazite (M) and zircon (Z) fractions are multigrain analyses. Inset shows detail of upper intercept, which we interpret as representing inheritance from country rock. We interpret lower intercept as age of leucosome production and kyanite growth. York linear regression at MSWD = 8.76 (MSWD—mean squared weighted deviation).

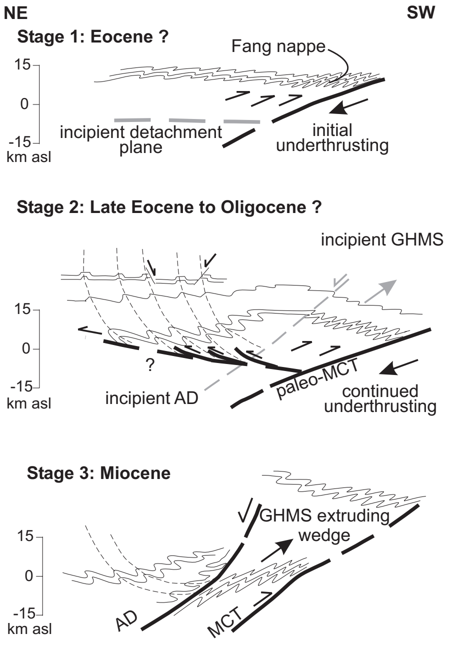

Figure 5. Proposed alternative dynamic model for formation of northeast-verging folds of central Nepal. Stages 1 to 3 correspond to first three stages of structural evolution of Tethyan sedimentary sequence as presented in Godin et al. (1999). See text for details. AD—Annapurna detachment, GHMS—Greater Himalayan metamorphic sequence, MCT—Main Central thrust, asl—above sea level.

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[1] GSA Data repository item 9914, U-Pb analytical methods and data, is available on request from Documents secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or www.geosociety.org/pubs/ftpyrs.htm.

tachment system, leucogranite production, and high-temperature and lower-pressure Neohimalayan metamorphism in the Greater Himalayan metamorphic sequence (Deniel et al., 1987; Hubbard and Harrison, 1988; Pêcher, 1989; Hodges et al., 1996; Vannay and Hodges, 1996). Northeast-verging folds generated during stage 2 were preserved above the South Tibetan detachment system, while those folds in the rocks below were transposed by southwest-verging deformation associated with the Main Central thrust. Stage 3 was followed by renewed shortening which produced southwest-verging kink folds and crenulation cleavages in the upper Kali Gandaki valley (Godin et al., 1999), and parts of the high-strain zone associated with the Annapurna detachment were reactivated as localized thrusts, such as the Kalopani shear zone (Vannay and Hodges, 1996).

DISCUSSION

Our compressional model for F2 folding presents a testable alternative to the classical gravity-induced extensional model applied to the northeast-verging folds in the central Nepal Himalaya. An Oligocene fan structure is one possible scenario that is internally consistent with available data and reconciles certain features that are otherwise difficult to explain. These include the apparent thickening of the Tethyan sedimentary sequence, the crosscutting relationships between the northeast-verging folds and extensional fabrics related to the Annapurna detachment, and the presence of a regionally important Oligocene thermal event in its footwall. Growth of an Oligocene fan structure would have thickened the Tethyan sedimentary sequence to 25 km, provoking kyanite-grade melting at depth. Furthermore, it would have significantly contributed to the rise of the Himalayan topographic front, leading to the Miocene gravitational instability that produced the South Tibetan detachment system (Burchfiel et al., 1992). Such an Oligocene structural and thermal event would bridge the gap between the initial early Eocene continental collision and the well constrained Miocene events of the central Nepal Himalaya. Possible tests would include fold topology with accurate determination of fold-related thickening, cleavage dating of the F2 folds, and detailed geophysical work that could highlight major structures hidden beneath the floor of the Kali Gandaki valley.

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REFERENCES CITED

Bordet, P., Colchen, M., Krummenacher, D., Le Fort, P., Mouterde, R., and Remy, M., 1971, Recherches géologiques dans l'Himalaya du Népal: Région de la Thakkhola: Paris, Éditions du Centre National de la Recherche Scientifique, 279 p.

Brown, R. L., and Nazarchuk, J. H., 1993, Annapurna detachment fault in the Greater Himalaya of central Nepal, *in* Treloar, P. J., and Searle, M. P., eds., Himalayan tectonics: Geological Society [London] Special Publication 74, p. 461–473.

Burchfiel, B. C., Chen Zhiliang, Hodges, K. V., Liu Yuping, Royden, L. H., Deng Changrong, and Xu Jiene, 1992, The South Tibetan detachment system, Himalaya orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt: Geological Society of America Special Paper 269, 41 p.

Burg, J.-P., Chaudry, M. N., Ghazanfar, M., Anczkiewicz, R., and Spencer, D., 1996, Structural evidence for back sliding of the Kohistan arc in the collisional system of northwest Pakistan: Geology, v. 24, p. 739–742.

Caby, R., Pêcher, A., and Le Fort, P., 1983, Le grand chevauchement central himalayen: Nouvelles données sur le métamorphisme inverse à la base de la Dalle du Tibet: Revue de Géologie Dynamique et de Géographie Physique, v. 24, p. 89–100.

Colchen, M., Le Fort, P., and Pêcher, A., 1981, Geological map of Annapurnas-Manaslu-Ganesh Himalaya of Nepal, *in* Gupta, H. K., and Delany, F. M., eds., Zagros-Hindu Kush-Himalaya geodynamic evolution: Washington, D.C., American Geophysical Union, scale 1:200,000.

Coleman, M. E., 1996, The tectonic evolution of the central Himalaya, Marsyandi valley, Nepal [Ph.D thesis]: Cambridge, Massachusetts Institute of Technology, 221 p.

Deniel, C., Vidal, C., Fernandes, A., and Le Fort, P., 1987, Age, origin and emplacement of an Himalayan leucogranite: The Manaslu example (Nepal): Contributions to Mineralogy and Petrology, v. 96, p. 78–92.

Froitzheim, N., 1992, Formation of recumbent folds during synorogenic crustal extension (Austroalpine nappes, Switzerland): Geology, v. 20, p. 923–926.

Fuchs, G., 1977, The geology of the Karnali and Dolpo regions, western Nepal: Jahrbuch der Geologischen Bundesanstalt, Wien, v. 120, p. 165–217.

Fuchs, G., Widder, R. W., and Tuladhar, R., 1988, Contributions to the geology of the Annapurna Range (Manang area, Nepal): Jahrbuch der Geologischen Bundesanstalt, Wien, v. 131, p. 593–607.

Godin, L., Brown, R. L., and Hanmer, S., 1999, High strain zone in the hanging wall of the Annapurna detachment, central Nepal Himalaya, *in* Macfarlane, A., et al., eds., Himalaya and Tibet: Mountain roots to mountain tops: Geological Society of America Special Paper 328.

Gradstein, F. M., von Rad, U., Gibling, M. R., Jansa, L. F., Kaminski, M. A., Kristiansen, I.-L., Ogg, J. G., Rohl, U., Sarti, M., Thorow, J. W., Westermann, G. E. G., and Wiedmann, J., 1992, The Mesozoic continental margin of central Nepal: Geologisches Jahrbuch, v. 77, p. 3–141.

Guillot, S., Pêcher, A., Rochette, P., and Le Fort, P., 1993, The emplacement of the Manaslu granite of central Nepal: Field and magnetic susceptibility contraints, *in* Treloar, P. J., and Searle, M. P., eds., Himalayan tectonics: Geological Society [London] Special Publication 74, p. 413–428.

Guillot, S., Hodges, K. V., Le Fort, P., and Pêcher, A., 1994, New constraints on the age of the Manaslu leucogranite: Evidence for episodic tectonic denudation in the central Himalayas: Geology, v. 22, p. 559–562.

Hodges, K. V., Parrish, R. R., and Searle, M. P., 1996, Tectonic evolution of the central Annapurna range, Nepalese Himalayas: Tectonics, v. 15, p. 1264–1291.

Hubbard, M. S., and Harrison, T. M., 1988, ^{40}Ar/^{39}Ar constraints on the thermal history of the Main Central thrust zone and Tibetan slab, eastern Himalaya: Tectonics, v. 8, p. 865–880.

Le Fort, P., Debon, F., Pêcher, A., Sonet, J., and Vidal, P., 1986, The 500 Ma magmatic event in Alpine southeast Asia, a thermal event at Gondwana scale: Sciences de la Terre Mémoire 47, p. 191–209.

Malavieille, J., 1984, Modélisation expérimentale des chevauchements imbriqués: Application aux chaînes de montagnes: Société Géologique de France Bulletin, v. 26, p. 129–136.

Molnar, P., and Tapponnier, P., 1978, Active tectonics of Tibet: Journal of Geophysical Research, v. 83, p. 5361-5375.

Pêcher, A., 1989, The metamorphism in the central Himalaya: Journal of Metamorphic Geology, v. 7, p. 31–41.

Ramsay, J. G., 1967, Folding and fracturing of rocks: New York, McGraw-Hill, 568 p.

Searle, M. P., Cooper, D. J. W., and Rex, A. J., 1988, Collision tectonics of the Ladakh-Zanskar Himalaya: Royal Society of London Philosophical Transactions, v. A326, p. 117–150.

Searle, M. P., Corfield, R. I., Stephenson, B., and McCarron, J., 1997, Structure of the north Indian continental margin in the Ladakh-Zanskar Himalayas: Implications for the timing of obduction of the Spontang ophiolite, India-Asia collision and deformation events in the Himalaya: Geological Magazine, v. 134, p. 297–316.

Vannay, J.-C., and Hodges, K. V., 1996, Tectonomorphic evolution of the Himalayan metamorphic core between the Annapurna and Dhaulagiri, central Nepal: Journal of Metamorphic Geology, v. 14, p. 635–656.

Willet, S., Beaumont, C., and Fullsack, P., 1993, Mechanical model for the tectonics of doubly vergent compressional orogens: Geology, v. 21, p. 371–374.

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