**TECTONIC EVOLUTION OF THE TETHYAN SEDIMENTARY SEQUENCE IN
THE ANNAPURNA AREA, CENTRAL NEPAL HIMALAYA**

By

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FRONTISPIECE

The majestic northeast face of Dhaulagiri (8167 m) is composed of Early Paleozoic limestones of the Tethyan sedimentary sequence. These sediments lie directly above the normal-sense Annapurna detachment, a segment of the South Tibetan detachment system.

ABSTRACT

The Annapurna detachment is part of the orogen-parallel extensional South Tibetan detachment system, which extends along most of the length of the Himalaya. It crops out in the Kali Gandaki area of central Nepal, where it juxtaposes the Tethyan sedimentary sequence in the hanging wall with rocks of the Greater Himalayan metamorphic sequence in the footwall.

A five-phase structural evolution for the Tethyan sedimentary sequence is proposed. The first phase is characterized by southwest-verging isoclinal folds (D_1). The second phase is represented by northeast-verging megascopic tight folds (D_2). These first two phases are transposed in a 1,500 meter-thick high-strain zone (D_t) affecting the lowermost part of the Tethyan sedimentary sequence and the uppermost part of the Greater Himalayan metamorphic sequence. The high-strain fabrics are associated with down-to-the-northeast normal shear-sense indicators, which are linked to initial ductile shearing along the Annapurna detachment. The fourth phase is post-peak metamorphic, and marks a return to southwest-vergent thrusting and folding (D_3). During this phase, parts of the Tethyan sedimentary sequence and the high-strain zone were reactivated as localized thrusts. The fifth phase (D_4) is a brittle event associated with east-west extension along the Thakkhola graben structures. Late top-to-the-northeast brittle normal faults also disrupt rocks within the high-strain zone during this phase and could mark the present-day southern termination of the Thakkhola graben.

U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of monazite and muscovite from footwall and hanging-wall rocks of the Annapurna detachment are presented. Early Oligocene crustal thickening led to Eohimalayan kyanite-grade metamorphism between 35 and 32 Ma. The resulting thermal event affected the Early Ordovician Formation III augen gneiss and produced kyanite-bearing leucosomes in the upper part of the Greater Himalayan metamorphic sequence. A weakly deformed leucogranitic dike intruding the immediate hanging wall yielded reversely discordant monazite ages between 23 and 22.5 Ma, which suggest that the ductile strain in the Annapurna detachment zone terminated at *ca.* 22 Ma. Based on a $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age, the D_3 deformation phase is interpreted to occur at

ca. 18 Ma. Rapid exhumation cooled the entire Greater Himalayan metamorphic sequence through the muscovite Ar closure temperature (330-430 °C) between 15 and 13 Ma. Muscovites from the immediate hanging wall of the Annapurna detachment yielded slightly younger ages, between 13 and 11 Ma, testifying to late hydrothermal activity in the Annapurna detachment zone. This thermal event could be linked with the initiation of brittle faulting related to the Thakkhola graben system.

The hanging wall of the Annapurna detachment 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. Results from this thesis 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. Accordingly, a new model is proposed in which the northeast-verging folds of the Kali Gandaki area represent the northern part of a Late Eocene to Oligocene contractional fan structure.

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“The mountain is the meeting of earth and heavens, home of the gods, and the term of human ascent. From above, it seems like the point of a vertical, the center of the world; from below, as seen from the horizon, it becomes the line of a vertical, the axis of the world, but also the ladder, the challenge to climb.”

Translated from “Le Dictionnaire des Symboles”, Éditions Robert Laffont.

*À mes parents, Marielle et Jean-Claude,
qui m'ont appris à ne jamais abandonner mes rêves.*

ORIGINAL CONTRIBUTION

The author carried out six months of field work in the upper Kali Gandaki area of central Nepal. This field work was accomplished with the aid of an assistant and a four-person support crew. Petrography, quartz petrofabric analysis, compilation, and analysis of structural and stratigraphic data was done at Carleton University by the author. Following this, a complete revision of the cross sections across the Tethyan sedimentary sequence of central Nepal was produced. As a direct result of this study, previously unrecognized features have been described and newly named. These include a 1,500 meter-thick high-strain zone located in the immediate hanging wall of the Annapurna detachment, and an enigmatic structural break termed the Lupra fault.

Heavy mineral separation of four rock samples for U-Pb geochronology, and 11 mica and hornblende separates for $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology were prepared by the author at Carleton University, under the supervision of Dr. Sharon Carr. Mass spectrometry and data reduction of the $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology were performed by Dr. Kip Hodges at the Massachusetts Institute of Technology (U.S.). U-Pb geochronology, including chemistry, mass spectrometry and data reduction, were entirely performed by the author at the NERC Isotope Geosciences Laboratory (U.K.) under the supervision of Dr. Randall Parrish. The interpretation of all the geochronology was done by the author, with the collaboration of Dr. Randall Parrish and Dr. Kip Hodges.

Chapter 4 and part of chapter 2 were published in scientific journals during the course of writing the thesis; all the data were collected by the author. The co-authors for these papers contributed to data interpretation.

This thesis led to the first direct U-Pb age constraint on a metamorphic event affecting the Himalayan metamorphic core, confirming the previously suggested Oligocene age for this event. Furthermore, this is the first study to reinterpret the origin of the northeast-verging folds affecting the Tethyan sedimentary sequence, and the first to propose the presence of an Oligocene structural fan to explain the Oligocene thermal event preserved in the Himalayan metamorphic core.

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CHAPTER 1

GENERAL INTRODUCTION

The Himalayan orogen extends for over 2000 km and straddles parts of Pakistan, India, Tibet (China), Nepal and Bhutan (Figure 1.1). The Himalayan belt outlines the world's most dramatic topographic front and holds some of the highest mountains with elevations reaching over 8000 m. This mountain chain marks the southern limit of the Tibetan plateau, which is the largest uplifted part of the Earth with an average elevation of 5000 m.

The Himalayan orogen was initiated at *ca.* 50 Ma, following the collision of the Indian and Eurasian plates (Gansser, 1964; Patriat and Achache, 1984; Rowley, 1998). This collision resulted in the closure of the Tethyan ocean, in the southward imbrication of the Indian crust, and in the northward continental subduction of India beneath Asia (Le Fort et al., 1975; Searle et al., 1987). Although the Himalayan orogen is one of the most impressive results of intercontinental collision and has been extensively studied, its tectonic evolution remains enigmatic.

The last two decades have seen a considerable increase in the recognition of orogen-parallel normal fault systems in active high-elevation orogenic fronts with accompanying coeval thrusting at lower structural levels. The Cordillera Blanca in the Andes of Peru (Dalmayrac and Molnar, 1981) and the Himalayan range south of the Tibetan plateau (Caby et al., 1983; Burg and Chen, 1984; Burg et al., 1984; Burchfiel and Royden, 1985; Burchfiel et al., 1992) are among the more intensely studied areas with

such extensional fault systems. In the Himalaya, down-to-the-northeast normal movement on the South Tibetan detachment system (Burchfiel et al., 1992) occurred in Miocene time (Guillot et al., 1994; Harrison et al., 1995; Hodges et al., 1996), coeval with some southeast-verging contractional structures associated with the Main Central thrust at deeper structural levels (Hubbard, 1989; Hubbard and Harrison, 1989; Hodges et al., 1992). The South Tibetan detachment system consists of a series of normal faults extending for at least 600 km along strike (Burchfiel and Royden, 1985), and regional correlations suggest that the system may be up to 2000 km in length (Burchfiel et al., 1992). This normal fault system is commonly localized at the contact between the deformed Indian continental margin, namely the Tethyan sedimentary sequence, and the metamorphic core of the orogen, termed the Greater Himalayan metamorphic sequence.

The kinematic history of the South Tibetan detachment system varies considerably along its strike length. Although it is clear that the system comprises a major structural break, its kinematic history is still poorly understood. Thrusting, normal faulting, and dextral shearing have all been proposed to explain field observations in certain localities along its contact (Pêcher, 1991; Burchfiel et al., 1992; Vannay and Steck, 1995; Hodges et al., 1996); however, the relationships between these proposed deformation episodes have not been clearly assessed. Furthermore, despite the fact that the Himalayan orogen is generally viewed as an asymmetric, south-verging orogen with in-sequence thrusting toward the south, kilometer-scale, north-verging folds and thrusts are observed throughout the Tethyan sedimentary sequence. Although not clearly documented, these structures have been classically interpreted as the result of gravity-induced sliding along the South Tibetan detachment system (Burchfiel et al., 1992 and

references therein). More recently, this interpretation has been challenged by Brown and Nazarchuk (1993). As an alternative, they speculated that the north-verging deformation could result from an earlier period of compression and crustal shortening.

The main objective of this thesis is to properly assess the geometric, kinematic, and timing relationships between the north-verging folds preserved in the Tethyan sedimentary sequence and the South Tibetan detachment system. The research project consisted of detailed structural analysis of the Tethyan sedimentary sequence, followed by U-Pb geochronology of samples from the Greater Himalayan metamorphic sequence and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of a suite of samples across the detachment zone. This latter part was done in order to gain a better understanding of the thermal evolution of the metamorphic core.

The study area is located in upper Kali Gandaki valley of central Nepal, in the vicinity of the Annapurna (8091 m) and Dhaulagiri (8167 m) mountains. Since the seminal work of Gansser (1964), this area has been the subject of intense geologic investigations (Table 1.1). Two of these studies resulted in the production of high-quality geologic maps. Bordet et al. (1971) produced a detailed geologic map of the upper Kali Gandaki valley, which was later incorporated into a regional compilation map of central Nepal (Colchen et al., 1981). The well-constrained stratigraphy and regional geology of the area combined with its relatively easy access made the upper Kali Gandaki valley an ideal location for this thesis.

Chapters 2, 3 and 4 are written in the form of independent papers to help facilitate publication in journals. Chapter 2 describes a five-phase structural evolution for the Tethyan sedimentary sequence and documents how the deformation style varies with

structural level. This chapter also describes the kinematic history of the Annapurna detachment, a segment of the South Tibetan detachment system (Brown and Nazarchuk, 1993). It will be shown that the Annapurna detachment is associated with a previously unrecognized 1,500 meter-thick high-strain zone preserved in its immediate hanging wall. This section of chapter 2 focusing on the Annapurna detachment and its high-strain zone (section 2.4) appeared as a paper in the *Geological Society of America Special Volume 324* (Godin et al., 1999a).

Chapter 3 presents U-Pb geochronology and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of samples collected in the vicinity of the Annapurna detachment. The geochronologic results indicate that an important thermal event affected the upper part of the metamorphic core during the Oligocene, prior to Miocene thermal and structural events. Furthermore, $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology on muscovites across the metamorphic core revealed that the timing of exhumation of the metamorphic core through the 370°C isotherm occurred between 15 and 13 Ma, comparable to other areas along the length of the Himalaya. The implications of the results on the thermal and tectonic history of the Himalayan metamorphic core are also discussed. This chapter will be the subject of a future contribution to the journal *Tectonics*.

Chapter 4 focuses on the origin of folds preserved in the hanging wall of the Annapurna detachment. These folds have been attributed to gravity-induced sliding along the detachment plane since the early 1970's without adequate testing. A testable and provocative new model for the origin of these folds that is compatible with available field data and numerical models is presented. Furthermore, this chapter presents the first direct U-Pb age constraint on a metamorphic event affecting the Himalayan metamorphic core,

confirming the previously suggested Oligocene age for this event. This chapter has been published in the journal *Geology* (Godin et al., 1999b).

Table 1.1: Previous geologic investigations in the central Nepal Himalaya

Type of study	Authors
Stratigraphic	Hagen, 1959; Bodenhausen et al., 1964; Bodenhausen and Egeler, 1971; Bordet et al., 1971; Fuchs, 1977; Colchen et al., 1981; Fort et al., 1982; Fuchs et al., 1988; Grastein et al., 1992; Fuchs, 1994
Structural	Bordet et al., 1971; Bouchez and Pêcher, 1976; Pêcher, 1977; Colchen et al., 1981; Caby et al., 1983; Le Fort et al., 1986a; Pêcher, 1991; Pêcher et al., 1991; Brown and Nazarchuk, 1993; Coleman, 1996a,b; Hodges et al., 1996; Godin et al., 1999a,b
Metamorphic and geochronologic	Pêcher, 1975; Le Fort, 1981; Arita, 1983; Le Fort et al., 1986a,b; Deniel et al., 1987a,b; Pêcher, 1989; Copeland et al., 1990; Nazarchuk, 1993; Schneider and Masch, 1993; Guillot et al. 1993; Guillot et al., 1994; Garzanti et al., 1994; Coleman and Hodges, 1995; Vannay and Hodges, 1996; Coleman, 1996b; Harrison et al., 1997; Coleman and Hodges, 1998; Godin et al., 1999b

Figure 1.1: Geologic map and regional tectonic framework of the Himalaya. The Himalayan orogen is divided into four longitudinal belts: (1) the Tethyan sedimentary sequence, (2) the Greater Himalayan metamorphic sequence, (3) the Lesser Himalayan sedimentary sequence and (4) the Sub-Himalaya or Siwalik mollasse. The Indus-Tsangpo suture zone represents the initial boundary between the Indian and Asian plates. HFT, Himalayan Frontal thrust; ITSZ, Indus-Tsangpo suture zone; KF, Karakoram fault; MBT, Main Boundary thrust; MCT, Main Central thrust; STDS, South Tibetan detachment system (from Sorkhabi and Stump, 1993).

Karakoram and Trans-Himalayan batholith	Tethyan sedimentary sequence	Outer crystallines
ITSZ sediments	STDS	Lesser Himalayan sedimentary sequence
Chilas-Jijal complex	Miocene leucogranites	MBT
ITSZ	Greater Himalayan metamorphic sequence	Siwalik molasse
Ophiolite klippe	MCT	Indo-Gangetic alluvial plains
		HFT

CHAPTER 2

THE ANNAPURNA DETACHMENT AND THE STRUCTURAL EVOLUTION OF THE TETHYAN SEDIMENTARY SEQUENCE IN ITS HANGING WALL, CENTRAL NEPAL HIMALAYA

ABSTRACT

The normal-sense Annapurna detachment is part of the orogen-parallel South Tibetan detachment system, which extends along most of the length of the Himalaya. It crops out in the Kali Gandaki area of central Nepal, where it juxtaposes the Tethyan sedimentary sequence in the hanging wall with rocks of the Greater Himalayan metamorphic sequence in the footwall.

A five-phase structural evolution for the Tethyan sedimentary sequence is proposed. The first phase is characterized by southwest-verging isoclinal folds (D_1). The second phase is represented by northeast-verging megascopic tight folds (D_2). These first two phases are transposed in a 1,500 meter-thick high-strain zone (D_t) affecting the lowermost part of the Tethyan sedimentary sequence and the uppermost part of the Greater Himalayan metamorphic sequence. The high-strain fabrics are associated with down-to-the-northeast normal shear-sense indicators, which are linked to initial ductile shearing along the Annapurna detachment. The fourth phase is post-peak metamorphic, and marks a return to southwest-vergent thrusting and folding (D_3). During this phase, parts of the Tethyan sedimentary sequence and the high-strain zone were reactivated as localized thrusts. The fifth phase (D_4) is a brittle event associated with east-west extension along the Thakkhola graben structures. Late top-to-the-northeast brittle normal faults also disrupt rocks within the high-strain zone during this phase and could mark the present-day southern termination of the Thakkhola graben.

The F_2 folds, classically interpreted to be the result of gravitational sliding along the South Tibetan detachment system, clearly predate ductile extensional faulting. This folding phase, which thickened the Tethyan sedimentary sequence, is probably related to an older compressional event. The Annapurna detachment represents a zone of superposed shearing; both normal and thrust shear-sense indicators are preserved.

2.1 INTRODUCTION

Thick sedimentary sequences undergoing regional deformation commonly display complex strain distribution that can result in a structural zonation due to differences in the distribution of strain and the prevailing deformation mechanisms. Such a zonation may reflect kinematic partitioning of strain, spatial variation of strain orientation and/or

magnitude, or accommodation of strain by different deformation mechanisms within the same body (Axen et al., 1998).

In central Asia, the northern advance of the Indian paleocontinent during the Tertiary period resulted in the closing of the Tethyan sea. This gave rise to the Himalayan mountains, clearly the most spectacular modern-day example of an intercontinental collision. Paleotethyan and Tethyan sediments, part of the northern continental shelf sequence of the Indian paleocontinent, have been intensely deformed during collision, and remnants of the sedimentary sequence are preserved along the length of the Himalayan orogen. In central Nepal, a near-complete 10 kilometer-thick Tethyan sedimentary sequence, from Cambrian to Cretaceous, is preserved. Prevailing anisotropies and rheological contrasts outlined by the stratigraphy within such a thick sedimentary sequence inevitably influenced the style of deformation, resulting in different deformation patterns at different structural levels.

This chapter addresses the structural and tectonic evolution of the Tethyan sedimentary sequence, as observed in the Kali Gandaki valley of central Nepal. Emphasis is placed on the structural evolution and the kinematics of deformation, but also on the variation of the deformation style with changing structural level. The topography of the area exposes >5 kilometer-high mountain faces, which permits the observation and study of different generations of structures and their manifestation at different crustal levels.

Results of detailed mapping and structural fabric analysis from the upper Kali Gandaki valley in central Nepal are presented. It is shown that the area was affected by five distinct deformation events with contrasting style and vergence, from Eocene-Oligocene contraction to Holocene east-west extension. The data show the presence of a

1,500 meter-thick high-strain zone located at the base of the Tethyan sedimentary sequence, characterized by an intense transposition fabric. This zone is attributed to normal-sense distributed ductile shearing associated with movement across the Annapurna detachment. Parts of the zone were later reactivated by southwest-vergent mesoscopic folding and related shearing. Subsequently, the zone was locally affected by brittle normal faults related to a late Neogene graben system.

2.2 GEOLOGIC SETTING

The area under investigation is located in the Kali Gandaki valley, in the Annapurna-Manaslu-Ganesh Himal of central Nepal (Figure 2.1). From south to north, the area comprises three important tectonostratigraphic units: (1) the Lesser Himalayan sedimentary sequence, composed of Precambrian to Mesozoic low-grade metasediments; (2) the metamorphic core of the Himalayan orogen, termed the Greater Himalayan metamorphic sequence, composed of highly strained kyanite- and sillimanite-grade gneisses intruded by variably deformed Miocene leucogranites; and (3) the Tethyan sedimentary sequence, a nearly continuous 10 kilometer-thick early Paleozoic to early Tertiary sedimentary sequence representing the Indian paleocontinental margin of the Tethys ocean (Bodenhausen and Egeler, 1971; Bordet et al., 1971; Colchen et al., 1986; Gradstein et al., 1992).

2.2.1 Tectonic elements of the Kali Gandaki valley

Previous workers have identified two main tectonic boundaries: (1) the Main Central thrust, which is a Miocene, crustal-scale, plastic-brittle shear zone that juxtaposes

the Greater Himalayan metamorphic sequence southward over the Lesser Himalayan sedimentary sequence (Bouchez and Pêcher, 1976; Pêcher, 1977); and (2) the Annapurna detachment, which is defined as a plastic-brittle normal fault juxtaposing the Tethyan sedimentary sequence in the hanging wall with the Greater Himalayan metamorphic sequence in the footwall (Caby et al., 1983; Brown and Nazarchuk, 1993). The Annapurna detachment is associated with a 1,500 meter-thick high-strain zone that affects green-schist facies, biotite-muscovite psammite of the Tethyan sedimentary sequence and amphibolite facies biotite-garnet-sillimanite and/or kyanite schist, garnet-diopside calc-silicate and leucogranitic gneiss of the Greater Himalayan metamorphic sequence (Godin et al., 1999a). The Annapurna detachment has been correlated by Brown and Nazarchuk (1993) with the South Tibetan detachment system described by Burchfiel et al. (1992). It is correlative with the Deurali and the Chame detachments described farther east in the Annapurna range, where the detachment splays into a complex zone of multi-stage extensional faults (Hodges et al., 1996; Coleman, 1996a). The South Tibetan detachment system was active in central Nepal at ~22 Ma (Guillot et al., 1994; Harrison et al., 1995; Hodges et al., 1996) and is coeval with some southeast-verging contractional deformation associated with the Main Central thrust at deeper structural levels. The earliest recorded motion on the Main Central thrust is associated with amphibolite-facies metamorphism at 23-21 Ma (Hubbard and Harrison, 1989; Hodges et al., 1996), with very recent motion being as young as Pliocene-Pleistocene (Macfarlane et al., 1992; Harrison et al., 1997). The Greater Himalayan metamorphic sequence, the Tethyan sedimentary sequence, the Main Central thrust and the Annapurna detachment are all well exposed in the Kali Gandaki valley.

Some of the most spectacular structural features affecting the Tethyan sedimentary sequence of central Nepal are northeast-verging megascopic folds. In the Annapurna sector, these folds are well exposed, especially on the east face of the Dhaulagiri-Dangar panorama (Figure 2.2). Most workers relate the formation of these folds to gravitational collapse and associate them with normal movement along the South Tibetan detachment system (Burchfiel et al., 1992 and references therein). However, it has been suggested that they could be the result of an older shortening event associated with crustal thickening (Brown and Nazarchuk, 1993; Godin et al., 1999a,b).

Late Tertiary to recent east-west extension of the southern Tibetan plateau resulted in a series of north-trending grabens (Molnar and Tapponnier, 1978). The Thakkhola graben is one of the southernmost of these grabens and hosts the northern part of the Kali Gandaki valley (Figure 2.2).

2.2.2 Tethyan sedimentary sequence

A well preserved Tethyan stratigraphy is exposed in the Kali Gandaki valley. From Kalopani to Kagbeni, a nearly continuous 10 kilometer-thick section is visible, ranging from Cambrian(?)–Ordovician calcareous schist of the Sanctuary Formation to Early Cretaceous detrital sediments of the Chukh Group (Figure 2.3).

The Paleozoic section is characterized by a calcareous series, mainly comprising massive limestone and calcareous shale with local dolomitic and quartzitic horizons. The lowest part of this section is the Sanctuary Formation (Pêcher, 1978), which comprises highly deformed black schist, sandstone and limestone. In the study area, it has only been observed on the Thulo Bugin ridge, in the core of the refolded Fang nappe (Figure 2.4).

Overlying the Sanctuary Formation is the Annapurna Formation (also known as the Yellow Formation or the Larjung series), visible just north of Kalopani (Bordet et al., 1971; Colchen et al., 1981). The Annapurna Formation is composed of calcareous biotite-grade psammitic and semi-pelitic schist and phyllite. Although there are no direct chronological data, the Sanctuary and Annapurna formations have been interpreted as being Cambrian, because they lie stratigraphically under the Ordovician Nilgiri Formation (Bordet et al., 1971). The overlying Nilgiri Formation is composed of gray micritic limestone, grading upwards into pink dolomitic sandstone, calcareous shale and siltstone. The Ordovician series is capped by a 400 meter-thick calcareous arkose and siltstone unit termed the North face quartzite (Bodenhausen et al., 1964). The upper portion of the Paleozoic is composed of alternating gritty dolomite, black shale, and limestone of the Sombre Formation (Silurian-Devonian), correlative with the Dark Band Formation of the Dolpo area, northwest of the Thakkhola region (Fuchs, 1977). The Carboniferous-Permian units consist of a turbidite sequence dominated by calcareous shale with a minor siliciclastic contribution (Lake Tilicho and Thini Chu formations; Bordet et al., 1971).

The Mesozoic stratigraphy is essentially composed of Triassic calcareous shale (Thini Formation), grading upwards to Jurassic fossiliferous limestone and black shale (Jomsom, Bagung and Lupra formations), which are capped by the detrital units (conglomerates, sandstones) of the Early Cretaceous Chukh Group. Complete detailed descriptions of the Mesozoic stratigraphy are given in Gradstein et al. (1992) and complementary observations can be found in Bordet et al. (1971). The Pliocene to Pleistocene Tetang and Thakkhola formations, comprised of red alluvial sandstone and

conglomerate (molasse) of continental provenance, along with Holocene alluvial sediments, fill the north-northeast to south-southwest oriented Thakkhola graben in the upper Kali Gandaki valley (Bordet et al., 1971; Fort et al., 1982).

2.3 STRUCTURAL EVOLUTION

The Tethyan sedimentary sequence in the Kali Gandaki area has undergone a complex structural evolution represented by the following: southwest-verging isoclinal folds (D_1); northeast-verging, tight, megascopic folds (D_2); post-peak metamorphic, southwest-verging kink folds (D_3) with related crenulation cleavages; and lastly northeast-trending, steeply-dipping normal faults and spaced cleavages (D_4) related to the Thakkhola graben system. The first two deformation phases are transposed at the base of the Tethyan sedimentary sequence into the extensional north-dipping Annapurna detachment (Brown and Nazarchuk, 1993) and related high-strain zone (D_t ; Godin et al., 1999a). This localized extensional event is itself overprinted by the southwest-verging deformation related to the D_3 phase. The Annapurna detachment and related high-strain zone will be described in detail in section 2.4.

2.3.1 Cross sections

Six northeast-trending balanced cross sections (Figure 2.5) have been constructed using the available data from the literature and from detailed structural mapping and panoramic photo analysis. The lack of geophysical data in central Nepal precludes geologic extrapolation below sea level, and the upper Mustang restricted area

limited detailed mapping to south of Kagbeni. Therefore the cross sections do not extend north of Kagbeni.

Three sections between 22 and 34 km long (A-A', B-B', and C-C') show the position of the Annapurna detachment and the related high-strain zone, with section A-A' extending south to the Main Central thrust. Sections D-D', E-E', and F-F' are considerably shorter (8 to 12 km long), and are located within the Thakkhola graben. Section C-C' is located outside the Thakkhola graben, 10 km to the west of the Dangardzong fault.

2.3.2 D₁: Initial southwest-verging deformation

The oldest structures (D₁) are represented by a schistosity (S₁) parallel to compositional layering defined by the preferred orientation of biotite and muscovite and/or by flattened detrital grains. Locally, this schistosity is axial planar to rootless F₁ isoclinal fold closures (Figure 2.6A, B and C). In some localities, a strong transposition of bedding planes is associated with this phase. Crustal-scale F₁ closures are visible near the summit of Fang in the Annapurna massif (Figure 2.4 and Figure 2.5), where an anticlinal structure called the Fang nappe is folded in the D₂ Nilgiri anticline (Colchen et al., 1981). It has been proposed that the F₁ isoclinal nappe originated as a southwest-verging anticline (Colchen et al., 1986; Brown and Nazarchuk, 1993). The vergence is apparent after unfolding and rotating the overturned limb of the Nilgiri F₂ structure. The complementary F₁ syncline has been cut out by the Annapurna detachment (Brown and Nazarchuk, 1993).

Within the Tethyan sedimentary sequence, the D_1 phase is most prominent in the Paleozoic rocks, and appears to decrease in intensity at higher structural and stratigraphic levels. F_1 folds have not been recognized in rocks younger than Carboniferous-Permian; D_1 is completely absent in the Mesozoic units. Furthermore, this phase has not produced duplication of strata within the exposed section other than the Fang Nappe (Figure 2.4 and Figure 2.5).

2.3.3 D_2 : Northeast-verging backfolding

The D_2 phase is characterized by a northeast-verging megascopic fold train that forms the most noticeable structures in the Kali Gandaki valley. The axial planar penetrative S_2 schistosity is defined by the preferred orientation of biotite, muscovite and elongate quartz grains in pelitic layers, or by a spaced cleavage in more competent layers. Locally, a well developed crenulation cleavage is preserved, coplanar with F_2 axial surfaces. Throughout the Kali Gandaki valley, the S_2 schistosity dips moderately to the southwest, but south of Larjung, it progressively rotates through the horizontal, then dips northeast, parallel to the Annapurna detachment.

Analysis of cross sections and field photographs indicate that the folds generally belong to class 1B to 2 of Ramsay (1967), intermediate between ideal parallel and ideal similar folds. The fold hinge zones are typically subangular to subrounded. The fold style of the F_2 varies considerably with structural level. At the highest preserved structural level, in the Lupra-Kagbeni area, the F_2 axial surfaces are sub-vertical, with steeply northeast- or southwest-dipping S_2 cleavages. The folds commonly display chevron or boxfold geometries (Figure 2.7A). At intermediate levels, in the Marpha-Jomsom area, F_2

folds are typically overturned to strongly inclined, with shallow southwest-dipping axial surfaces and gently ($\sim 12^\circ$) east-southeast-plunging axes, with a penetrative axial-plane cleavage (S_2). At these localities, folds tend to be parallel (class 1B) (Figure 2.7B), more representative of buckling mechanisms. At lower structural levels, F_2 folds are tight to isoclinal, with overturned to recumbent axial surfaces (Figure 2.7C). The folds commonly display thinning of the limbs characteristic of passive-flow folds (Hobbs et al., 1976; p.185; Twiss and Moores, 1992).

The F_2 folds visible in the Kali Gandaki valley generally constitute structures parasitic to crustal-scale northeast-verging folds visible on the west face of the Nilgiris, where Ordovician limestones are folded in a kilometer-scale overturned antiform (Figure 2.4 and Figure 2.5) (Bordet et al., 1971). Macroscale examples of parasitic folds of the Nilgiri anticline include the Marpha anticline and the Jomsom syncline (sections A-A' and E-E'; Figure 2.5). These structures are part of a major fold train that extends at least to the upper reaches of the Kali Gandaki in the upper Mustang-Lo Manthang area 50 km north of Kagbeni (Hagen, 1959; also reconnaissance work by the author). They have also been observed in the upper Dolpo, northwest of the Thakkhola region (R.L. Brown, unpublished data). As shown in section C-C' of figure 2.5, the F_2 folds display similar style from south to north (see also the Syang and Dangar structures in figure 2.2). There is no indication that the F_2 fold train diminishes in tightness or amplitude north of Kagbeni.

2.3.4 D₃: Post-peak metamorphic southwest-verging deformation

D₃ structures are characterized throughout the valley by a post-peak metamorphic crenulation cleavage (S₃). This cleavage dips systematically to the northeast and is axial planar to microscopic to mesoscopic kink folds, which consistently verge to the southwest (Figure 2.8A and B). In the northern part of the map area, F₃ folds dominate the deformation style and locally have attained crustal proportions, such as the Thorung North anticline, which is an angular-hinged, kilometer-scale anticline folding Jurassic rocks (Figure 2.9). In this area, the D₃ folds and cleavages clearly overprint upright F₂ folds, such as the F₂ Lupra syncline (Figure 2.10A and B).

Although F₂ fold style varies considerably with structural level, the interference pattern of the southwest-verging D₃ on F₂ commonly displays the type 3 of Ramsay (1967). Southwest-verging F₃ kink folds overprint tight to open upright F₂ folds at higher levels (Figure 2.11A), and inclined to recumbent isoclinal to tight F₂ folds at lower levels (Figure 2.11B). The overprinting relationship of D₃ on D₂ is also visible in thin section. In the two examples presented in Figure 2.12 (A and B), the northeast-dipping asymmetric S₃ crenulation cleavage affects both the planar S₀₋₁ plane and the penetrative, oblique to bedding, continuous S₂ schistosity.

The D₃ phase is associated with top-to-the-southwest thrust faulting. In the structurally high levels, the Kagbeni structure (section F-F' of Figure 2.5) is bounded to the north by a southwest-verging thrust complex. This structure is localized within Cretaceous rocks of the Chukh Group. The minor offset and the southwest-vergence of the faults, along with the fact that the faults appear to be younger than the upright F₂ folds suggest that this structure is related to the D₃ phase of deformation. Unfortunately, due to

its proximity with the Mustang restricted area, the Kagbeni structure and related thrusts have not been studied in detail. In the lowest part of the section, in both the lowermost part of the Tethyan sedimentary sequence and the uppermost part of the Greater Himalayan metamorphic sequence, D_3 is associated with post-peak metamorphic, localized top-to-the-southwest shear zones (Figure 2.13A, B, C and D). These shear zones are up to 10 meter-thick and could be correlative with other reverse-sense shear zones observed near the Annapurna detachment, such as the Kalopani and Modi Khola shear zones described by Vannay and Hodges (1996) and Hodges et al. (1996), respectively.

2.3.5 D_4 : East-west extension and the Thakkhola graben

D_4 structures consist of brittle fractures and normal-sense faults related to the Thakkhola graben. These structures typically are associated with calcite veins and fault breccias. The S_4 is a spaced cleavage that is characteristically oriented northeast-southwest, with sub-vertical dips (Figure 2.14A). It is most noticeable north of Marpha, where the Thakkhola graben faults are more prominent.

One of these faults, the Dangardzong fault (Hagen, 1959; Bodenhausen and Egeler, 1971), also named the Thakkhola fault (Bordet et al., 1971), bounds the western margin of the graben. In the area of Dangardzong, it juxtaposes Jurassic limestone of the Jomsom Formation with Carboniferous-Permian rocks of the Thini Chu Formation. At this locality, the Dangardzong fault has approximately 4000 m of vertical displacement (Colchen et al., 1986). Where the fault cuts through competent layers, such as the Jomsom Formation limestones, the fault is associated with brecciated zones (Figure

2.14B). The Muktinath fault (Hagen, 1959; Bordet et al., 1971) is part of a series of faults with smaller offsets that characterize the eastern side of the Thakkhola graben. The general geometry of the graben is asymmetric, with the western side having dropped along one fault, whereas faulting on the eastern side is distributed on a series of fault planes (Bordet et al., 1971; Fort et al., 1982).

S₄ cleavages and northeast-trending subsidiary faults have not been observed south of the Annapurna detachment. Hurtado and Hodges (1998) report that some extensional faulting related to the Thakkhola graben system has occurred in the detachment area, near the village of Taglung, but does not affect the Greater Himalayan metamorphic sequence structurally below the Annapurna detachment. Furthermore, some discrete northwest-trending brittle faults affect the Annapurna detachment zone. The Formation III augen orthogneiss locally displays fractured feldspar and quartz grains (Figure 2.14C). These observations support the idea that the Annapurna detachment marks the southern boundary of the Thakkhola graben (Brown and Nazarchuk, 1993; Godin et al., 1999a).

2.3.6 The Lupra fault

Sections D-D', E-E' and F-F' (Figure 2.5) highlight the Lupra fault and the higher-level structures preserved within the Thakkhola graben. The Lupra fault is a newly named structure that had been previously recognized (Colchen et al., 1986; Gradstein et al., 1992), but whose importance had not been evaluated. The Lupra fault is a steeply north-dipping, west-striking fault clearly visible in the cliffs above the Kali Gandaki river, a few kilometers north of Jomsom. The trace of the fault can be observed on the

south slope of the Syang peaks where it marks a clear structural break (Figure 2.2 and section C-C'), and extends 20 km to the east. It terminates abruptly just south of the village of Lupra, where it is cut by a north-striking subsidiary fault of the Thakkhola graben system (Figure 2.3). It has not been observed east of this point. The Lupra fault is best expressed within the down-dropped block of the Thakkhola graben, where it has a greater offset (sections D-D', E-E' and F-F'; Figure 2.5).

On the west bank of the Kali Gandaki river, the fault marks a sharp contrast between recumbent D_2 folding to the south, with a weakly folded homoclinal panel to the north (section F-F' of Figure 2.5 and Figure 2.15). At this locality, the footwall is composed of an overturned limb of a north-verging F_2 fold, within Jurassic rocks of the Jomsom, Bagung and Lupra formations. The hanging wall is comprised of a north-dipping homoclinal panel of Triassic to Early Jurassic rocks with normal stratigraphic polarity (Thini and Jomsom formations). Based on the stratigraphic evidence of this locality, the Lupra fault can be interpreted as a reverse fault that juxtaposes Triassic rocks in its hanging wall with Late Jurassic rocks in its footwall.

On the east bank of the Kali Gandaki, just south of the village of Lupra, the Lupra fault juxtaposes rocks of similar age (Lower Jurassic), but with very contrasting structural style (sections D-D' and E-E' of Figure 2.5). In this area, the Lupra fault marks the boundary between upright F_2 folds in the hanging wall and recumbent F_2 folds in the footwall. It therefore appears that the Lupra fault also marks a clear structural break. On this basis, the Lupra fault can be interpreted as a normal fault juxtaposing higher-level structures next to lower-level structures.

The available kinematic data on the fault are very limited. The Lupra fault surface has not been directly observed. The fault trace is located under scree slopes mainly comprised of very friable shales of the Lupra Formation or on inaccessible cliff faces. Therefore no fault slip data, such as slickenlines, extensional fractures or stylolites have been observed. Significant strike-slip motion along the Lupra fault can not be ruled out, although no evidence has been found.

From the geologic map of the Annapurna-Manaslu-Ganesh Himalaya (Bordet et al., 1971; Colchen et al., 1981), the only remnants of Cretaceous rocks of central Nepal are preserved within the Thakkhola graben. They appear to be bounded by the Dangardzong fault to the west, the Muktinath fault to the east, and the Lupra fault to the south. Furthermore, the Lupra fault also marks the southern limit of the Pleistocene-Holocene lacustrine sediments that fill part of the Thakkhola graben, mainly comprising the flat plains of the Dangardzong and Phalla villages (Fort et al., 1982).

The strong expression of the Lupra fault within the Thakkhola graben, the higher-level structures and young sediments preserved in its hanging wall, and its steeply-dipping nature all support an important normal-sense component for the fault, and a possible link with the Thakkhola graben. This suggests that the normal-sense component of the Lupra fault is related to the D_4 phase of deformation. The apparent old-over-young stratigraphic relationship visible in the Kali Gandaki could represent some earlier thrust motion along the fault plane. The fact that the Lupra fault cuts out the hinge of a F_2 fold in its footwall would suggest that the old thrust motion would be late- D_2 or even D_3 .

2.4 HIGH-STRAIN ZONE AND THE ANNAPURNA DETACHMENT

The contact between the Annapurna Formation and the Greater Himalayan metamorphic sequence is visible in a stream gully just northwest of the village of Kalopani and corresponds to the Annapurna detachment (Figure 2.16A and B). Gansser (1964) noted that although this contact appears conformable, it delineates a clear boundary between two domains of contrasting structural style. Many workers followed Gansser, and although some proposed a faulted contact (Bodenhausen and Egeler, 1971; Bordet et al., 1971; Caby et al., 1983; Colchen et al., 1986; Pêcher, 1991), the Annapurna detachment was not clearly documented until the 1990's (Brown and Nazarchuk, 1993). Mapping and structural analysis reveal the presence of a 1,500 meter-thick high-strain zone localized in the lowermost part of the Tethyan sedimentary sequence and the uppermost part of the Greater Himalayan metamorphic sequence, which is linked kinematically with normal-sense ductile shearing associated with the Annapurna detachment. This high-strain zone straddles the Annapurna detachment and affects rocks from both the hanging wall and the footwall. The high-strain zone affects the lowermost section of the Nilgiri Formation, the entire Annapurna Formation, and the uppermost 100 m of Formation III within the Greater Himalayan metamorphic sequence.

It has been shown in the previous section that the Tethyan sedimentary sequence has been affected by three phases of folding with contrasting vergence (D_1 , D_2 and D_3). North of Khanti, the angular relationships between S_1 , S_2 and S_3 are well preserved. South of Khanti, the D_1 and D_2 structures are progressively rotated and transposed into near parallelism. Near Larjung, 1,500 m structurally above the base of the Tethyan sedimentary sequence, the primary stratigraphy and the D_1 and D_2 structures are

completely transposed into a broad high-strain zone, and only one penetrative fabric (S_t) with an associated down-dip mineral lineation (L_m) is generally preserved. Locally, clear crosscutting relationships are observed between S_2 and S_t , implying that the northeast-verging folds predate the penetrative fabric associated with the high-strain zone.

2.4.1 Transposition fabrics

In the biotite calcareous schist and psammite of the Annapurna Formation, the high-strain transposition fabric (S_t) is characterized by a continuous schistosity with a northwest strike and a 30° dip. The down-dip mineral-elongation lineation (L_m) is outlined by biotite aggregates and muscovite blades. In thin section, the Annapurna Formation is highly schistose; quartz grains are strained and flattened, and the biotite-muscovite schistosity is continuous and pervasive. Locally, recrystallization of fine-grained quartz-calcite matrix has also produced incipient coarse-grained quartz ribbons associated with coarse-grained calcite. Post-transposition annealing, outlined by polygonal quartz grains and recrystallized calcite, is pervasive throughout this zone and has obliterated part of the transposition fabric.

In the area of Kalopani, rocks from the Greater Himalayan metamorphic sequence (Formation III) within the high-strain zone are composed of laminated sillimanite-biotite-garnet pelitic schist, garnet-diopside-hornblende calc-silicate schist and kyanite-sillimanite-bearing leucosomes, interlayered with garnet-tourmaline two-mica leucogranitic sheets up to 100 meter-thick. As in the Annapurna Formation, these units contain a penetrative fabric defined by a continuous biotite ($\pm$ muscovite) schistosity, as well as an associated down-dip mineral-elongation lineation. This fabric can be followed

through the upper part of the Greater Himalayan metamorphic sequence into the base of the Tethyan sedimentary sequence. On the basis of this continuity, it is suggested that the penetrative fabric affecting the uppermost part of the Greater Himalayan metamorphic sequence is correlative with S_t observed in the lowermost part of the Tethyan sedimentary sequence.

2.4.2 Shear-sense indicators

In the vicinity of Kalopani, shear-sense indicators associated with the high-strain zone are readily visible, especially near the contact between the Tethyan sedimentary sequence and the Greater Himalayan metamorphic sequence. Mesoscale shear-sense indicators include extensional shear bands (Figure 2.17A) and systematically asymmetric isoclinal folds (Figure 2.17B). Other mesoscale shear-sense indicators include pegmatite dike arrays that have been extended or shortened according to their orientation with respect to the shear plane (see also Figure 6e of Godin et al., 1999a). Microscale shear-sense indicators include extensional shear bands (Figure 2.18A and B), and S-C fabrics, which consistently indicate down-to-the-northeast normal shearing across the high-strain zone.

Quartz crystallographic preferred orientations were measured in the hanging-wall rocks of the Annapurna Formation at three different localities. Quartz *c*-axis measurements were done on partly annealed quartz ribbons and on flattened quartz grains using thin sections cut perpendicular to the foliation and parallel to the lineation (XZ plane of the finite ellipsoid of deformation). Annealing was important in these thin sections and may have diluted the petrofabric, producing a relatively diffuse asymmetric

pattern. Nevertheless, the petrofabric measurements reveal asymmetric quartz *c*-axis fabrics compatible with normal top-to-the-northeast shearing (Law, 1990) (Figure 2.19). This suggests that the last increments of finite strain recorded by the quartz petrofabrics in the Annapurna Formation before the annealing phase reflect the same kinematic framework as the mesoscale shear-sense indicators visible in the immediate footwall, as well as the D_2 transposition in the hanging wall.

The transposition resulting from shearing along the Annapurna detachment is also visible at the crustal scale. The regional S_2 and the axial surface traces of the F_2 folds show a conspicuous rotation approaching the high-strain zone. This is readily observed on the east face of the Dhaulagiri-Tukche mountains (Figure 2.16), in the cross sections (Figure 2.5), and in the stereonet that will be presented in the following section. The sense of curvature of both foliations and of F_2 axial surface traces is compatible with top-to-the-northeast sense of shear. These data indicate that the distributed ductile shearing within the high-strain zone is late- to post- D_2 .

Quartz-feldspar-tourmaline pegmatite veins intruding the Annapurna Formation are 15-20° more steeply dipping than the S_1 foliation. These veins are interpreted as having been injected along tension fractures, perpendicular to the principal instantaneous extensional direction. Accordingly, the systematic obliquity of this vein array is compatible with the other normal top-to-the-northeast shear-sense indicators.

2.4.3 Thermal overprinting of the high-strain zone

Metamorphic assemblages at the base of the Tethyan sedimentary sequence typically contain biotite + muscovite ± albite ± tremolite ± chlorite, indicative of upper

greenschist facies metamorphism. The biotite-in isograd occurs 1,500 m structurally above the Annapurna detachment, coinciding with the upper boundary of the high-strain zone. This assemblage overgrows part of the high-strain zone fabric, as evidenced by the coarsening of micas and quartz and by the presence of polygonal strain-free quartz grains, but is clearly deformed by post-metamorphic southwest-verging D_3 kinks (Figure 2.20).

Recent studies of the Tethyan sedimentary sequence of central Nepal have locally established a metamorphic gradient. The highest metamorphic temperatures are attained at the deepest structural level in the Cambrian limestones (Garzanti et al., 1994; Schneider and Masch, 1993). In the Marsyandi valley 60 km east of the Kali Gandaki, Schneider and Masch (1993) estimated temperatures up to 530°C (± 30) at the deepest structural level near the detachment fault in the Nilgiri Formation, as calculated by calcite-dolomite solvus geothermometry. They also showed a constant decrease in temperature toward structurally higher levels, as low as $350\text{--}390^{\circ}\text{C}$ in the Devonian strata. Similarly, in the Kali Gandaki valley, illite and chlorite crystallinity, vitrinite reflectance, and conodont color alteration index studies indicate average temperatures of 380°C within the Late Devonian pelites (Garzanti et al., 1994).

Available isotopic data for the uppermost Greater Himalayan metamorphic sequence suggest that the immediate footwall of the Annapurna detachment reached temperatures above 650°C during the Miocene (see chapter 3 for details). This is further supported by the presence of Miocene leucogranitic dikes injected into the Annapurna Formation (Chapter 3). Heat from the Greater Himalayan metamorphic sequence could have contributed to rheological weakening of the immediate hanging-wall rocks and localization of the high-strain zone. This heating event outlasted ductile normal faulting

in the high-strain zone, as evidenced by annealing, followed by cooling prior to development of D_3 and associated thrusting.

2.4.4 High-strain zone reactivation

Several lines of evidence indicate that the high-strain zone was affected by subsequent localized southwest-verging deformation, which is attributed to the D_3 event. It is clear that the S_3 spaced cleavage is superimposed on the high-strain zone within the Tethyan sedimentary sequence and is not affected by the rotational component which reoriented S_1 and S_2 . Furthermore, top-to-the-southwest shear-sense indicators, including oblique boudinaged calcite veins (Figure 2.13A and B), are locally associated with systematic southwest-verging D_3 kinks.

Late discrete brittle fault zones up to 3 meter-thick cut S_1 within the leucogranitic sheets. The faults trend parallel to S_1 (320/40NE) and show normal sense of movement. The magnitude of displacement on these faults cannot be determined as they are confined to leucogranitic sheets and do not cut across stratigraphy. Their brittle nature and their crosscutting relationship with respect to all penetrative fabrics indicate that they are post- D_3 . The link between these late brittle orogen-parallel faults and the orogen-perpendicular Thakkhola graben structures remains unclear, although geographically, the graben faults do not extend south of the leucogranitic sheets. It is possible that these orogen-parallel discrete brittle fault zones represent the southern termination of the Thakkhola graben system.

2.5 STRAIN DISTRIBUTION

This section describes the spatial distribution of the five deformation phases and their related structural fabrics. A generalized deformed-state cross section is produced from the six balanced cross sections presented earlier. The study area is divided into six structural domains. It will be shown that a boundary between the lower and higher structural levels is outlined by the Lupra fault. Finally, a bed-length restoration of the generalized deformed-state cross section is proposed, yielding minimum estimates of shortening for the various structural levels.

2.5.1 Structural domains

The study area has been divided into six structural domains based on fabric orientation, deformation style and intensity, and dominant phase of deformation. The domains are oriented parallel to the regional tectonic trend and represent six different structural levels (Figure 2.21).

Domains 1 and 2 are at the structurally lowest level. They coincide with the Annapurna detachment-related high-strain zone described earlier (see also Godin et al., 1999a). Stratigraphically, domains 1 and 2 are limited to Formation III (domain 1) and the Annapurna Formation (domain 2). The penetrative planar fabric S_t (average N305/30) with the associated down-dip mineral elongation lineation (L_m) are the dominant fabrics in both of these domains. Domain 2 is distinguished from domain 1 by the presence of S_3 (average N276/39). The lithologic contact between the Tethyan sedimentary sequence and the Greater Himalayan metamorphic sequence therefore marks the southern limit of D_3 kink folding and associated S_3 crenulation cleavage. It is possible that some post-peak

metamorphic, (post- D_1), south-verging thrusts such as the Kalopani shear zone (Vannay and Hodges, 1996) could be the structurally lower equivalent of the D_3 deformation preserved in the Tethyan sedimentary sequence.

The distinction between domains 3, 4, 5 and 6 is mainly based on the presence or absence of D_1 deformation, on the orientation of S_2 , and on the folding style of F_2 . In all four of these domains, both D_3 and D_4 are present and have the same characteristics from one domain to the other.

Domain 3 marks the southern limit of preserved S_2 . In this domain, S_2 is generally sub-horizontal, becoming north-dipping near domain 2, where it is transposed in the high-strain zone. The F_2 folds are recumbent, close to isoclinal. The F_2 folds become more open in domains 4 and 5, with steeper south-dipping axial surfaces. Furthermore, the Marpha area in the southern zone of domain 5 marks the structurally highest level where preserved F_1 hinges have been observed. This limit coincides stratigraphically with the Paleozoic-Mesozoic transition. D_1 -related deformation has not been observed in the Mesozoic strata.

Domain 6 is bounded by three normal faults, the Dangardzong fault to the west, the Muktinath fault to the east, and the Lupra fault to the south. This domain is at the structurally highest level. It preserves upright, chevron-style F_2 folds, with steeply north- or south-dipping S_2 . These F_2 folds, such as the Lupra syncline, are overprinted by the regional S_3 crenulation cleavage and associated southwest-verging F_3 kink folds (Figure 2.10).

2.5.4 Restoration

The generalized deformed-state cross section (Figure 2.22A) displays recumbent F_2 folds in the lower structural levels, and upright F_2 folds in the higher structural level. Restoration of this generalized deformed-state cross section was performed to obtain minimum estimates on the amount of shortening that affected the Tethyan sedimentary sequence.

Bed-length restoration was undertaken using the contact between the Kagbeni and Muding Units (K2-K3 interface), the contact between the Thini Chu and Thini formations (CP-T interface), and the contact between the Nilgiri Formation and the Silurian unnamed gritty dolomitic level (O-S interface). The section was pinned at the northeastern limit of the section, rather than at the Annapurna detachment. This was done in order to maintain a free southern boundary necessary for the restoration of the Annapurna detachment-related deformation. The restoration has been simplified by assuming that deformation was plain-strain and that the main folding mechanism was buckling. Although it is recognized that part of the Tethyan sedimentary sequence has undergone some volume-loss through pressure-solution and passive-flow folding, especially in the Paleozoic strata, the above assumptions provide a reasonable approximation of the deformation style and permits the calculation of minimum shortening values.

The restoration was done in three steps. Step 1 restores the 800 m normal-sense offset attributed to the Lupra fault (Figure 2.22B). In this step, the layers are also restored prior to motion on other D_4 faults found in the section.

Step 2 undoes the rotational effect that the Annapurna detachment had on the F_2 axial surface traces (Figure 2.22C). This step assumes a minimum fault displacement value for the Annapurna detachment of 10 km based on the metamorphic omission between the Greater Himalayan metamorphic sequence and the Tethyan sedimentary sequence. With an average dip angle of 35° , this yields a minimum throw of 6 km. These values compare well with estimates made on other segments of the South Tibetan detachment system, such as the Chomolungma detachment on Mount Everest (Burchfiel et al., 1992) and the Gonto La detachment in the eastern part of the Himalaya (Edwards et al., 1996). In this step, the complementary F_1 syncline that had been cut by the Annapurna detachment (Brown and Nazarchuk, 1993) is projected onto the section.

Finally, a simple geometrical bed-length unfolding of the F_2 folds is performed in step 3 (Figure 2.22D). This yields different minimum shortening estimates for the three interfaces considered. The minimum amount of shortening increases with structural depth, from 24% for the K2-K3 interface, to 32% for the CP-T interface, to 43% for the O-S interface. The unfolding of the F_1 Fang nappe and complementary syncline would considerably increase the amount of shortening for the lower Paleozoic level.

There are at least two possibilities for explaining the low shortening estimates of the Mesozoic level. The increasing values toward the Paleozoic strata could represent a D_2 strain gradient. Such a strain gradient would imply a northward-verging basal décollement plane. The absence of D_2 -related features in the Greater Himalayan metamorphic sequence suggests that this D_2 décollement was located at the base of the Tethyan sedimentary sequence. Alternatively, the low Mesozoic values could reflect the presence of unrecognized contractional features that have not been accounted for in the

restoration. It has already been proposed that the Lupra fault could have an early thrust-sense component, which, if related to the D_2 phase, would increase the shortening estimates for the restored Mesozoic level. For further discussion on restoration models, section restoration, shortening estimates and dynamic folding models, the reader is referred to chapter 4 (see also Godin et al., 1999b).

2.6 DISCUSSION

Figure 2.23 summarizes the five-phase structural evolution of the Tethyan sedimentary sequence in the Kali Gandaki area.

2.6.1 Interpretation of D_1 structures

The D_1 phase of deformation is characterized by southwest-verging rootless isoclinal folds, locally associated with a near-complete bedding transposition. This phase is most prominent in the Paleozoic strata. The only visible crustal-scale expression of the D_1 phase is the refolded Fang nappe responsible for the stratigraphic inversion of the lowermost Tethyan sedimentary sequence.

This phase is interpreted as representing the manifestation of early southeast-verging deformation related to initial growth of the Himalayan fold-thrust belt. The D_1 strain gradient, increasing in intensity at the bottom of the Tethyan sedimentary sequence is compatible with a south-verging ductile shear zone active during this time at lower structural levels. The position of this D_1 shear zone is presently unknown.

Although timing of this phase is not well constrained in the Nepal Himalaya, it has been inferred that the earliest deformation to have affected the Tethyan sedimentary

sequence may be Early to Middle Eocene (DeCelles et al., 1998; Hodges et al., 1996; Vannay and Hodges, 1996), similar to age constraints obtained for the earliest deformation in the Ladakh-Zaskar area (Searle et al., 1988). Vannay and Hodges (1996) related the Fang nappe to Middle Eocene to Oligocene thrusting, coeval with underthrusting of the Greater Himalayan metamorphic sequence beneath the Tethyan sedimentary sequence, and with Eohimalayan prograde metamorphism. Alternatively, Godin et al. (1999b) proposed that the D_1 phase could have originated during initial underthrusting in Eocene time, before the Eohimalayan thermal events (see also chapters 3 and 4).

2.6.2. Interpretation of D_2 structures

The D_2 structures are characterized by northeast-verging, high-amplitude tight F_2 folds at low structural level, and upright tight to open F_2 folds at high structural level. There is an associated regional southwest-dipping, oblique-to-bedding, penetrative S_2 schistosity that progressively becomes more vertical as its morphology changes to a spaced cleavage at higher levels. Three types of F_2 folds have been recognized, each distinctive of a structural level. At the lowest observable level, the F_2 folds are passive-flow folds with attenuated limbs. At intermediate levels, they take on a buckle fold geometry, to become chevron folds at the highest structural levels. The progression from chevron-style folding at high structural levels to passive-flow folding at lower levels and the D_2 strain gradient implied by the shortening estimates are compatible with the presence of a northeast-verging décollement plane that the F_2 fold train would root into.

Experimental and theoretical studies indicate that the main variables controlling the active folding mechanism within a multilayered material are viscosity and anisotropy (Biot, 1964; Ramsay, 1967; Gosh, 1968; Cobbold et al., 1971). A low viscosity contrast between the layers will favour passive-flow folding. Alternatively, a significant viscosity contrast is necessary for buckle folding. Buckling will be favored where competent layers are separated by layers of more ductile material. Furthermore, the presence of a well-defined anisotropy, such as layering or schistosity, will favour chevron folding (Cobbold et al., 1971).

It is therefore not surprising to observe passive-flow folding in the lowest part of the Tethyan sedimentary sequence, where the temperatures were the highest (Schneider and Masch, 1993; Garzanti et al., 1994). Passive-flow folds are also found in the Silurian-Devonian Sombre Formation, comprised mainly of black shales. Although this unit is somewhat structurally higher, its low competency most probably influenced its folding style.

The Paleozoic strata commonly display parallel fold geometries. The thick limestone unit of the Nilgiri Formation, acting as a rigid layer caught between the more ductile units of the Sombre and Annapurna formations, would therefore tend to buckle. Parallel folds are also found in the relatively stiff Jurassic limestone units (Jomsom and Bagung formations), which are capped by the black shale of the Lupra Formation, and underlain by the Triassic calcareous shale of the Thini Formation.

The Mesozoic strata, more precisely the Late Jurassic Lupra Formation and Cretaceous Chukh Group, are composed of a fine regular layering of clastic units

(conglomerates, sandstones and shales). Such very distinct anisotropies coinciding with repetitive rheological contrasts therefore favoured chevron-style folding.

From these observations, it appears that the F_2 fold style observed through the 10 kilometer-thick sedimentary succession was controlled by two factors. Firstly, the structural position acted as the main controlling factor for the dominant folding mechanism. The second aspect that controlled the folding mechanism appears to be the stiffness of a given layer (with its viscosity) and its relative position with respect to other layers of differing competency. This second aspect explains the local variation from buckling to passive-flow folding that is observed in the upper Paleozoic strata.

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 F_2 folds have been interpreted to be the result of gravitational sliding along the South Tibetan detachment system (Burchfiel et al., 1992 and references therein). Lately, this idea has been challenged (Brown and Nazarchuk, 1993; Godin et al., 1999a,b).

Janecke et al. (1998) noted five criteria that distinguish extensional folds from contractional folds: (1) a complete or near absence of reverse faults of the same age as the folds, (2) fold patterns that are inconsistent with formation in a fold-thrust belt, (3) a close spatial association between folds and normal faults, (4) crosscutting relationships that show that normal faults and folds are of the same age, and (5) growth strata that are consistent with deposition during extensional deformation. Furthermore, (6) gravity-induced sliding folds tend to be initiated with a steeply dipping layering or anisotropy, with the folding being restricted to the ductile layer (Froitzheim, 1992; Burg et al., 1996).

In the Kali Gandaki valley, several observations argue against an extensional origin for the F_2 folds. Using the same set of criteria as above, the following objections are made. (1) The F_2 folds are interpreted to be Miocene, and most possibly as old as Oligocene (Godin et al., 1999b). Since the onset of continental collision, a series of foreland- and hinterland-directed thrusts affected the Tethyan sedimentary sequence (Steck et al., 1993; Ratschbacher et al., 1994; Searle et al., 1997). Although this does not preclude some coeval extension, certainly the dominant deformation style within the Tethyan sedimentary sequence is contractional. (2) The geometry of the F_2 fold train is consistent with the presence of an underlying north-verging basal shear zone. Contractional folds developing above a décollement plane commonly display a variation of deformation style with structural level similar to that observed in the Kali Gandaki valley. Examples of such structural zonations above décollement surfaces include the Lachlan fold belt of southern Australia (Gray, 1995), the Variscan fold belt of southwest England (Sanderson, 1979), the Cariboo mountains in the Canadian Cordillera (Murphy, 1987), and in the Pyrenees (De Sitter and Zwart, 1960). The F_2 fold style observed in the Kali Gandaki valley is therefore compatible with formation in a northeast-verging fold-thrust belt. (3) The association between the F_2 folds and the Annapurna detachment is equivocal. The F_2 northeast-verging fold train is not restricted to the Annapurna detachment and its related high-strain zone. It extends north of the detachment for over 30 km, and accounts for a minimum of 150% structural thickening of the cover sequence (Chapter 4; Godin et al., 1999b). (4) Crosscutting relationships between the F_2 folds and the Annapurna detachment indicate that the folds formed prior to extension (Godin et al., 1999a). The cleavage related to the folds is overprinted by the ductile fabric associated

with the high-strain zone and the Annapurna detachment (Godin et al., 1999a). (5) There are no known growth strata related to extensional deformation along the Annapurna detachment. The only sediments deposited in the hanging wall of the Annapurna detachment are the Pliocene to Pleistocene Tetang and Thakkhola formations that are part of the Thakkhola graben fill (Bordet et al., 1971; Fort et al., 1982). (6) Finally, the pre-D₂ restoration presented in this chapter does not support the possibility that the Tethyan sedimentary sequence was substantially tilted prior to D₂ folding (Godin et al., 1999b; see also chapter 4).

Still, the question remains: what is the origin of the northeast-verging F₂ folds? Burchfiel et al. (1992) have suggested that they are compensational structures resulting from the southward extrusion of the Greater Himalayan metamorphic sequence. However, the northern extent of these folds would necessitate a regional-scale decrease in dip and northern continuation of the detachment, requiring a mechanism capable of producing a crustal-scale asymmetric fold train on an extensive “flat”. Furthermore, the Tethyan sedimentary sequence has clearly been thickened and shortened by the D₂ folds, rather than thinned and extended. These observations suggest that the D₂ folds were produced during a compressional event, subsequently overprinted by the extensional Annapurna detachment. In chapter 4, a dynamic model for the formation of these folds is proposed (see also Godin et al., 1999b).

2.6.3 High-strain zone and the Annapurna detachment

The transposition zone of the Annapurna detachment, characterized by a penetrative biotite-muscovite foliation (S_t) and associated down-dip mineral-elongation

lineation (L_m), is present in both the uppermost part of the Greater Himalayan metamorphic sequence and the lowermost units of the Tethyan sedimentary sequence. This high-strain zone, over 1,500 meter-thick, is associated with normal top-to-the-northeast shear-sense indicators and is interpreted to be an extensional shear zone that roots to the north. It separates two domains of contrasting structural style, distinguished by the presence of northeast-verging folds within the Tethyan sedimentary sequence that have no equivalent in the Greater Himalayan metamorphic sequence. It is clear from this study that the reorientation of both S_2 and the axial surface traces of northeast-verging F_2 folds in the high-strain zone is compatible with normal faulting. Furthermore, these data indicate that the ductile shearing is late- or even post- D_2 . Subsequent southwest-verging D_3 thrust motion was superimposed on the high-strain zone.

The Annapurna detachment extends east into the Annapurna Sanctuary as the Deurali detachment (Hodges et al., 1996), and farther east in the Marsyandi valley as the Chame detachment (Coleman, 1996a). Due to the difficult access within the Annapurna Sanctuary, the hanging-wall rocks of the Deurali detachment have not been studied in detail, and a high-strain zone has not been recognized there. In the Marsyandi valley, extensional deformation is localized in two mylonite zones and one brittle normal fault zone, which step structurally higher with time (Coleman, 1996a). The relatively thick high-strain zone in the Kali Gandaki valley is thus distinct in character compared to its lateral equivalents. This might suggest that the deformation was distributed through a wider zone, compared to the narrower mylonitic zones of the Marsyandi. This also suggests that the lowermost Tethyan sedimentary sequence was weaker in the Kali Gandaki valley, which could in turn reflect hotter conditions.

A weakly deformed leucogranitic dike intruding in the immediate hanging wall of the Annapurna detachment yielded reversely discordant monazites between 23 and 22.5 Ma, which suggest that the ductile strain in the high-strain zone terminated at *ca.* 22 Ma (see chapter 3). Data from Modi Khola valley of the Annapurna Sanctuary indicate that the Deurali detachment was active at *ca.* 22.5 Ma (Hodges et al., 1996). Extensional faulting in this area stepped structurally higher to the Machhapuchhare detachment between 19 Ma and 15 Ma (Hodges et al., 1996). In the Marsyandi valley, the Chame detachment juxtaposes the same units as in the Kali Gandaki valley along a west-directed normal-sense shear zone (Coleman, 1996a). At the top of the Greater Himalayan metamorphic sequence, two deformed leucogranitic dikes intruding a *ca.* 35 Ma granite (Hodges et al., 1996) yielded reversely discordant monazite ages between 34 and 24 Ma (Coleman, 1996b). Coleman interprets the 34 Ma age as inheritance from the 35 Ma granite and the 24 Ma age as a maximum age for the ductile movement along the Chame detachment. Farther to the east in the Dudh Khola, near Manaslu, two undeformed leucogranites yielded monazite and zircon ages of 18-19 Ma (Coleman, 1996b). In the central Nepal area, it is thus possible to envisage ductile normal-sense shearing along the South Tibetan detachment system occurring between 24 and 19 Ma.

2.6.4. Interpretation of D₃ structures

The D₃-related structures are characterized by microscopic to mesoscopic, post-peak metamorphic southwest-verging F₃ kink folds. These folds are associated with a regional northeast-dipping S₃ crenulation cleavage. In the structurally lowest part of the Tethyan sedimentary sequence, the D₃ deformation is associated with localized

southwest-verging shear zones. Both the F_3 kink folds and the localized D_3 thrusts overprint the Annapurna detachment high-strain zone.

The Kalopani shear zone (Vannay and Hodges, 1996) is located in the immediate footwall of the Annapurna detachment, within the Greater Himalayan metamorphic sequence. It is a north-dipping, post-peak metamorphic, top-to-the-southwest shear zone that lies at the same structural level as the Modi Khola shear zone observed farther east in the Annapurna range (Hodges et al., 1996). The Modi Khola shear zone is several hundred meter-thick and affects the uppermost part of the Greater Himalayan metamorphic sequence up to the top of the Annapurna Formation (Hodges et al., 1996). Such post-metamorphic structural discontinuities within the Greater Himalayan metamorphic sequence have also been recognized in the Langtang region of Nepal (Reddy et al., 1993) and farther east in Bhutan (Kakhtang thrust of Davidson et al., 1995) and are interpreted as out-of-sequence thrusts within the Himalayan southward-propagating thrust system.

The Modi Khola shear zone has been assigned a post-detachment (D_t) and a post- D_2 age based on crosscutting relationships (Hodges et al., 1996). Furthermore, the consistency of the $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite cooling ages throughout the Greater Himalayan metamorphic core (Vannay and Hodges, 1996; see also chapter 3) in the Kali Gandaki valley suggests that the major deformation associated with the Kalopani and the Modi Khola shear zones was terminated by 15-13 Ma. It is suggested that the F_3 kink folds found within the Tethyan sedimentary sequence are the high structural level expression of this out-of-sequence thrusting within the Greater Himalayan metamorphic sequence, and

that the 15-13 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite cooling ages obtained by Vannay and Hodges (1996) represent a minimum age for the D₃ phase.

2.6.5. Evolution of the Lupra fault and the Thakkhola graben system

Structural features attributed to the D₄ deformation phase comprise meter-scale brittle top-to-the-northeast normal faults within the Annapurna detachment zone. They also include northeast-trending normal faults, such as the Dangardzong and Muktinath faults, and a regionally distributed, sub-vertical northeast-trending spaced cleavage (S₄). Although the Lupra fault appears to record an early thrusting history, its brittle normal motion is assigned to the D₄ phase.

The D₄ deformation phase directly expresses itself in the Kali Gandaki valley as the Thakkhola graben system. Hydrothermal muscovite extracted from a calcite vein crosscutting the Annapurna Formation and associated with the Thakkhola fault system yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ age of *ca.* 14 Ma (Coleman and Hodges, 1995). Coleman and Hodges interpreted this as a minimum age for the onset of east-west extension within the Thakkhola fault system, and is therefore interpreted as the age of the D₄ phase. ^{14}C dating on faulted terraces indicate recent activity (<10 ka) on the Dangardzong fault (Hurtado and Hodges, 1998).

It is proposed that the Lupra fault represents a remnant of the initial Thakkhola graben. The Thakkhola graben could have initiated along a portion of the Dangardzong and Muktinath faults, with the Lupra fault acting as the southern termination. As the graben developed, the extension propagated southward. Today, the graben fault system

extends south to the Annapurna detachment (Hurtado and Hodges, 1998), and east at least to the Marsyandi valley (Coleman and Hodges, 1995).

2.7 CONCLUSIONS

1. The Tethyan sedimentary sequence in the Kali Gandaki valley has undergone five phases in its structural evolution.

2. The first phase displays rootless isoclinal folds with an associated foliation parallel to compositional layering. This phase has only been observed in the Paleozoic strata where it is related to southwest-verging deformation features such as the Fang nappe. The formation of these features is attributed to initial southward thrusting of the Tethyan cover sequence over the Indian continent during the Eocene.

3. The D_2 phase structures are characterized by spectacular northeast-verging megascopic folds and regional southwest-dipping axial planar schistosity. These folds display a strain gradient increasing with structural depth. This strain gradient is interpreted as evidence for a northward-verging décollement plane localized at the contact between the Tethyan sedimentary sequence and the underlying Greater Himalayan metamorphic sequence. The formation of the F_2 folds is not kinematically compatible with previously proposed gravity models.

4. In the Kali Gandaki area, the immediate hanging wall of the Annapurna detachment is characterized by a 1,500 meter-thick extensional shear zone (D_t). This zone is distinct in nature from other segments of South Tibetan detachment system, namely the Deurali and Chame detachments visible to the east. This high-strain zone transposes southwest-verging D_1 and D_2 phase structures. On the basis of crosscutting relationships,

the northeast-verging D_2 folds were produced prior to or during the early stages of ductile motion on the Annapurna detachment.

5. Greenschist facies thermal overprinting outlasted D_1 and resulted in partly annealed extensional fabrics in the high-strain zone.

6. Reactivation of the high-strain zone occurred during the southwest-verging, post-metamorphic D_3 phase of deformation, which is associated with kink folds, regionally northeast-dipping crenulation cleavages, and localized top-to-the-southwest shear zones.

7. The normal-sense component of the Lupra fault could mark an initial stage in the evolution of the Thakkhola graben system. As the graben developed, the extensional faulting propagated southward.

8. Late brittle top-to-the-northeast normal faults (D_4) affecting the high-strain zone and the Annapurna detachment could be coeval with the recent Thakkhola graben faults and, as such, may represent the present-day southern termination of the graben system.

Figure 2.1: Geologic map of central Nepal, simplified and modified after Colchen et al. (1981): GHMS, Greater Himalayan metamorphic sequence; MCT, Main Central thrust; Sct Fm, Sanctuary Formation; STDS, South Tibetan detachment system; TSS, Tethyan sedimentary sequence; box locates the study area and Figure 2.3.

Figure 2.2: Panoramic view of the Dhaulagiri-Dangar mountains, of the Thakkhola graben (in the upper Mustang restricted area) and of the Thorung mountains, as seen from the top of a ridge south of Lupra. Superimposed line drawing show the folding style and the main faults. The area photographed is all part of the hanging wall of the Annapurna detachment.

Figure 2.3: Detailed geologic map of the upper Kali Gandaki valley. The Cretaceous Dzung unit and the Neogene Thakkhola Formation shown in the stratigraphic column have not been mapped during the course of this study, but crop out in the vicinity of Kagbeni. Geology adapted from Bordet et al. (1971) and Colchen et al. (1981); stratigraphy modified from Bodenhausen and Egeler (1971), Bordet et al. (1971), Colchen et al. (1981) and Gradstein et al. (1992). A-A', B-B', C-C', D-D', E-E' and F-F' locate the section lines of Figure 2.19. Detailed versions of the map with plotted structural data and location of stations can be found in the back pocket.

Map 2. GEOLOGIC MAP OF THE KALI GANDAKI VALLEY, ANNAPURNA-DHAULAGIRI REGION, CENTRAL NEPAL

Geology and stratigraphy modified from Bordet et al. (1971), Colchen et al. (1986) and Gradstein et al. (1992). Compiled by Laurent Godin, Ph.D. thesis, Carleton University, 1996.

Neogene	Pliocene	Thakkhola Fm*	hiatus
	(K4)	Dzong unit*	
	(K3)	Muding unit	
	(K2)	Kagbeni unit	
	(K1)	Chukh unit	
	(J3)	Lupra Fm	
	(J2)	Bagung Fm	
	(J1)	Jomsom Fm	
	(T)	sandstone	
	(T)	Thini Fm	
	(CP)	Thini Chu Fm	
	(CP)	Lake Tilicho Fm	
	(D)	alternating black shale & limestone	
	(S)	Sombre Formation	
	(O)	gritty dolomite	
	(O)	Nilgiri Fm	
	(Ca)	Annapurna Fm	
	(Es)	Sanctuary Fm	
	(AD)	Annapurna detachment	
	(Fm III)	Greater Himalayan metamorphic sequence	
	(Fm II)		
	(Fm I)		
	(MCT)	Main Central thrust	
	(LHSS)	Lesser Himalayan sedimentary sequence	

* not shown

Figure 2.4: Photograph of the west face of the Nilgiri and Annapurna mountains, as seen from the Dhaulagiri ice fall. The line drawing indicates the projected stratigraphic contacts of the lower Paleozoic units that outline the F_2 Nilgiri anticline and the refolded F_1 Fang nappe. The snow-covered face is approximately 3000 meter-high. Abbreviations as in Figure 2.3.

Figure 2.5: Six northeast-southwest geologic cross sections. The section lines are indicated on Figure 2.3. Abbreviations as in Figure 2.3 except asl: above sea level. See text for discussion.

NNE

SSW

0 5 km

Figure 2.6: Deformation features related to the D₁ deformation phase. A: Outcrop photograph of an isolated F₁ fold hinge within the Annapurna Formation near Khanti. B: Sketch drawing of hand sample L94-21, collected in the Silurian-Devonian Sombre Formation, near Marpha. C: Photomicrograph with cross-polars of the same sample (L94-21) showing near-complete bedding transposition.

Figure 2.7: Various folding styles related to the D₂ deformation phase. A: Outcrop photograph of the Cretaceous Chukh unit affected by F₂ box-folds, near Kagbeni. B: Near parallel (class 1B) F₂ folds in unnamed Devonian limestones, north of Marpha. C: Passive-flow folds (class 2) in the lower part of the Sombre Formation, south of Marpha.

High structural level

Box-fold

Class 1B

Class 2

Low structural level

Figure 2.8: Deformation features related to the D_3 deformation phase. A: S_3 cleavage in Middle Jurassic limestone (Bagung Formation), south of Kagbeni. B: Southwest-verging F_3 kink folds overprinting F_2 folds in the Silurian-Devonian Sombre Formation, near Marpha.

Figure 2.9: Panoramic photograph of the Thorung La region, as seen from Dangardzong. The Kangar ridge and the plains near Panda Khola in the foreground are within the Thakkhola graben. The F_3 Thorung anticline and upright to inclined northeast-verging F_2 folds are visible in the background. Abbreviations as in Figure 2.3.

Figure 2.10: D_2 - D_3 relationships in the Panda Khola, near Lupra. A: Photograph of the cliffs north of Lupra. The undulations of the steeply south-dipping stratigraphy are related to F_3 folding. Line drawing (B) and photograph (C) of the F_2 upright Lupra syncline overprinted by F_3 southwest-verging kink folds. T marks the stratigraphic polarity.

Figure 2.11: Outcrop photographs showing fold interference patterns between F_2 and F_3 .

A: Upright F_2 folds refolded by F_3 kinks in the Late Jurassic Lupra Formation on the northern limb of the F_2 Lupra syncline, south of Kagbeni.

B: F_3 kinks superimposed on tight inclined F_2 folds within the Silurian-Devonian Sombre Formation, Marpha area.

Figure 2.12: Photomicrographs showing fabric relationships between S_{0-1} , S_2 and S_3 . A: sample L95-156 from the Silurian-Devonian Sombre Formation, in the Syang Khola near Jomsom. B: sample L95-161 from the Carboniferous-Permian Thini Chu Formation, west of Dangardzong.

Figure 2.13: D_3 localized, post-peak metamorphic shear zones. Outcrop photograph (A) and line drawing (B) of the Annapurna Formation near Larjung displaying localized thrust reactivation of the high-strain zone; the extended (boudinaged) dike, in which the line connecting the centers of the boudins rotates toward the flow plane, is compatible with top-to-the-southwest thrust motion (Hanmer and Passchier, 1991). Outcrop photograph (C) and line drawing (D) of a 5 meter-thick shear zone within Formation III of the Greater Himalayan metamorphic sequence southeast of Taglung that could be correlative with the Kalopani shear zone of Vannay and Hodges (1996).

Figure 2.14: Deformation features related to the D₄ deformation phase. A: Steeply-dipping S₄ spaced cleavage in the Carboniferous-Permian Thini Chu Formation, south of Jomsom. B: Brecciated limestone of the Jomsom Formation in the immediate hanging wall of the Dangardzong fault. C: Fragmented feldspar grains seen in a photomicrograph from a cataclastic zone within the Formation III augen orthogneiss, north of Kalopani.

Figure 2.15: Exposure of the Lupra fault on the west bank of the Kali Gandaki river, north of Jomsom. Although the stratigraphic relationships allude to a thrust motion, the juxtaposition of high-level structures in the hanging wall with lower-level features in the footwall strongly suggests an important normal-sense component for the Lupra fault. T marks the stratigraphic polarity.

Figure 2.16: A: Panoramic photograph of the east face of the Dhaulagiri-Tukche mountains showing the position of the Annapurna detachment, as seen from the Thulo Bugin ridge. B: 2000 meter-high exposure of the Annapurna detachment, north of Kalopani.

Figure 2.17: Shear-sense indicators associated with the high-strain zone visible in outcrops. A: Photograph of extensional shear bands (SB) affecting a dolomitic horizon within the Annapurna Formation on Thulo Bugin ridge. B: Photograph of asymmetric isoclinal folds within biotite + muscovite ($\pm$ sillimanite) schist of the Formation III (Greater Himalayan metamorphic sequence), north of Kalopani.

Figure 2.18: Shear-sense indicators associated with the high-strain zone visible in thin sections cut parallel to the lineation (L_m) and perpendicular to the foliation (S_t). A: Normal-sense extensional shear band and calcite “ribbon” texture in calcite-rich psammitic horizon of the Annapurna Formation. B: Extensional shear bands in quartz-rich psammitic horizon of the Annapurna Formation. Both cross-polars with field view of 0.5 cm: Cal, calcite; Ms, muscovite, Qtz, quartz; SB, extensional shear band. S_t is indicated.

Figure 2.19: Quartz *c*-axis orientations from three localities within the Annapurna Formation; point maxima defining asymmetry (Law, 1990). S marks the trace of the high-strain zone fabric (S_t) and L is the mineral-elongation lineation (L_m). These sections correspond to the XZ plane of the finite ellipsoid of deformation. Contours represent 4%, 6%, 8% and 10% of total data.

Figure 2.20: Partly annealed quartz ribbons used to measure crystallographic preferred orientations, affected by a late post-peak metamorphic southwest-verging D_3 kink. Cross-polars with field view of 0.5 cm: Cal, calcite; Ms, muscovite; Qtz, quartz; S_1 and S_3 are indicated.

Figure 2.21: Subdivision of the study area into six structural domains based on predominant deformation phase, fabric orientation, deformation style and strain intensity. Stereonets show the regional orientation of structural features (equal-area, lower hemisphere stereographic plots). The S_2 progressively rotates into parallelism with the high-strain zone fabric (S_t). Regionally, the S_3 and S_4 remain constant and are superposed on the high-strain zone and earlier fabrics.

Figure 2.22: Schematic three-step bed-length restoration of the F_2 folds with minimum shortening estimates. AD, Annapurna detachment; MCT, Main Central thrust.

Generalized deformed-state cross section

Step 1 :
Restoration of Lupra fault and
other faults within the sequence

Step 2 :
Restoration of the Annapurna
detachment and its rotational
effect on the F_2 axial surface
traces

Step 3 :
Simple geometrical bed-length
unfolding of the F_2 folds

0 5 km

Figure 2.23: Five-phase structural evolution of the Tethyan sedimentary sequence in the Kali Gandaki valley. AD, Annapurna detachment; Bt, biotite; Ms, muscovite; Qtz, quartz.

NE	Macroscopic	Mesoscopic	Description	SW
D₁	<p>Fang-type, isoclinal F_1 folds</p>	<p>D_1 bedding transposition Sombre Fm, Marpha (L-21)</p>	<ul style="list-style-type: none"> - southwest-verging rootless isoclinal folds (F_1) - locally observed near-complete bedding transposition - Bt-Ms bedding-parallel schistosity (S_1) 	
D₂	<p>Nilgiri-type, high-amplitude, tight F_2 folds</p>	<p>penetrative S_2 schistosity Sombre Fm, Marpha (L-28)</p>	<ul style="list-style-type: none"> - northeast-verging, high-amplitude tight folds (F_2) at low structural levels - upright chevron folds (F_2) at high structural levels - regional southwest-dipping, oblique-to-bedding, penetrative schistosity (S_2) - S_2 defined by Bt+Ms and elongated Qtz - S_2 is a spaced cleavage in more competent layers 	
D₁	<p>high-strain zone associated with normal faulting (AD)</p>	<p>asymmetric folds and s-c fabrics Fm III, Kalopani (L-102)</p>	<ul style="list-style-type: none"> - strong transposition (S_1) localized in the lower part of the Tethyan sedimentary sequence - S_1 is a penetrative, composite S_{0+1+2} Bt-Ms schistosity - normal, top-to-the-northeast shear-sense indicators (s-c fabrics, asymmetric folds and Qtz c-axis fabrics) 	
D₃	<p>southwest-verging F_3 kinks and thrust faulting</p>	<p>F_3 kinks and boudinaged veins Annapurna Fm, Khanti (L-16)</p>	<ul style="list-style-type: none"> - microscopic to mesoscopic F_3 kink folds with regional southwest vergence - northeast-dipping, axial-planar, post-metamorphic crenulation cleavage (S_3) - localized reactivation of high-strain zone by top-to-the-southwest thrust motion 	
D₄	<p>northeast-verging brittle normal faults and Thakkhola graben structures (?)</p>	<p>brittle normal faults Fm III, Kalopani (L-116)</p>	<ul style="list-style-type: none"> - metre-scale brittle top-to-the-northeast normal faults within the AD zone - brittle, NE-SW-trending normal faults associated with the Thakkhola graben - sub-vertical NE-SW-trending spaced cleavage (S_4) 	

CHAPTER 3

CRUSTAL THICKENING, MELT PRODUCTION AND EXHUMATION OF THE HIMALAYAN METAMORPHIC CORE OF CENTRAL NEPAL: INSIGHT FROM U-Pb GEOCHRONOLOGY AND $^{40}\text{Ar}/^{39}\text{Ar}$ THERMOCHRONOLOGY

ABSTRACT

U-Pb geochronology and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology from footwall and hanging-wall rocks of a segment of the South Tibetan detachment system exposed in the Annapurna area of central Nepal Himalaya are presented. These data bring additional constraints on the timing of metamorphism, crustal thickening, melt production, and normal faulting resulting in exhumation of the Himalayan metamorphic core.

Early Oligocene crustal thickening led to Eohimalayan kyanite-grade metamorphism between 35 and 32 Ma. The resulting thermal event affected the Early Ordovician Formation III augen gneiss and produced kyanite-bearing leucosomes in the upper part of the metamorphic core. This event is linked with underthrusting of the Greater Himalayan metamorphic sequence below the Tethyan sedimentary sequence and the growth of an Oligocene fan structure that has thickened the Tethyan sedimentary sequence to 25 km, thus provoking kyanite-grade melting at deeper structural levels.

Regional correlations indicate that the Annapurna detachment was active during Early Miocene time. A weakly deformed leucogranitic dike intruding into the immediate hanging wall yielded reversely discordant monazite ages between 23 and 22.5 Ma, which suggest that the ductile strain in the Annapurna detachment zone terminated at *ca.* 22 Ma. Based on a $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age, renewed southwest-verging deformation (D_3) is interpreted to occur at *ca.* 18 Ma.

Rapid exhumation resulting from extensional faulting cooled the entire metamorphic core through the muscovite Ar closure temperature (330-430 °C) between 15 and 13 Ma. Muscovites from the immediate hanging wall of the Annapurna detachment yielded slightly younger ages, between 13 and 11 Ma, testifying to late hydrothermal activity in the Annapurna detachment zone. This thermal event could be linked with the initiation of brittle faulting associated with the Thakkhola graben system.

3.1 INTRODUCTION

The metamorphic core of the Himalayan orogen, termed the Greater Himalayan metamorphic sequence, is a southward extruded wedge bounded by the Main Central thrust and the South Tibetan detachment system (Burchfiel et al., 1992). Between the time of the India-Eurasia collision (52-45 Ma; for review see Rowley, 1998) and the

climax of crustal shortening, when segments of the Main Central thrust and the South Tibetan detachment system were active at *ca.* 21 Ma, there was a 30 Ma period about which little is known. This period has been elusive in the metamorphic core due to the strong thermal overprinting that occurred during the Miocene. Nevertheless, there is a growing body of evidence pointing to a distinct Oligocene thermal event in the central Nepal Himalaya (Hodges et al., 1996; Vannay and Hodges, 1996; Coleman, 1996b; Godin et al., 1999b). An important key to better constraining this event resides in detailed mapping and high-precision U-Pb dating of melts in the upper section of the Greater Himalayan metamorphic sequence, where the Miocene overprint due to thrusting along the Main Central thrust is less pronounced. The first part of the chapter focuses on bridging this time gap by constraining the timing of melt production within the metamorphic core of the central Nepal Himalaya with the aid of U-Pb geochronology. The second objective of this chapter focuses on better understanding the cooling history of the metamorphic core during its exhumation with the aid of $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology.

3.2 GEOLOGIC SETTING

The area under investigation is located in the Kali Gandaki valley of central Nepal (Figure 3.1). From south to north, the area comprises three tectonostratigraphic units: (1) the Lesser Himalayan sedimentary sequence, composed of Precambrian to Mesozoic low-grade metasediments; (2) the Greater Himalayan metamorphic sequence, composed of highly strained kyanite- and sillimanite-grade gneisses intruded by variably deformed Miocene leucogranites; and (3) the Tethyan sedimentary sequence, a nearly continuous,

10 kilometer-thick early Paleozoic to early Tertiary sedimentary pile, representing the Indian continental margin of the Tethys ocean (Bodenhausen and Egeler, 1971; Bordet et al., 1971; Colchen et al., 1981; Gradstein et al., 1992).

Previous workers have identified two main tectonic boundaries: (1) the Main Central thrust, a Miocene crustal-scale plastic-brittle shear zone that juxtaposes the Greater Himalayan metamorphic sequence southward over the Lesser Himalayan sedimentary sequence (Bouchez and Pêcher, 1976; Pêcher, 1977); and (2) the Annapurna detachment, which is defined as a plastic-brittle normal fault juxtaposing the Tethyan sedimentary sequence in the hanging wall with the Greater Himalayan metamorphic sequence in the footwall (Caby et al., 1983; Brown and Nazarchuk, 1993). The Annapurna detachment is associated with a 1,500 meter-thick high-strain zone that affects green-schist facies biotite-muscovite psammite of the Annapurna Formation of the Tethyan sedimentary sequence with amphibolite facies biotite-garnet-sillimanite schist, garnet-diopside calc-silicate and leucogranitic gneiss of the Greater Himalayan metamorphic sequence in its footwall (Godin et al., 1999a). The Annapurna detachment has been correlated by Brown and Nazarchuk (1993) with the South Tibetan detachment system described by Burchfiel et al. (1992). It is correlative with the Deurali and the Chame detachments described farther east in the Annapurna range, where the detachment splays into a complex zone of multi-stage extensional faults (Hodges et al., 1996; Coleman, 1996a). The South Tibetan detachment system was active at ~20 Ma and is broadly coeval with southeast-verging contractional structures associated with the Main Central thrust at deeper structural levels (Hubbard and Harrison, 1989; Hodges et al., 1996). The Greater Himalayan metamorphic sequence, the Tethyan sedimentary

sequence, the Main Central thrust and the Annapurna detachment are all spectacularly exposed in the Kali Gandaki valley.

3.2.1 Tethyan sedimentary sequence

In the vicinity of Taglung and Kalopani (Figures 3.2 and 3.3), the lowest part of the preserved Tethyan sedimentary sequence is the Cambrian(?)–Ordovician Annapurna Formation, also known as the Yellow Formation or Larjung series (Bordet et al., 1971; Colchen et al., 1986). Although there are no direct chronological data, this unit has been interpreted as being of Cambrian age, because it stratigraphically lies under the Ordovician Nilgiri Formation (Bordet et al., 1971). The Annapurna Formation is essentially composed of calcareous biotite-grade psammitic and semi-pelitic schist and phyllite, and is separated from the underlying Formation III by the Annapurna detachment (Brown and Nazarchuk, 1993; Godin et al., 1999a). Overlying the Annapurna Formation, the Nilgiri Formation is composed of gray micritic limestone, grading upwards into pink dolomitic sandstone, calcareous shale and siltstone. The Ordovician series is capped by a 400 meter-thick calcareous arkose and siltstone unit (the “North face quartzite” of Bodenhausen et al., 1964). The upper portion of the Paleozoic is composed of alternating gritty dolomite, black shale and limestone of the Sombre Formation (Silurian–Devonian), correlative with the Dark Band Formation of the Dolpo area, northwest of the Thakkhola region (Fuchs, 1977).

3.2.2 Greater Himalayan metamorphic sequence

In the Kali Gandaki valley, the Greater Himalayan metamorphic sequence consists of a 5 kilometer-thick section of northeast-dipping gneisses (Figures 3.2 and 3.3), which are subdivided into three formations (Colchen et al., 1986). Formation I consists of kyanite-garnet bearing pelitic gneiss and migmatite and lies in the structurally lowest position. Formation II is essentially composed of diopside-garnet-amphibole-bearing calc-silicate gneiss and rests above Formation I. Formation III is characterized by highly migmatitic quartzo-feldspathic sillimanite-bearing schist and calc-silicate gneiss with discordant lenses of variably strained garnet-tourmaline augen orthogneiss, and is found at the top of the Greater Himalayan metamorphic sequence in most transects throughout the orogen (Colchen et al., 1986).

3.2.3 Metamorphism of the Greater Himalayan metamorphic sequence

The Greater Himalayan metamorphic sequence of the eastern and central Himalaya has been affected by two major metamorphic events (Brunel and Kienast, 1986; Hodges et al., 1988a; Pêcher, 1989; Swapp and Hollister, 1991; Inger and Harris, 1992; Macfarlane, 1992); the Eohimalayan and the Neohimalayan. The Eohimalayan metamorphic event is considered to be Eocene to Oligocene in age (Hodges and Silverberg, 1988; Inger and Harris, 1992; Hodges et al., 1994). Evidence of Himalayan crustal thickening at this time include Barrovian metamorphism (Searle and Rex, 1989; Hodges et al., 1988a), anatexis related to crustal thickening beginning at 35 Ma (Hodges et al., 1996), early thrust stacking and related compressional structures that occurred subsequent to the mid-Eocene collision and suturing, but initiated before development of

the Main Central thrust (Burg and Chen, 1984; Searle, 1986; Searle et al., 1988), initiation of uplift/exhumation of the Himalaya and onset of foreland basin sedimentation at *ca.* 35 Ma (Najman et al., 1994), and possible Oligocene folding of the Tethyan sedimentary sequence in central Nepal (Godin et al., 1999a,b). The Eohimalayan event has been constrained in the Dinggyê area of southern Tibet by $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology at *ca.* 25 Ma (Hodges et al., 1994). In the Annapurna area of central Nepal, this phase is interpreted to occur somewhat earlier, in Late Eocene to Early Oligocene (*ca.* 36 Ma; Coleman, 1996b; Hodges et al., 1996; Vannay and Hodges, 1996; Godin et al., 1999b) and is thought to be linked with underthrusting of the metamorphic core below the Tethyan sedimentary sequence (Vannay and Hodges, 1996). Godin et al. (1999b) have proposed that the Oligocene thermal event is linked with the building of a structural fan within the Tethyan sedimentary sequence, which in turn instigated kyanite-grade metamorphism at lower structural level (see also chapter 4).

The second (“Neohimalayan”) major metamorphic event affecting the Greater Himalayan metamorphic sequence is far better understood. It occurred during the Early to Middle Miocene (Hubbard and Harrison, 1989; Pêcher, 1989; Hodges et al., 1992) and coincides with thrusting along the Main Central thrust, production of the High Himalayan granites (Schärer et al., 1986; Deniel et al., 1987a; Le Fort et al., 1987; Hodges et al., 1988a), and onset of the South Tibetan detachment system at higher structural levels (Burchfiel et al., 1992). The heat source for this thermal event and the resulting anatexis melting remains problematic (see review in Hodges et al., 1988a). It has been suggested that the melting was triggered by the influx of metamorphic fluids from the footwall of the Main Central thrust, and that the hanging wall had retained enough residual heat from

the first thermal event to permit melting (Le Fort, 1981). Some workers have attributed the melting to frictional heating along the Main Central thrust (Le Fort, 1975; Scholtz, 1980). It has also been proposed that the Greater Himalayan metamorphic sequence could have been heated as a consequence of the delamination of the Indian lithosphere, and subsequent upwelling of the asthenosphere (Bird, 1978). Other workers have attributed the melting to heat concentration and thermal buffering near the top of the Greater Himalayan metamorphic sequence (Jaupart and Provost, 1985; Hodges et al., 1988b). More recently, Harris and Massey (1994) suggested that the Miocene leucogranites were the product of decompression melting, linking the anatexis of pelites from the Greater Himalayan metamorphic sequence with exhumation along the South Tibetan detachment system.

3.3 U-Pb GEOCHRONOLOGY

U-Pb geochronology was undertaken to precisely constrain the thermal events that affected rocks in the vicinity of the Annapurna detachment. Analysis of accessory minerals with high closure temperatures, such as monazite and zircon (700°C and 750°C, respectively; Copeland et al., 1988; Parrish and Tirrul, 1989; and most probably higher i.e. Spear and Parrish, 1996), is the most reliable method of dating the crystallization of granitic melts. The U-Pb geochronology study focused on three main questions. (1) Is the Formation III augen orthogneiss described by Bordet et al. (1971) an old basement, as suggested by Le Fort et al. (1986b), or is it part of an Oligocene magmatic event as discussed by Hodges et al. (1996) and Coleman (1996b), or is it part of the Miocene leucogranite suite injected into the uppermost part of the Greater Himalayan

metamorphic sequence throughout most of the Himalaya? (2) Is there geochronologic evidence for an Oligocene thermal event in central Nepal, as suggested by Vannay and Hodges (1996), Hodges et al. (1996) and Coleman (1996b)? Finally, (3) what is the nature of the Miocene thermal event present in the Kali Gandaki valley?

Previous U-Pb work in this valley includes dating of variously deformed pegmatites within the Greater Himalayan metamorphic sequence. Two leucogranitic pegmatites within the Greater Himalayan metamorphic sequence were dated using single and multigrain fractions of monazite and thorite. An undeformed coarse-grained pegmatite crosscutting the planar fabric related to the Main Central thrust zone yielded an interpreted crystallization age of 21.0 ± 0.5 Ma (Nazarchuk, 1993). Above the high-strain zone of the Main Central thrust shear zone, a multiply deformed leucogranite body in the calc-silicate gneiss was interpreted to crystallize at 22.5 ± 0.1 Ma (Nazarchuk, 1993). These data provide minimum and maximum age constraints for ductile movement along the Main Central thrust in the Kali Gandaki valley.

3.3.1 Sample description and U-Pb results

Four samples were chosen for U-Pb geochronologic dating (see location on Figures 3.2 and 3.3). Three of those were collected in the immediate footwall of the Annapurna detachment, the fourth one was sampled in the immediate hanging wall. Complete analytical U-Pb data are presented in Table 3.1, and analytical procedures can be found in Appendix A.

Formation III augen orthogneiss (L96-208)

A foliated leucogranite from the immediate footwall of the Annapurna detachment was sampled near Kalopani (Figure 3.4A). This granitic horizon is part of the 300 meter-thick augen orthogneiss of Formation III (Bordet et al., 1971). It comprises several phases, which can all be observed within the same outcrop, from coarse pegmatitic to aplitic. Enclaves of biotite-garnet schist are also present. Mineralogically, the leucogranitic gneiss contains biotite, muscovite, tourmaline and garnet. Although it is only weakly foliated in some localities, extensional fabrics related to the Annapurna detachment are well developed in its uppermost part (Godin et al., 1999a). This unit has been described by Le Fort et al. (1986b) as a granitic augen gneiss of Cambrian age, based on Rb-Sr data obtained from numerous samples collected in central Nepal. This rock is part of a mappable unit which intrudes the calc-silicate and the biotite-garnet schist present in Formation III.

Four zircon and three monazite fractions were analyzed. The zircon fractions selected ranged in shape from 100 micron-long pink prismatic crystals to 100 microns in diameter clear yellow equant to tabular crystals, all of which had no visible core under plane polarized or reflective light. All the zircon fractions were multigrain analyses, except for the single grain fraction Z2. None of the zircon fractions were air abraded. The monazites separated for analysis were pale green euhedral crystals between 100 and 200 microns in size with no visible inclusions. Fractions M1 and M2 were multigrain analyses, containing 23 and 68 grains respectively; whereas fraction M3 was a single grain analysis.

The three monazite fractions fall on a well defined discordia line with an upper intercept of 483.6 ± 9.1 Ma and a lower intercept of $31.5 +2.7/-3.0$ Ma with a MSWD of 1.66 (Figure 3.4B). As inheritance in monazite from peraluminous Himalayan granites is not unusual (Copeland et al., 1988), the position of these monazites with respect to concordia most likely reflects mixing between an older inherited Cambrian-Ordovician component and a younger *ca.* 30 Ma thermal event. The upper intercept age is consistent with Rb-Sr data from the same unit, which yielded an age of 513 ± 30 Ma (Le Fort et al., 1986b), and supports an Early Ordovician magmatic crystallization age for the Formation III augen gneiss.

There are several possible explanations for the spread of discordant zircon analyses. Fractions Z1 and Z3 fall near the upper intercept of the discordia line made by the monazite fractions. A York linear regression taking into account all monazite fractions with fractions Z1 and Z3 yields an upper intercept age of 483.6 ± 9.0 Ma and a lower intercept of 36.2 ± 3.7 Ma with a MSWD of 16.4. If the zircon fractions had been air abraded following Krogh (1982) to minimize lead loss, they would have most probably plotted closer to the concordia-discordia junction, therefore supporting the magmatic Ordovician age obtained from the monazite fractions. However, the four zircon fractions fall on a poorly defined discordia line with a Proterozoic upper intercept of $1454.9 +37.6/-36.8$ Ma and a lower intercept of 416.4 ± 7.2 Ma with a MSWD of 30.5. Given the fact that most Himalayan leucogranites yield very poor resolvable zircon ages due to inheritance problems, the linear regression analysis of the four zircon fractions should be used with caution. Nevertheless, the zircon analyses support an Ordovician magmatic age incorporating some older Proterozoic inheritance.

Sillimanite-bearing pelitic schist of Formation III (L96-221c)

A sillimanite-bearing pelitic schist located in the high-strain zone of the Annapurna detachment near Taglung was sampled (Figure 3.5). This unit is exposed approximately 100 m structurally above the augen orthogneiss of Formation III, and less than 100 m below the Annapurna Formation. The pelitic schist is interlayered with diopside-garnet calc-silicate gneiss, and is laterally discontinuous. It contains up to 10 centimeter-thick kyanite- and sillimanite-bearing leucosomes. It is a rusty-colored highly weathered schist, containing quartz, feldspar, biotite, garnet and sillimanite. This is the first known occurrence of sillimanite in central Nepal west of the Modi Khola drainage.

Three single-grain sub-equant to round monazite fractions were analyzed from sample L96-221c (Figure 3.6A). They ranged in color from pale green to yellow, and from 50 to 150 microns in size. Fraction M1 is the only concordant analysis, yielding an age of 33.4 ± 0.1 Ma. A York linear regression obtained using all fractions yielded an unprecise upper intercept of $355^{+108/-104}$ Ma and a lower intercept of $33.7^{+1.2/-1.9}$ Ma with a MSWD of 4.53. The large error of the upper intercept renders geologic interpretation tentative. Given the low number of fractions analyzed, only the concordant M1 fraction and the lower intercept of the linear regression can be taken into account. This set of data supports an Oligocene metamorphic event at *ca.* 33.5 Ma, which was also interpreted from the nearby sample L96-208. Fractions M2 and M3 could be Ordovician metamorphic monazites related to the emplacement of the nearby Formation III augen gneiss that were partly reset during the Oligocene.

Kyanite-bearing leucosome within Formation III (L96-221b)

A kyanite-garnet-muscovite bearing leucosome within the sillimanite-bearing pelitic schist of Taglung was collected in the immediate footwall of the Annapurna detachment (Figure 3.5). The leucosome is 10 centimeter-thick and is affected by extensional structures related to the Annapurna detachment. The leucosome is part of a series of melts containing kyanite, sillimanite and garnet that make up to 15% of the volume of the pelitic schist. This is the first documented occurrence of kyanite this high structurally in the Greater Himalayan metamorphic sequence.

Five multigrain discordant monazite and zircon fractions and one single-grain monazite from sample L96-221b define a good linear array with a lower intercept of 35 ± 3 Ma and an upper intercept of 460 ± 11 Ma with a MSWD of 8.76 (Figure 3.6B). The zircons were clear to cloudy euhedral and prismatic crystals, with an average size of 200 microns. All the monazites analyzed were clear green euhedral crystals ranging in size from 50 to 200 microns. The upper-intercept Ordovician age is interpreted as inheritance from the host pelitic schist. This interpretation is supported by other Ordovician ages obtained from samples of Formation III (samples L96-208 and L96-221b). The lower intercept is interpreted as the magmatic crystallization age of the leucosome during kyanite-grade metamorphism. Petrographic textures indicate that the kyanite was stable with the other phases, namely muscovite and sillimanite, precluding the possibility of old kyanite being incorporated in the melt as porphyroclast. The monazite and zircon array most likely reflects the mixture of inherited monazite and zircon from an Ordovician metamorphic event with a *ca.* 35 Ma magmatic component produced during crystallization in the kyanite + melt stability field of an anatectic melt. This interpretation

is supported by the fact that fractions M1, M2 and M3 are linearly regressed to the same upper and lower intercept (466.4 ± 4.7 Ma and 36.3 ± 1.3 Ma, respectively) with almost perfect statistical fit (MSWD = 0.1).

Crosscutting leucogranitic dike within the Annapurna Formation (L95-123e)

A 3 meter-wide leucogranitic dike intruding the lowest section of the Annapurna Formation was collected 3 km north of Kalopani, in a gully cutting down through the Annapurna detachment (Figure 3.7A). This dike clearly crosscuts the main extensional ductile fabric (S_t) within the calcareous biotite-grade psammitic and semi-pelitic schist and phyllites, but is itself weakly foliated. The dike is fine-grained and contains plagioclase, quartz, tourmaline, muscovite with minor amount of garnet.

Three monazite and two zircon fractions were analyzed. Two distinct morphologies of zircons were found. Fraction Z1 contained 10 cloudy 200 microns, equant euhedral crystals. Fraction Z2 contained 20 clear, prismatic, 150 micron-long crystals. Both zircon analyses were highly discordant, indicating that there are more than two components of inherited radiogenic ^{206}Pb involved in mixing, probably in the form of invisible cores. Furthermore, these two fractions are multigrains and provide a mixture of all the individual ages of zircon. The geologic significance of these analyses is therefore limited.

Fraction M1 comprised of a 100 microns, single light yellow monazite fragment whereas the five monazites of fraction M2 were 50 to 100 microns, round, yellow crystals. A different morphology constituted the fraction M3, which was composed of 6 small 50 microns green euhedral monazites. The first two monazite analyses are

concordant and reversely discordant, respectively, and plot above *ca.* 22.5-23.0 Ma (Figure 3.7B). Fraction M3 plots slightly older and is concordant at 28.0 ± 0.4 Ma. The reversely discordant pattern is common for young monazite and most likely results from excess ^{230}Th -derived ^{206}Pb incorporated in magmatic grains during crystallization (Schärer, 1984; Parrish, 1990). The $^{207}\text{Pb}/^{235}\text{U}$ ages for these analyses are interpreted as the best estimates of the crystallization age of the mineral, following Parrish (1990). The concordant M3 monazite at 28 Ma could be coincidental, plotting at the intersection between concordia and the discordia from the upper intercept to the young fraction, which contains excess ^{206}Pb due to ^{230}Th incorporation. Alternatively, M3 could be a monazite that grew during a thermal event at 28 Ma or slightly older, which was then assimilated by the leucogranitic melt at 22.5 Ma. The distinct euhedral morphology of fraction M3 with respect to the two other does not support this alternative.

3.3.2 Summary of U-Pb results

Sample L96-208 yielded an upper intercept monazite and zircon age of 483.6 ± 9.0 Ma, therefore supporting an Ordovician crystallization age for the Formation III augen gneiss preserved in the upper part of the Greater Himalayan metamorphic sequence. All three samples analyzed from the upper metamorphic core (L96-221b,c and L96-208) indicate clear evidence for an Oligocene thermal event, with monazite ages between 31.5 and 35.0 Ma. Furthermore, the kyanite-bearing leucosome (L96-221c), which yielded an interpreted crystallization age of 35 ± 3 Ma, provides a strong argument for Oligocene-age metamorphism. Lastly, a late-kinematic leucogranitic dike (L95-123e)

injected into the lowermost part of the Annapurna Formation indicates that major ductile motion along the Annapurna detachment was completed by *ca.* 22 Ma.

3.4 $^{40}\text{Ar}/^{39}\text{Ar}$ THERMOCHRONOLOGY

In order to constrain the youngest part of the tectonothermal history and to complement the U-Pb data obtained from the vicinity of the Annapurna detachment, 11 mineral separates from 8 samples were analyzed by the $^{40}\text{Ar}/^{39}\text{Ar}$ method. Muscovite, biotite and hornblende mineral separates were selected to obtain a range of cooling ages with respect to the different isotopic closure temperatures of the respective minerals. Results are presented and interpreted in conjunction with published $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronologic investigations of the area (e.g. Coleman and Hodges, 1995; Coleman, 1996b; Vannay and Hodges, 1996; Coleman and Hodges, 1998).

In the Marsyandi valley, 60 km east of the Kali Gandaki, Coleman and Hodges (1998) analyzed a suite of samples collected from the hanging wall and footwall of the extensional Chame detachment shear zone, located at the top of the Greater Himalayan metamorphic sequence. The results show a clear contrast in cooling histories across the fault. The hanging-wall rocks indicate evidence of Oligocene regional metamorphism synchronous with the development of major deformation features in the Tethyan sedimentary sequence (29.9 Ma to 27.1 Ma), whereas footwall samples suggest a Middle Miocene cooling history (16.6 Ma to 14.1 Ma). In contrast, Vannay and Hodges (1996) analyzed a suite of samples at different structural levels within the Greater Himalayan metamorphic sequence in the Kali Gandaki valley. This study was limited to the footwall rocks of the Annapurna detachment, as no samples were analyzed from the hanging wall.

One hornblende sample from the calc-silicate unit of Formation III yielded a 37.2 ± 2.8 Ma age, which they interpreted as clear evidence of the presence of an Oligocene thermal event in the Kali Gandaki valley. They also observed no correlation between muscovite cooling ages and structural position within the Greater Himalayan metamorphic sequence. They concluded that the entire metamorphic core homogeneously cooled below 330-430 °C between 15 and 13 Ma.

3.4.1 Sample description

Eight samples were collected for thermochronology. Five samples come from the immediate footwall of the Annapurna detachment, in the metamorphic rocks of Formation III. These samples are all strongly affected by normal-sense, ductile shearing associated with the Annapurna detachment. They comprise biotite + garnet schist (L95-110 and L95-117), foliated garnet + biotite + muscovite + tourmaline leucogranitic augen gneiss (L95-116 and L95-119), and diopside + hornblende + garnet-bearing calc-silicate gneiss (L95-123). Two samples were collected from the hanging-wall psammite of the Annapurna Formation, less than 1000 m above the Annapurna detachment. They include a finely layered quartz + calcite + muscovite + biotite psammite (L94-10) and a fine-grained muscovite-bearing limestone, containing up to 55% muscovite (L95-104). The last sample was collected from the Ordovician muscovite-bearing limestone of the Nilgiri Formation (L95-143). Muscovite occurs in this sample in fine bands within the limestone. These bands are crenulated by second-generation (S_2) axial planar crenulation cleavage associated with F_2 northeast-verging folds (Figure 3.8). In outcrop as well as in thin section, rocks from the area of station L95-143 also display third-generation kink folds

and related spaced cleavage that have deformed pre-existing micas (Figures 2.12 and 3.8; see also Map 3). All the samples were collected within the high-strain zone of the Annapurna detachment as described by Godin et al. (1999a), except for sample L95-143, which sits well above the structural influence of the detachment.

Estimated isotopic closure temperatures for Ar are 300-350°C for biotite, 330-430°C for muscovite, and $530 \pm 50^\circ\text{C}$ for hornblende (McDougall and Harrison, 1988). Although all the ages obtained are within Himalayan time (younger than 50 Ma; Molnar, 1984), the biotite analyses systematically yielded older ages (27.3 to 13.1 Ma) than muscovites (18.1 to 11.8 Ma) (Table 3.2). This is common in biotite analyses from certain types of metamorphic terranes, and is usually interpreted as a result of incorporation of unresolved excess argon from the environment. This excess argon is rarely distinguished from radiogenic argon, the $^{40}\text{Ar}/^{39}\text{Ar}$ spectrum measurements adding little additional information (Roddick et al., 1980; McDougall and Harrison, 1988). For this reason, the biotite data are not included in the discussion. The hornblende separate did not yield a reliable plateau or isochron age. A second aliquot of the same separate was analyzed without success. The combined results of both aliquots were plotted on an inverse isochron diagram, which yielded an imprecise age of 46.1 ± 9.5 Ma. Due to their imprecision and poorly-constrained $^{40}\text{Ar}/^{36}\text{Ar}$ ratio, the hornblende ages are not considered reliable. Six muscovite separates (L94-10, L95-104, L95-116, L95-117, L95-119 and L95-143) yielded geologically meaningful and well-constrained ages. These results are presented and discussed in the following section. Analytical procedures follow the methods of Vannay and Hodges (1996) and Hodges et al. (1994), and are given in appendix A. Results are summarized in Table 3.2. Complete incremental heating data,

biotite and hornblende plateau and isochron diagrams, and SEM chemical analyses of the samples can be found in appendices B, C and D, respectively.

3.4.2 Muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ results

Footwall samples within the high-strain zone

Muscovites from three samples (L95-116, L95-117 and L95-119) collected in the immediate footwall of the Annapurna detachment yielded flat release spectra with plateau ages ranging from 15.7 ± 0.2 to 13.5 ± 0.1 Ma (Figure 3.9A, B and C). Inverse isochron ages fall within uncertainty of the plateau ages and range from 15.5 ± 0.3 to 13.4 ± 0.2 Ma. Samples L95-116 and L95-117 have well constrained, near modern day atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ ratios of 324 ± 23 and 300.3 ± 5.6 defined through regression analysis (modern atmosphere = 295.5), with MSWD of 0.86 and 1.31, respectively. Sample L95-119 has a less precise isochron age because most data cluster near the $^{39}\text{Ar}/^{40}\text{Ar}$ axis, resulting in poorly constrained initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio. We therefore choose to rely on the plateau age (with 84.4% of the total ^{39}Ar released) for sample L95-119.

Hanging-wall samples within the high-strain zone

Hanging-wall samples (L94-10 and L95-104) yielded flat plateau ages of 12.8 ± 0.3 and 12.1 ± 0.1 Ma, respectively, with 61.6 and 100% of the total ^{39}Ar released (Figure 3.9D and E). The isochron ages are similar at 12.7 ± 0.4 and 11.8 ± 0.4 Ma using all the increments in the regression calculation. In both samples, the initial atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ ratio is well constrained and is close to the present day atmosphere (320 ± 20 and 331 ± 54 , respectively).

Hanging-wall sample above the high-strain zone

Sample L95-143, collected 8 km structurally above the trace of the Annapurna detachment, yielded a well defined plateau age of 17.9 ± 0.4 Ma (100% of ^{39}Ar) (Figure 3.9F). The isochron age of 18.1 ± 0.7 Ma is within uncertainty of the plateau age, and shows no evidence for excess Ar, with an initial atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 286 ± 29 defined through regression analysis.

3.4.3 Summary of muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ results

The three footwall samples yielded muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages between 15.5 ± 0.3 Ma and 13.4 ± 0.2 Ma. There is no correlation between the age and the structural position of the samples within the Greater Himalayan metamorphic sequence. These ages coincide with the data obtained by Vannay and Hodges (1996), and support a homogeneous cooling through the muscovite closure temperature of the metamorphic core between 15 and 13 Ma. The immediate hanging-wall rocks yielded younger ages, between 12.7 ± 0.4 Ma and 11.8 ± 0.4 Ma, testifying for rejuvenation of the $^{40}\text{Ar}/^{39}\text{Ar}$ systematics within the high-strain zone. Since brittle faults are present within the Annapurna detachment zone (Chapter 2), and the Thakkhola graben faults appear to terminate at the Annapurna detachment (Hurtado and Hodges, 1998), it is proposed that these young ages reflect hydrothermal circulation during the brittle stages of extension related to the D₄ structural phase (see chapter 2). Finally, the sample lying at the highest structural level yielded the oldest age (18.1 ± 0.7 Ma). Since S₃-related muscovite is present in this sample and in the surrounding outcrops, this cooling age is interpreted to

reflect the minimum age of formation of third-generation kink folds affecting the Tethyan sedimentary sequence (F_3 ; see also chapter 2).

3.5 DISCUSSION

Table 3.3 summarizes the isotopic ages obtained in this study. These data bring additional constraints to the timing of the various structural events that affected rocks from the upper Kali Gandaki valley, as described in chapter 2.

3.5.1 Implication for the age of Formation III

The protolith age of the Greater Himalayan metamorphic sequence is generally regarded to be Precambrian to early Paleozoic (Colchen et al., 1986). The crystallization and magmatic age of the Formation III leucogranitic augen gneiss obtained in this study is interpreted to be 484 ± 9 Ma and is within error of the Rb-Sr age published by Le Fort et al. (1986b). Hodges et al. (1996) dated a similar granitic orthogneiss of Formation III from the Modi Khola drainage. Their study showed zircons linearly regressing to $502 \pm 21/-15$ Ma, and monazites clustering around 36 Ma. Although their data revealed complicated U-Pb systematics, they support an early Paleozoic magmatic age for the source of the zircons, and an overprinting magmatic and/or thermal event occurring during the Oligocene period. In light of the data presented in this chapter, and of the data presented by Le Fort et al. (1986b) and Hodges et al. (1996), it is proposed that the Formation III augen gneiss is Late Cambrian to Early Ordovician. Furthermore, detrital zircon populations in Formation I equivalent rocks from the Langtang area of central Nepal indicate a maximum depositional age for their sedimentary protolith of *ca.* 980 Ma

(Parrish and Hodges, 1996). Considering that there is limited evidence for any structural disruption within the metamorphic sequence and that the sequence is generally viewed as a conformable one (Colchen et al., 1986), it seems plausible that the Greater Himalayan metamorphic sequence represents a maximum depositional range of 980 Ma to 484 Ma.

As suggested by Le Fort et al. (1986b), the leucogranitic gneiss of Formation III could be part of an important *ca.* 500 Ma plutonic belt which encompasses part of eastern Gondwana, from Afghanistan to Antarctica. The initial very high Sr isotope ratios imply a large contribution of evolved material with limited mantle contribution (Le Fort et al., 1986b). This belt could be considered as a “megazone of crustal extension and thinning along which the lower crust melted to a fair amount in rather dry conditions” (Le Fort et al., 1986b).

3.5.2 Implication for Eohimalayan metamorphism and Oligocene crustal thickening

The results presented in this chapter support a growing body of evidence indicating that an important thermal event affected the upper part of the Greater Himalayan metamorphic sequence during Oligocene time (Table 3.4). Monazites from three different samples yielded linear regressions or concordant fractions within error of each other at *ca.* 34 Ma. Furthermore, most previous evidence for the existence of an Eohimalayan event relied on petrographic observations from the base of the Greater Himalayan metamorphic sequence and no direct U-Pb geochronologic data had been obtained to relate high-pressure metamorphism with the Oligocene period (Hodges et al., 1988a; Pêcher, 1989). The kyanite-bearing leucosome (L96-221b), which yields an interpreted crystallization age of 35 ± 3 Ma, thus provides the first firm indication of

Oligocene kyanite-grade metamorphism affecting the Greater Himalayan metamorphic sequence. Other ages obtained in central Nepal that support an Eohimalayan magmatic or metamorphic event include a U-Pb monazite age of 36.3 ± 0.4 Ma from Formation III orthogneiss of the Modi Khola section 30 km east of the Kali Gandaki (Hodges et al., 1996). Migmatites from the top of the Greater Himalayan metamorphic sequence in the Marsyandi valley also show a clear indication of an Oligocene monazite crystallization event that may be related to Eohimalayan metamorphism (Coleman, 1996b).

The cause of the Eohimalayan Oligocene thermal event remains unclear. Geothermobarometric estimates indicate that the rocks from the uppermost part of the metamorphic core of the Kali Gandaki valley equilibrated at temperatures reaching $600 \pm 40^\circ\text{C}$, and at a depth between 30 and 40 km (Vannay and Hodges, 1996). The metamorphic core must have been buried to these depths during Oligocene time, before being thermally overprinted by well constrained Miocene events. Since the overlying Tethyan sedimentary sequence averages 10 km in stratigraphic thickness (Bordet et al., 1971; Colchen et al., 1986), over 15 km of thickening of the cover sequence is required to account for the burial of the uppermost metamorphic core. Early nappe structures in the overlying Tethyan sedimentary sequence such as the Fang nappe could be associated with underthrusting of the Greater Himalayan metamorphic sequence to these depths (Vannay and Hodges, 1996; Coleman, 1996b). Another model proposes that the Oligocene history was dominated by bulk crustal thickening within the Tethyan sedimentary sequence without the “formation of major compensational structures” (Hodges et al., 1996). However, the 10 kilometer-thick Tethyan sedimentary sequence preserved in the hanging wall of the Annapurna detachment is folded by megascopic, second-generation,

northeast-verging folds such as the Nilgiri anticline. A third model implies that these folds occurred prior to extension along the Annapurna detachment and could account for as much as 15 km of thickening within the cover sequence (Godin et al., 1999b). Growth of an Oligocene structural fan could have thickened the overlying Tethyan sedimentary sequence to 25 km, provoking kyanite-grade melting at deeper structural levels (Godin et al., 1999b; see also chapter 4). Although somewhat contrasting, all three proposed models have two important common observations. (1) The Greater Himalayan metamorphic sequence was underthrust below the over-riding Tethyan sedimentary sequence during Oligocene time, and (2) this underthrusting occurred under a thickening Tethyan sedimentary sequence. The boundary conditions under which this thickening took place remain poorly understood.

3.5.3 Implication for the timing of exhumation of the metamorphic core

In the central Nepal Himalaya, Miocene leucogranites have been found in the Kali Gandaki valley (Nazarchuk, 1993), in the Modi Khola drainage (Hodges et al., 1996), in the Manaslu area (Copeland et al., 1990; Guillot et al., 1994; Harrison et al., 1995), and in the Marsyandi valley (Coleman, 1996b). Although some constitute extensive intrusion complexes, such as the Manaslu leucogranite, most are in the form of smaller granitic bodies and leucosomes. The weakly deformed leucogranitic dike (L95-123e) intruding in the immediate hanging wall of the Annapurna detachment yielded reversely concordant monazites between 23 and 22.5 Ma, which suggests that the extensional ductile strain of the high-strain zone (D_t ; Godin et al., 1999a; see also chapter 2) terminated at *ca.* 22.5 Ma, in agreement with regional correlation that indicates that the South Tibetan

detachment system was active during Early Miocene. Nazarchuk (1993) dated two other leucogranitic bodies lying in the hanging wall of the Main Central thrust, within the Greater Himalayan metamorphic core of the Kali Gandaki valley. Both samples yielded interpreted Miocene crystallization ages of 22.5 ± 0.1 Ma and 21.0 ± 0.5 Ma, bracketing the age of ductile thrust-related fabrics in the Kali Gandaki valley between 22.5 and 21 Ma. It therefore appears that by 21 Ma, major ductile motion had occurred on both the Main Central thrust and the Annapurna detachment.

The $^{40}\text{Ar}/^{39}\text{Ar}$ work from this chapter, combined with that of Vannay and Hodges (1996), reveals that muscovite cooling ages from the lowest to the highest structural level in the Greater Himalayan metamorphic sequence are between 15.5 ± 0.3 Ma and 13.0 ± 0.3 Ma (Figure 3.10). In the Greater Himalayan metamorphic sequence of the Kali Gandaki valley, retrograde Neohimalayan metamorphism reached 540°C to depths of 24 km (Vannay and Hodges, 1996). U-Pb data for leucogranites and migmatitic leucosomes from the same area indicate that anatectic melting and Neohimalayan metamorphism peaked between 22.5 ± 0.1 Ma and 21.5 ± 0.5 Ma (Nazarchuk, 1993). The muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages are therefore interpreted as representing cooling through $330\text{--}430^\circ\text{C}$ between 15 Ma and 13 Ma following Miocene Neohimalayan metamorphism. The lack of $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age variation with respect to structural level supports the fact that the Greater Himalayan metamorphic sequence cooled homogeneously. This supports field evidence that there has been limited structural disruption of the metamorphic core since the Middle Miocene in the Kali Gandaki valley and that the sequence thermally behaved in a homogeneous fashion during its exhumation. It follows that the D_3 -related shear zones discussed in chapter 2 (Kalopani and Modi Khola shear zones) are at least 15 Ma

old, but younger than the latest ductile motion on the Annapurna detachment constrained at *ca.* 22.5 Ma.

Compilation of the available isotopic data from the Annapurna area (Figure 3.11) indicates that the Greater Himalayan metamorphic sequence was affected by crustal thickening prior to 35 Ma, leading to Eohimalayan Oligocene metamorphism. Following a 15 Ma period, the Himalayan metamorphic core started exhuming in Early Miocene. The cooling rate at which this exhumation occurred averages 25°C/Ma and is comparable with other rates obtained in the Everest and Manaslu regions (see review in Searle, 1995).

3.5.4 Implication for the age of the Thakkhola graben

Although there seems to be consistency in the thermal history of the Greater Himalayan metamorphic sequence along the length of the Nepal Himalaya, there is a clear contrast in the thermal regime within the lowermost Tethyan sedimentary sequence. In the Marsyandi valley, phlogopites and biotites sampled in the immediate hanging wall of the Chame detachment, the lateral equivalent of the Annapurna detachment, yielded cooling ages between 29 Ma and 27 Ma (Coleman, 1996b; Coleman and Hodges, 1998), which are interpreted as preserved Eohimalayan ages. In contrast, muscovites from the immediate hanging-wall rocks of the Annapurna detachment in the Kali Gandaki yielded younger ages of *ca.* 13-12 Ma, indicating the presence of a younger thermal overprint.

The hanging-wall rocks of the Annapurna detachment in the vicinity of Kalopani are affected by brittle faults related to the Thakkhola graben system (D₄ of chapter 2), which do not extend structurally lower in the Greater Himalayan metamorphic sequence (Brown and Nazarchuk, 1993; Hurtado and Hodges, 1998). Instead, it appears that D₄

brittle deformation is transferred to the Annapurna detachment, where west-striking brittle faults are observed (Chapter 2). These west-striking features are thought to represent the present-day southern termination of the Thakkhola graben (Godin et al., 1999a; Chapter 2). Furthermore, in the Marsyandi valley, Coleman and Hodges (1995) obtained $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 14.2 ± 0.9 Ma and 14.1 ± 0.9 Ma from hydrothermal muscovites that were collected from extensional fractures related to the Thakkhola graben system. It is therefore proposed that the young (*ca.* 13-12 Ma) muscovite ages obtained in the immediate hanging wall of the Annapurna detachment reflect the timing of D₄ brittle extension related to the Thakkhola graben. It is highly probable that late hydrothermal activity associated with this brittle event has contributed in resetting the Ar systematics of the rocks from the immediate hanging wall of the Annapurna detachment. The Tethyan sedimentary sequence/Greater Himalayan metamorphic sequence contact is characterized by a strong rheological contrast in rock types, between psammites and leucogranitic augen gneisses. This anisotropy might have favored the localization of brittle faulting at the base of the Tethyan sedimentary sequence, thus limiting the extent of graben-related faults and associated thermal rejuvenation of the muscovites within the Greater Himalayan metamorphic sequence. These interpretations support the suggestion of Coleman and Hodges (1995) that the Tibetan plateau had to be uplifted by Middle Miocene time.

3.5.5 Implication for the timing of the northeast-verging folds

Some of the most spectacular structural features preserved in the hanging wall of the Annapurna detachment are megascopic northeast-verging F₂ folds. Since the

pioneering work of French researchers in the Dhaulagiri-Annapurna range of central Nepal (Bordet et al., 1971; Caby et al., 1983), these folds have been interpreted as the result of gravity-induced sliding along the South Tibetan detachment system (Burchfiel et al., 1992 and references therein). More recently, Brown and Nazarchuk (1994) and Godin et al. (1999b) questioned this interpretation for central Nepal. As an alternative, they proposed that the northerly verging folds could result from an early period of compression and crustal thickening related to the growth of an Oligocene structural fan. Although there is structural evidence that these folds predate the main ductile motion on the South Tibetan detachment system (Guillot et al., 1993; Godin et al., 1999a), there are no absolute isotopic constraints on the age of these folds.

Muscovites extracted from a sample containing S_2 axial planar cleavages from the upper Ordovician strata of the Tethyan sedimentary sequence yielded a cooling age of 18.1 ± 0.7 Ma. This age is to be interpreted with caution. Throughout the Tethyan sedimentary sequence, conspicuous S_3 crenulation cleavage and related kink folds are observed (Chapter 2). This is particularly true for the Paleozoic strata, where D_3 deformation is also related with localized southwest-verging thrust-sense shear zones (Figure 2.12). Since the D_3 deformation is pronounced in the Ordovician units, it is proposed that the 18.1 ± 0.7 Ma muscovite age obtained for sample L95-143 represents the timing of D_3 deformation.

The timing of the F_2 northeast-verging folds is constrained indirectly. It has been shown in chapter 2 that the ductile fabric associated with the high-strain zone of the Annapurna detachment transposed the older S_2 schistosity. Given the fact that the interpreted minimum age for ductile motion on the Annapurna detachment is *ca.* 22 Ma,

it follows that the F_2 folds had to be developed well before the Early Miocene. This interpretation is supported by the fact that the *ca.* 22 Ma Manaslu granite to the east also postdates F_2 northeast-verging folds (Guillot et al., 1993, 1994).

3.6 CONCLUSIONS

1. The Formation III augen gneiss from the Greater Himalayan metamorphic sequence has an interpreted magmatic and crystallization age of 484 ± 9 Ma. Pelites in the vicinity of the augen gneiss also contain Ordovician monazites, suggesting a preserved Ordovician metamorphic/thermal event in the uppermost Greater Himalayan metamorphic sequence of central Nepal.

2. There is clear evidence of a preserved Oligocene thermal event in the Kali Gandaki valley. U-Pb dating of monazites and zircons from the uppermost Greater Himalayan metamorphic sequence yielded lower intercept ages of *ca.* 34 Ma. This thermal event is interpreted to coincide with kyanite-grade Eohimalayan metamorphism within the Greater Himalayan metamorphic sequence and crustal thickening within the Tethyan sedimentary sequence. A possible mechanism for this thickening is the growth of an Oligocene fan structure that produced northeast-verging folds in the Tethyan sedimentary sequence (see Chapter 4).

3. A weakly deformed leucogranitic dike intruding into the immediate hanging wall of the Annapurna detachment yielded reversely discordant monazites between 23 and 22.5 Ma, which suggests that the ductile strain of the detachment terminated at *ca.* 22 Ma.

4. Following a 15 Ma period, exhumation and cooling of the Greater Himalayan metamorphic sequence initiated at *ca.* 22 Ma. Rapid tectonic exhumation resulting from extensional faulting along the Annapurna detachment cooled the entire metamorphic core through the muscovite Ar closure temperature (330-430°C) between 15 and 13 Ma.

5. Late thermal activity in the immediate hanging wall of the Annapurna detachment affected muscovites within the high-strain zone. These muscovites yielded younger $^{40}\text{Ar}/^{39}\text{Ar}$ ages between 13 and 11 Ma. It is proposed that brittle extensional motion related with the Thakkhola graben system is related to this late thermal activity.

Table 3.1: U-Pb analytical data from the upper Kali Gandaki valley, central Nepal

Fraction ^a	wt. ^b mg	U ppm	Pb ^c ppm	²⁰⁶ Pb/ ²⁰⁴ Pb ^d	Pb ^{ee} pg	²⁰⁸ Pb/ ²⁰⁶ Pb ^e	²⁰⁶ Pb/ ²³⁸ U ^f	²⁰⁷ Pb/ ²³⁵ U ^f	²⁰⁷ Pb/ ²⁰⁶ Pb ^f	²⁰⁶ Pb/ ²³⁸ U Ma ^f	²⁰⁷ Pb/ ²³⁵ U Ma ^f	corr. ^g coef.	²⁰⁷ Pb/ ²⁰⁶ Pb Ma ^f
<i>LG95-123e, crosscutting leucogranitic dike, Amapurna Formation, Kalopani</i>													
M1 (1) f	0.0020	6377	68	185	13	2.348	0.0036 ± 0.43	0.0228 ± 1.83	0.0455 ± 1.58	25.4 ± 0.2	22.9 ± 0.8	0.65	-28.1 ± 77.0
M2 (5) r	0.0020	7654	101	181	22	3.095	0.0037 ± 0.40	0.0223 ± 1.65	0.0438 ± 1.42	23.7 ± 0.2	22.4 ± 0.7	0.66	-124.0 ± 69.5
M3 (6) r	0.0040	8189	107	395	20	2.412	0.0043 ± 0.27	0.0279 ± 0.78	0.0466 ± 0.63	28.0 ± 0.2	28.0 ± 0.4	0.64	28.1 ± 30.5
Z1 (10) eq	0.0200	8397	123	2149	81	0.034	0.0151 ± 0.19	0.1312 ± 0.26	0.0630 ± 0.14	96.7 ± 0.4	125.2 ± 0.6	0.85	706.6 ± 5.8
Z2 (20) el	0.0100	2395	19	1217	12	0.056	0.0083 ± 0.36	0.0731 ± 0.48	0.0641 ± 0.31	53.1 ± 0.4	71.6 ± 0.7	0.76	744.7 ± 13.0
<i>LG96-208, Granitic gneiss, Fm. III, Kalopani</i>													
M1 (23) r	0.1600	3370	242	5330	133	2.921	0.0209 ± 0.62	0.1552 ± 0.72	0.0598 ± 0.34	133.1 ± 1.6	146.5 ± 2.0	0.88	370.1 ± 15.5
M2 (68) r	0.1900	2620	135	2892	113	4.802	0.0101 ± 0.27	0.0718 ± 0.31	0.0515 ± 0.14	64.9 ± 0.4	70.4 ± 0.4	0.89	261.7 ± 6.5
M3 (1) f	0.0090	3405	32	1395	8	0.717	0.0061 ± 0.56	0.0412 ± 0.86	0.0488 ± 0.60	39.4 ± 0.4	41.0 ± 0.7	0.72	138.6 ± 28.5
Z1 (42) el	0.1480	676	44	25515	17	0.040	0.0693 ± 0.24	0.5395 ± 0.26	0.0565 ± 0.10	431.7 ± 2.0	438.1 ± 1.9	0.92	471.8 ± 4.6
Z2 (1) el	0.0300	883	125	18678	12	0.138	0.1354 ± 0.18	1.4920 ± 0.21	0.0799 ± 0.09	818.6 ± 2.8	927.1 ± 2.5	0.89	1195.0 ± 3.7
Z3 (32) eq	0.0720	1065	70	21889	15	0.046	0.0694 ± 0.17	0.5434 ± 0.18	0.0568 ± 0.05	432.6 ± 1.4	440.7 ± 1.3	0.96	482.8 ± 2.4
Z4 (2) eq	0.0400	906	71	17176	11	0.065	0.0802 ± 0.16	0.7064 ± 0.17	0.0639 ± 0.07	497.5 ± 1.5	542.6 ± 1.5	0.93	737.2 ± 2.8
<i>LG96-221b, Kyanite-bearing leucosome, Fm. III, Taglung</i>													
M1 (7) r	0.0487	23158	1673	10822	174	2.030	0.0271 ± 0.32	0.2052 ± 0.33	0.0550 ± 0.07	172.2 ± 1.1	189.5 ± 1.1	0.98	411.2 ± 3.2
M2 (63) r	0.1556	27470	1931	12735	483	2.440	0.0233 ± 0.74	0.1752 ± 0.75	0.0546 ± 0.08	148.2 ± 2.2	164.0 ± 2.3	0.99	97.5 ± 3.4
M3 (29) f	0.0876	41584	1426	5792	487	2.121	0.0125 ± 0.57	0.0904 ± 0.58	0.0525 ± 0.07	80.0 ± 0.9	87.9 ± 1.0	0.99	305.9 ± 3.6
M4 (1) f	0.0023	37341	7262	9749	36	2.383	0.0654 ± 0.29	0.5037 ± 0.31	0.0559 ± 0.13	408.2 ± 2.3	414.2 ± 2.1	0.92	447.3 ± 5.6
Z1 (11) eq	0.0500	3394	47.93	3732	51	0.002	0.0156 ± 0.19	0.1145 ± 0.21	0.0533 ± 0.09	99.6 ± 0.4	110.1 ± 0.4	0.91	343.0 ± 4.0
Z2 (10) el	0.0400	2167	35.24	2250	53	0.003	0.0179 ± 0.19	0.1324 ± 0.22	0.0536 ± 0.10	114.4 ± 0.4	126.2 ± 0.5	0.90	355.2 ± 4.5

Table 3.1: (continued)

Fraction ^a	wt. ^b mg	U ppm	Pb ^c ppm	$^{206}\text{Pb}^d$ ^{204}Pb	Pb ^{c,e} pg	$^{208}\text{Pb}^e$ ^{206}Pb	$^{206}\text{Pb}^f$ ^{238}U	$^{207}\text{Pb}^f$ ^{235}U	$^{207}\text{Pb}^f$ ^{206}Pb	$^{206}\text{Pb}^f$ ^{238}U Ma	$^{207}\text{Pb}^f$ ^{235}U Ma	corr. ^g coef.	$^{207}\text{Pb}^f$ ^{206}Pb Ma
<i>LG96-221c, Sillimanite-bearing pelitic schist, Fm. III, Taglung</i>													
M1 (1) r	0.0114	12439	143.2	1588	29	1.515	0.0052 ± 0.19	0.0334 ± 0.27	0.0466 ± 0.16	33.4 ± 0.1	33.4 ± 0.2	0.80	30.3 ± 7.9
M2 (1) eq	0.0103	13016	163.2	1950	27	1.301	0.0062 ± 0.21	0.0407 ± 0.27	0.0478 ± 0.15	39.7 ± 0.2	40.5 ± 0.2	0.82	89.8 ± 7.3
M3 (1) r	0.0034	10677	192.9	1205	11	2.428	0.0060 ± 0.22	0.0398 ± 0.51	0.0481 ± 0.43	38.6 ± 0.2	39.7 ± 0.4	0.55	103.7 ± 20.5

^a M, monazite; Z, zircon; (3), indicates number of grains analyzed; eq=euhedral and equant; el=euhedral and elongate; f=fragment; r=round.

^b Weighing error = 0.001 mg.

^c Radiogenic Pb.

^d Measured ratio, corrected for spike and Pb fractionation of 0.13% ± 0.03%/AMU.

^e Total common Pb in analysis corrected for fractionation and spike.

^f Corrected for blank Pb and U, and common Pb (Stacey-Kramers model Pb composition equivalent to the interpreted age of the individual minerals); errors at 1 standard error of the mean in percent for ratios and 2 standard errors of the mean when expressed in Ma.

^g Correlation coefficient between the two radiogenic Pb/U ratios.

Table 3.2: Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ results^a from the Kali Gandaki valley

Sample	Mineral	Plateau age (Ma) ^b	^{39}Ar (%) ^c	Isochron age (Ma) ^d	^{39}Ar (%) ^e	$(^{40}\text{Ar}/^{36}\text{Ar})_0$	MSWD ^g
L94-10	Ms	12.8 ± 0.3	61.6	12.7 ± 0.4	100	320 ± 20	1.45
L95-104	Ms	12.1 ± 0.1	100	11.8 ± 0.4	100	331 ± 54	1.47
L95-116	Ms	15.7 ± 0.2	98.5	15.5 ± 0.3	100	324 ± 23	0.86
L95-117	Ms	13.5 ± 0.1	74.9	13.4 ± 0.2	100	300.3 ± 5.6	1.3
L95-119	Ms	14.3 ± 0.2	84.4	13.9 ± 0.4	67	359 ± 47	1.66
L95-143	Ms	17.9 ± 0.4	100	18.1 ± 0.7	100	286 ± 29	1.48
L94-10	Bt	27.1 ± 0.2	88.2	27.3 ± 0.6	75	281 ± 39	1.39
L95-110	Bt	14.5 ± 0.3	100	14.5 ± 0.3	100	293 ± 16	1.21
L95-116	Bt	22.2 ± 0.2	72	22.1 ± 0.3	100	277.7 ± 8.6	1.66
L95-119	Bt	13.0 ± 0.2	100	13.1 ± 0.2	100	289 ± 11	0.74
L95-123	Hbl	no plateau	n/a	no isochron	n/a	n/a	n/a
L95-123	Hbl	no plateau	n/a	52.1 ± 8.1	69	1170 ± 880	1.03

Note: ^aAll uncertainties quoted at the 2 σ confidence level. For each sample, the interpretation of the best apparent age is shown in bold. ^bCalculated following methods outlined in Hodges et al. (1994). ^cPercentage of total ^{39}Ar in the sample that was released in the heating steps included in the plateau. ^dCalculated using a least squares linear regression with correlated errors (York, 1969). ^ePercentage of total ^{39}Ar in the heating steps used for the regression. ^gMean squared weighted deviation. Ms, muscovite; Bt, biotite; Hbl, hornblende.

Table 3.3: Timing of tectonic events in the upper Kali Gandaki valley

Timing	Thermal and/or magmatic event	Structural event
<i>ca.</i> 14-12 Ma to present	- Hydrothermal circulation within the high-strain zone of the Annapurna detachment	- Brittle deformation related to the Thakkhola graben (D ₄)
<i>ca.</i> 15-13 Ma	- Homogeneous cooling of the Greater Himalayan metamorphic sequence, without any major structural disruption (see also Vannay and Hodges, 1996)	
between 22 Ma and 15 Ma	- Thermal overprinting within the high-strain zone of the Annapurna detachment (Godin et al., 1999a)	- Renewed southwest-verging deformation in the Tethyan sedimentary sequence (D ₃), and out-of-sequence thrusting in the Greater Himalayan metamorphic sequence
<i>ca.</i> 23-22.5 Ma	- Late kinematic leucogranitic dike, Neohimalayan metamorphism (Hubbard and Harrison, 1989)	- Late stages of ductile extensional deformation related to the Annapurna detachment (D ₁)
<i>ca.</i> 35 Ma	- Kyanite-grade Eohimalayan metamorphism and leucosome production	- Northeast-verging folding in the Tethyan sedimentary sequence (D ₂)
between 45 Ma and 35 Ma (?)		- Early nappe structures in the Tethyan sedimentary sequence (D ₁)
<i>ca.</i> 52-45 Ma	India-Asia collision (Rowley, 1998 and references therein)	
<i>ca.</i> 484 Ma	- Crystallization age of Formation III augen gneiss and metamorphism of surrounding pelites	- Crustal extension and thinning (Le Fort et al., 1986b)

Table 3.4: Summary of evidence for Oligocene events in the Himalaya

Type of evidence	Description	Reference
Petrographic-metamorphic	- Pre-Miocene, pre-MCT Barrovian-type metamorphism (eastern, central and western Himalaya)	Brunel and Kienast, 1986; Hodges et al., 1988a; Pêcher, 1989; Searle and Rex, 1989
Structural	- Early thrust stacking and related compressional structures which occurred subsequent to the mid-Eocene collision and suturing but initiated before development of the Miocene MCT - Pre-STDS folding of the Tethyan sedimentary sequence (central Nepal)	Burg and Chen, 1984; Searle, 1986; Searle et al., 1988; Patel et al., 1993; Steck et al., 1993 Godin et al., 1999a,b
Geochronologic	- 38 Ma hornblende cooling ages obtained in the GHMS (northwest Himalaya) - 25 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende age from uppermost GHMS (Dinggyê area of southern Tibet, eastern Himalaya) - Initiation of uplift/exhumation of the Himalaya and onset of foreland basin sedimentation at ca. 35 Ma - 35-36 Ma monazite ages in Fm. III, GHMS (central Nepal) - 37 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende age from Fm. III, GHMS (central Nepal) - Monazites with ca. 35 Ma inherited component from Fm. III, GHMS (central Nepal) - 27 to 30 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ phlogopite and biotite cooling ages from the lower TSS (central Nepal) - 35 Ma monazite age from a kyanite-bearing leucosome injected in the uppermost GHMS (central Nepal) - 33 to 31 Ma monazite ages from Fm. III, GHMS (central Nepal)	Treloar et al., 1988 Hodges et al., 1994 Najman et al., 1994 Hodges et al., 1996 Vannay and Hodges, 1996 Coleman, 1996a; Coleman and Hodges, 1998 Godin et al., 1999b; this study

Figure 3.1: Geologic map of central Nepal, simplified and modified after Colchen et al. (1981): GHMS, Greater Himalayan metamorphic sequence; MCT, Main Central thrust; Sct Fm, Sanctuary Formation; STDS, South Tibetan detachment system; TSS, Tethyan sedimentary sequence; box locates the study area and Figure 3.2.

Figure 3.2: Detailed lithologic map of the upper Kali Gandaki valley showing location of samples used for U-Pb geochronology and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology. A-A' locates the section line of Figure 3.3. AD, Annapurna detachment; MCT, Main Central thrust.

Figure 3.3: Northeast-southwest geologic cross section showing the distribution of samples used for U-Pb geochronology and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology. The section line is indicated on Figure 3.2. AD, Annapurna detachment; MCT, Main Central thrust; asl, above sea level.

Figure 3.4: A: Outcrop photograph of sample L96-208. B: Concordia plot for sample L96-208 with a York linear regression line at mswd of 1.66 through the discordant monazite data. The upper intercept of 483.6 ± 9.1 Ma is interpreted as the magmatic crystallization age of the granitic gneiss, and the lower intercept of $31.5 +2.7/-3.0$ Ma is interpreted as the age of an Oligocene thermal event. mswd, mean squared weighted deviation. See text for explanation and discussion of data.

B

Figure 3.5: Outcrop photograph of station L96-221 showing sample location of L96-221b and L96-221c. Kyanite is present throughout the outcrop, and coexists with sillimanite in the pelitic schist and in some leucosomes.

Figure 3.6: A: Concordia plot of sample L96-221c with a York linear regression line at mswd of 4.53 through the discordant monazite data. B: Concordia plot of sample L96-221b with a York linear regression line at mswd of 8.76 through the discordant monazite and zircon data. A regression line through just the monazite data yields a mswd of 0.1, with an upper and lower intercept of 466.4 ± 4.7 Ma and 36.3 ± 1.3 Ma, respectively. mswd, mean squared weighted deviation. See text for explanation and discussion of data.

Figure 3.7: A: Outcrop photograph of station L95-123, where sample L95-123e was collected. The leucogranitic dike is injected through Formation III calc-silicate gneisses and Annapurna Formation psammites, all within the high-strain zone related to the Annapurna detachment. Bt, biotite; Di, diopside; Grt, garnet; Hbl, hornblende; Ms, muscovite. The high-strain zone fabric (S_1) is indicated. B: Concordia plot of sample L95-123e. M-1 is a single grain analysis, whereas M-2 and M-3 are multigrain analyses. The ages indicated are $^{207}\text{Pb}/^{235}\text{U}$ ages. See text for explanation and discussion of data.

Figure 3.8: Photomicrograph of sample L95-143 showing S_2 muscovite crenulation cleavage developed in the Nilgiri Formation limestone, affected by S_3 crenulations. Cross polars. S_{0-1} , S_2 and S_3 are indicated. Cal, calcite; Ms, muscovite.

Figure 3.9: A to F: $^{40}\text{Ar}/^{39}\text{Ar}$ release spectra and inverse isotope correlation diagrams of muscovite samples used for thermochronology. The shaded steps within the release spectra indicate the increments used for calculating plateau ages. The shaded squares on the inverse plots indicate which points were used in the linear regression. See text for explanation and discussion of data.

A)

B)

C)

D)

E)

F)

Figure 3.10: Northeast-southwest geologic cross section of Figure 3.3 showing the distribution of muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ isochron ages obtained in the upper Kali Gandaki valley. The section line is indicated on Figure 3.2. AD, Annapurna detachment; MCT, Main Central thrust; asl, above sea level.

Figure 3.11: Temperature-time plot for the uppermost Greater Himalayan metamorphic sequence (GHMS) and the lowermost Tethyan sedimentary sequence (TSS) in the Annapurna area of central Nepal. Kali Gandaki data from Nazarchuk (1993), Vannay and Hodges (1996) and this study; Marsyandi data from Coleman and Hodges (1998); and Modi Khola data from Hodges et al. (1996). The Everest and Manaslu cooling curves are from Searle (1995). The temperature estimates for the Eohimalayan and the Neohimalayan events are taken from Vannay and Hodges (1996). See text for discussion. MCT, Main Central thrust; STDS, South Tibetan detachment system; Ky, kyanite; Sill, sillimanite.

CHAPTER 4

BACKFOLDS IN THE CORE OF THE HIMALAYAN OROGEN: AN ALTERNATIVE INTERPRETATION

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. This chapter proposes 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.

4.1 INTRODUCTION

This chapter 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.* 22 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., 1987b; 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, 1989; Burchfiel et al., 1992; Hodges et al., 1996). Despite recent structural studies in the Ladakh-Zaskar 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., 1999a). 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.

4.2 GEOLOGIC SETTING

From south to north, the Kali Gandaki valley in central Nepal (Figure 4.1) 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 kilometer-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 phases in its structural evolution (Chapter 2; Godin et al., 1999a) represented by the following: (1) southwest-verging isoclinal folds (F_1), (2) northeast-verging, tight, megascopic folds (F_2), (3) transposition of F_1 and F_2 into the extensional north-dipping Annapurna detachment (Brown and Nazarchuk, 1993) and related high-strain zone (D_i ; Godin et al., 1999a), (4) post-peak metamorphic, southwest-verging kink folds (F_3) 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.

In the Annapurna sector, the spectacular F_2 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) (Figure 4.2). 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).

4.3 FOLD GEOMETRY AND RESTORATION

In the Annapurna area, F_2 folds have interlimb angles of 20° to 55° (average 35°). 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. F_2 folds are typically moderately inclined to overturned, with shallow southwest-dipping axial surfaces and gently ($\sim 12^\circ$) east-southeast-plunging axes, with a penetrative axial-plane cleavage (S_2). The general vergence of the fold train is toward the northeast in the lower structural levels, becoming progressively more upright at higher levels. F_2 folds have been observed by the author in reconnaissance studies as far north as Lo Monthang, 75 km from the Annapurna detachment.

Three northeast-trending balanced cross sections (Figure 4.2), 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 Early 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 F_2 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., 1999a). 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 (Figure 4.2).

To help quantify the amount of vertical and horizontal deformation that affected the rocks of central Nepal, two end-member restoration models are presented (Figure 4.3). Model 1 attributes the F_2 folding entirely to drag along the Annapurna detachment. Model 2 assumes that the F_2 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 F_2 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 F_2 folds provides minimum estimates for horizontal and vertical shortening of the Silurian rocks by the F_2 folds of $44\% \pm 8\%$ and $37\% \pm 3\%$, respectively, yielding a minimum fault displacement of 10 km and a minimum throw of 6.4 km (Figure 4.3A). However, field evidence presented in chapter 2 indicates that these geometrical constraints are not the appropriate boundary conditions. The F_2 folds are deflected and transposed by a high-strain zone associated with the Annapurna detachment (Godin et al., 1999a). Accordingly, the F_2 fold system may have

been generated prior to ductile normal faulting. Furthermore, as noted above, the F_2 folds extend well to the north of the Annapurna detachment. It is therefore suggested that the F_2 folds formed during a pre-detachment compressional event and that bedding was nearly horizontal prior to folding (Figure 4.3B). Restoring these folds to a pre-faulting orientation undoes the rotational effect that the Annapurna detachment had on the axial surfaces. Applying the above restoration method yields minimum estimates of $43\% \pm 7\%$ horizontal shortening and $\sim 150\%$ 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/exhumation calculated for the footwall rocks of the detachment (Vannay and Hodges, 1996).

4.4 TIMING

Detailed structural mapping has demonstrated that the stratigraphy and the D_1 and D_2 structures affecting the Tethyan sedimentary sequence are cut and completely transposed into the ductile high-strain zone associated with the Annapurna detachment (Chapter 2; Godin et al., 1999a) and, as noted, that the northeast-verging F_2 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 this 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, 1996b; Hodges et al., 1996; Vannay and Hodges, 1996; Coleman and Hodges, 1998; Chapter 3). However there are no unequivocal constraints on potential pre-Miocene kyanite-grade metamorphism. 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 has been obtained (Figure 4.4; see also Chapter 3). This age is interpreted to be the time of magmatic crystallization of the leucosome during kyanite-grade metamorphism. This age is considered 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 (see chapter 3). 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., 1986b).

4.5 ALTERNATIVE DYNAMIC MODEL

A testable alternative model is proposed to explain the presence of northeast-verging folds in the hanging wall of the Annapurna detachment (Figure 4.5), 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).

It is envisaged 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-Zaskar 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 detachment system, leucogranite production, and high-temperature and lower-pressure Neohimalayan metamorphism in the Greater Himalayan metamorphic sequence (Deniel et al., 1987b; Hubbard and Harrison, 1989; 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., 1999a), 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).

4.6 DISCUSSION

The proposed compressional model for F_2 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 F_2 folds, and detailed geophysical work that could highlight major structures hidden beneath the floor of the Kali Gandaki valley.

Figure 4.1: 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. (1999a). 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 4.2.

Figure 4.2: 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 F_2 Nilgiri anticline. Abbreviations as in Figure 4.1 except asl = above sea level.

Figure 4.3: 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.

A Model 1: Drag folding related to extensional faulting

B Model 2: Contraction-generated folding

Part 1 - Northeast-verging contraction

Part 2 - Ductile extensional deformation

Figure 4.4: U-Pb concordia diagram for kyanite-bearing leucosome (L96-221b) sampled in immediate footwall of Annapurna detachment, near Kalopani (see Figure 4.1 for location). All monazite (M) and zircon (Z) fractions are multigrain analyses. Inset shows detail of upper intercept, which is interpreted as representing inheritance from country rock. The lower intercept is interpreted as age of leucosome production and kyanite growth. York linear regression at MSWD = 8.76 (MSWD = mean squared weighted deviation).

Figure 4.5: Proposed alternative dynamic model for formation of northeast-verging folds of central Nepal. Stages 1 to 3 correspond to first three phases of structural evolution of Tethyan sedimentary sequence as presented in Godin et al. (1999a). See text for details. AD = Annapurna detachment, GHMS = Greater Himalayan metamorphic sequence, MCT = Main Central thrust, asl = above sea level.

NE

SW

Stage 1: Eocene ? **Stage 2: Late Eocene to Oligocene ?** **Stage 3: Miocene**

CHAPTER 5

CONCLUDING STATEMENT

The Himalayan orogen hosts the world's highest and most dramatic mountains. As one of the most impressive examples of intercontinental collision, it serves as a great natural laboratory to study orogenic processes and remains the most frequent example against which other older orogens are compared.

The previous chapters aimed at providing additional constraints on the tectonic evolution of the Himalayan orogen for the central Nepal region. From this study, the structural evolution of the Tethyan sedimentary sequence is better understood, the timing of the thermal events within the Greater Himalayan metamorphic sequence is better constrained, and a new working hypothesis for the tectonic evolution of the Tethyan sedimentary sequence is proposed. This final chapter summarizes the major results of the thesis and discusses the implications of these new data for future Himalayan research.

5.1 CONTRIBUTION TO HIMALAYAN GEOLOGY

The thesis has contributed to Himalayan research in the fields of structural geology, geochronology and tectonics. As a direct result of this study, five phases of deformation have been recognized within the Tethyan sedimentary sequence, and previously unrecognized features have been described and newly named. These include a 1,500 meter-thick high-strain zone located in the immediate hanging wall of the Annapurna detachment, and an enigmatic structural break termed the Lupra fault.

U-Pb geochronology has confirmed the previously suggested Cambrian-Ordovician age for Formation III, the uppermost unit of the Greater Himalayan metamorphic sequence. Furthermore, monazite U-Pb ages from Formation III indicate an important thermal event during the Oligocene that affected the upper part of the Himalayan metamorphic core in the upper Kali Gandaki valley. This event is interpreted to be linked with crustal thickening related to second-phase northeast-verging folds within the Tethyan sedimentary sequence. This was followed by ductile extension along the Annapurna detachment, which terminated by 22 Ma, as evidenced by a late kinematic dike crosscutting the high-strain zone of the Annapurna detachment. Based on a $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age, renewed southwest-verging deformation is interpreted to occur at *ca.* 18 Ma. $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology on muscovites across the metamorphic core revealed that the timing of exhumation of the metamorphic core through the 370°C isotherm occurred homogeneously between 15 Ma and 13 Ma. Finally, brittle extension related to the north-trending Thakkhola graben is interpreted to have been under way by *ca.* 12 Ma.

The results from the structural and geochronologic studies presented in chapters 2 and 3 support an alternative interpretation for the formation of the spectacular northeast-verging folds visible in the Kali Gandaki valley. In chapter 4, the thesis finally proposes a new model in which the second-phase northeast-verging folds represent the northern part of a late Eocene to Oligocene contractional fan structure, thereby recording some of the earliest contraction of this part of the orogen, which instigated an Oligocene thermal event in the underlying metamorphic core.

5.2 IMPLICATIONS

The data presented in chapter 3 support the idea that the bulk of the sedimentary protolith of the Greater Himalayan metamorphic sequence had a depositional age of 980 Ma to 484 Ma, as previously suggested by Parrish and Hodges (1996) and Parrish et al. (1997). A corollary of this is that there is no evidence in the Kali Gandaki valley for involvement of Indian crystalline basement in the Greater Himalayan metamorphic sequence, and that the metamorphic core does not represent gneissic basement upon which units of the Lesser Himalayan sedimentary sequence were deposited. This has direct implications for palinspastic restoration of the Himalayan orogen. Recent attempts to restore the central part of the orogen have been based on the assumption that the Greater Himalayan metamorphic sequence represents basement for the Lesser Himalayan sedimentary sequence (Schelling and Arita, 1991; Schelling, 1992; Srivastava and Mitra, 1994). In contrast, our data are consistent with the suggestion of Parrish and Hodges (1996) that the sedimentary protoliths of the Greater Himalayan metamorphic sequence were deposited above more distal equivalents of the Lesser Himalayan sedimentary sequence.

A central outcome of the thesis is the proposed Oligocene structural fan accounting for crustal thickening of the Tethyan sedimentary sequence, which in turn instigated thermal events structurally below in the Greater Himalayan metamorphic sequence. This model provides a dynamic link between the Eocene continental collision and the Neohimalayan Miocene events. It is also a first attempt to link the Eohimalayan metamorphism with a distinct tectonic event.

The proposed structural fan model speculates on the existence of an Oligocene décollement surface lying below the Tethyan sedimentary sequence. Such a surface may have been imaged by wide-angle seismic data and termed the Main Himalayan thrust (Makovsky et al., 1996). It has been proposed that the Main Himalayan thrust represents the basal décollement that dips gently northward beneath the Himalaya and the Tethyan belt (Makovsky et al., 1996). Surface geologic data, earthquake, and deep seismic reflection observations imply that the Main Frontal thrust is the tip of the active Main Himalayan thrust (Schelling and Arita, 1991; Ni and Barzangi, 1984; Zhao et al., 1993; Wu et al., 1998). It is possible that the Oligocene décollement surface implied by the structural fan model presented in chapter 4 coincides with the location of the Main Himalayan thrust described by Makovsky et al. (1996), and that the basal décollement surface was active for an extended period of time.

5.3 UNANSWERED QUESTIONS AND FUTURE RESEARCH DIRECTIONS

There remain many unanswered questions pertaining to the geology of the Kali Gandaki valley that can serve as a guide for future research:

1. The kinematics and timing of the Lupra fault are uncertain. Furthermore, the role of the Lupra fault in the evolution of the Thakkhola graben is enigmatic. It is not clear if the fault is a local feature, or if it holds regional significance. Is it confined to the present-day configuration of the Thakkhola graben or does it extend west beyond the Syang peaks?

2. The tectonic evolution of the Thakkhola graben system is far from being completely understood. How do the north-trending features of the Thakkhola graben

system relate kinematically and dynamically with the west-trending brittle features visible near the Annapurna detachment? Does the South Tibetan detachment system mark the transition zone between contrasting strain fields of the extensional Tibetan plateau and the contractional Himalayan frontal zone? If so, how did this transitional zone evolve?

3. Dextral orogen-parallel shearing has been implied by Pêcher (1991) and Vannay and Steck, (1995) to account for the presence of sub-horizontal lineations near the Greater Himalayan metamorphic sequence/Tethyan sedimentary sequence contact. Although there are some horizontal mineral lineations outlined by sillimanite in the Manaslu area (Pêcher, 1991; Guillot et al., 1993), there is no unequivocal field evidence for large-scale dextral shearing in the Kali Gandaki valley. Is there other evidence beside east-west trending sub-horizontal lineations to support the large-scale shearing suggested by Pêcher (1991), or is this shear zone model simply not applicable to the geology of the Kali Gandaki valley?

4. The Kalopani and Modi Khola shear zones are interpreted as out-of-sequence thrusts affecting the uppermost Greater Himalayan metamorphic sequence (Vannay and Hodges, 1996; Hodges et al., 1996). Until very recently, the metamorphic core was perceived as a structurally undisturbed slab (Colchen et al., 1986). The findings of Vannay and Hodges, along with those of Hodges et al. (1996), Reddy et al. (1993) and Davidson (1995) demonstrate the presence of structural discontinuities within the Greater Himalayan metamorphic sequence. How these zones relate to the thermal evolution and exhumation of the metamorphic core remain enigmatic.

5. Of crucial importance to the structural fan model presented in chapter 4 is the absolute age of formation of the F_2 northeast-verging folds. The present knowledge of their age relies on indirect interpretation from crosscutting relationships, and the only attempt to constrain their age isotopically is not conclusive (Chapter 3). Although reconnaissance work in 1994 in the upper Mustang area has permitted the observation of northeast-verging structures, no detailed map or structural data are available for the Tethyan sedimentary sequence north of Kagbeni. Are the F_2 northeast-verging folds preserved as far north as the Indus-Tsangpo suture zone?

6. As presented in chapter 4, an Oligocene structural fan is one possible interpretation to explain the presence of Eohimalayan events in the underlying Greater Himalayan metamorphic sequence. This new model has yet to be tested by the Himalayan geoscientific community. As such, it presents an alternative that proposes a link between the Eocene collision and the Miocene events. A corollary of this model is that the Main Central thrust may have a pre-Miocene history, as proposed by Dewey et al. (1988) and Hodges et al. (1988a). It is also possible that the South Tibetan detachment system marks the location of a pre-Miocene thrust that has been obliterated by Miocene extension. Furthermore, since the major shortening structures in the Himalaya are progressively younger from north to south, it is reasonable to think that there might be a pre-Miocene major thrust somewhere between the Main Central thrust and the Indus-Tsangpo suture zone. Presently, only a handful of studies have focused on complete cross-sections of the Tethyan sedimentary sequence (e.g. Ratschbacher et al., 1994; Searle et al., 1997); the present knowledge of its structural and temporal evolution remains tentative.

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Appendix A. (continued)

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Appendix B: Analytical procedures

U-Pb analytical Method

Heavy mineral concentrates were obtained from 1-5 kg samples by using standard crushing techniques, a Rodger's table and heavy liquids at Carleton University, Ottawa (Canada). Magnetic separation, spiking and data acquisition were performed at the NERC National Isotope Geosciences Laboratory, in Keyworth (U.K.). All mineral separates were hand-picked in alcohol under reflected and plane polarized light. Mineral fractions were chosen based on size, morphology, fractures, inclusions, clarity and visible inheritance seen as cores. Isotopic data were obtained on a VG 354 mass spectrometer in single collector peak jumping mode using an ion-counting Daly detector. The analytical method followed those outlined by Parrish et al., (1987), Parrish and Krogh (1987), Roddick (1987), and Noble et al. (1993). Dead time corrections for the detector were based on numerous measurements of the NIST U500 standard. Pb isotope ratios were corrected for initial common Pb in excess of calculated laboratory blank Pb using a Stacey and Kramers (1975) common Pb evolution model. Laboratory Pb and U blanks were approximately 10-20 and < 0.5 picograms, respectively. Decay constants used are those recommended by Steiger and Jäger (1977).

$^{40}\text{Ar}/^{39}\text{Ar}$ Analytical method

Pure mineral separates were obtained through standard crushing techniques, a Rodger's table, magnetic separation, and "paper shaking" technique. The separates were hand-picked at Carleton University to an estimated purity of > 99 %. Mica samples

weighted an average of 50 mg, whereas hornblende separates averaged 150 mg. The separates were washed in water, acetone and ethanol prior to packaging in Al-foil for irradiation. The samples were irradiated in the McMaster University research reactor, along with synthetic salts and the fluence monitor Fish Canyon sanidine (28.03 Ma; Cebula et al., 1986; Renne et al., 1994). The irradiation parameter J was determined by Ar-ion laser analysis of the monitors.

Gas was extracted from the samples using a double vacuum resistance furnace and analysed on a MAP 215-50 mass spectrometer at MIT. All data were corrected for blank, interfering reactions, and mass fractionation prior to the calculation of model ages or analysis on isotope correlation diagrams. Additional details regarding analytical procedures in the MIT laboratory are found in Hodges et al. (1994). Plateau ages reported in chapter 3 were calculated using the approach recommended by Fleck et al. (1977), and their quoted uncertainties are based on the standard error of the weighted mean age of increments on the plateau. Isochron ages were derived from linear-regression fits to sample increments plotted on the $^{39}\text{Ar}/^{40}\text{Ar}$ vs. $^{36}\text{Ar}/^{40}\text{Ar}$ inverse isochron diagram (Roddick et al., 1980). Fitting procedures followed those recommended by York (1969), and the quoted uncertainties in isochron ages and derived $^{40}\text{Ar}/^{36}\text{Ar}$ ratios include contributions from the error in J , the data scatter about the best-fit line, and analytical uncertainties. Unlike plateau or total gas ages, isochron ages presume no prior knowledge of the initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio; for this reason, the interpretations are based largely on these results.

Appendix C. Plateau and reverse isochron diagrams for biotite and hornblende samples

Appendix C. (continued)

Appendix C. (continued)

Appendix D: $^{39}\text{Ar}/^{40}\text{Ar}$ Incremental heating data

L94-10 Muscovite

J value: $3.51\text{E-}03 \pm 8.76\text{E-}06$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) [†]	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
900	3.13(1.20)	0.448(0.014)	0.041	0.14	7.60	10.70 $\pm$ 49.75
950	2.56(3.05)	0.910(0.031)	0.043	0.30	24.51	16.97 $\pm$ 62.12
1000	2.47(0.64)	0.368(0.010)	0.088	0.61	27.07	46.00 $\pm$ 31.68
1050	2.56(0.79)	1.170(0.011)	0.170	1.22	24.37	13.09 $\pm$ 12.47
1100	0.67(1.64)	2.050(0.018)	0.301	2.29	80.01	24.58 $\pm$ 14.75
1125	1.18(0.82)	2.320(0.020)	0.295	3.34	65.17	17.67 $\pm$ 6.56
1150	1.92(0.45)	1.340(0.009)	0.469	5.02	43.23	20.34 $\pm$ 6.26
1175	2.06(0.12)	1.840(0.004)	2.963	15.58	39.24	13.46 $\pm$ 1.24
1200	0.59(0.18)	3.880(0.010)	4.347	31.09	82.55	13.44 $\pm$ 0.86
1225	0.33(0.19)	4.080(0.013)	2.059	38.43	89.96	13.94 $\pm$ 0.88
1250	0.87(0.25)	3.640(0.013)	1.354	43.26	74.17	12.88 $\pm$ 1.30
1300	1.17(0.32)	3.020(0.012)	1.304	47.91	65.33	13.64 $\pm$ 1.97
1350	0.99(0.17)	3.270(0.010)	1.975	54.96	70.38	13.59 $\pm$ 0.94
1400	0.58(0.10)	4.100(0.010)	5.498	74.56	82.70	12.74 $\pm$ 0.45
1450	0.48(0.13)	4.380(0.016)	2.211	82.45	85.53	12.35 $\pm$ 0.57
1550	0.20(0.33)	4.490(0.015)	2.311	90.69	94.03	13.22 $\pm$ 1.36
1925	0.21(0.37)	4.460(0.013)	2.661	100.00	93.70	13.28 $\pm$ 1.53
Total Gas [‡]						13.60 $\pm$ 0.71

[†]: Numbers in parentheses indicate 2 σ errors in individual ratios. [‡]: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. ⁺: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. [#]: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. ^{*}: Uncertainties, quoted at 2 σ , include propagated error in the irradiation parameter J . [‡]: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2 σ) include the propagated errors in J and isotopic measurements.

4 9 5 1

Appendix D: (continued)

L95-104 Muscovite

J value: $3.47\text{E-}03 \pm 9.39\text{E-}06$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) ⁺	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
950	2.42(2.02)	1.577(0.022)	0.077	0.25	28.35	11.23 $\pm$ 23.57
975	1.73(1.79)	1.422(0.043)	0.080	0.50	48.96	21.44 $\pm$ 22.99
1025	2.60(2.66)	1.240(0.017)	0.134	0.93	23.09	11.63 $\pm$ 39.46
1050	1.09(1.56)	1.992(0.017)	0.192	1.54	67.86	21.22 $\pm$ 14.32
1075	3.11(2.05)	2.565(0.021)	0.245	2.32	8.20	2.00 $\pm$ 14.78
1100	1.03(1.11)	2.801(0.018)	0.330	3.36	69.42	15.48 $\pm$ 7.28
1125	1.96(1.22)	3.011(0.016)	0.400	4.64	41.98	8.72 $\pm$ 7.48
1150	1.87(0.39)	2.848(0.011)	0.585	6.49	44.63	9.80 $\pm$ 2.54
1175	1.15(0.20)	3.163(0.007)	2.400	14.12	66.00	13.04 $\pm$ 1.19
1200	0.43(0.10)	4.395(0.013)	5.293	30.95	87.26	12.42 $\pm$ 0.44
1250	0.30(0.15)	4.788(0.015)	5.035	46.96	90.94	11.88 $\pm$ 0.57
1300	0.52(0.13)	4.560(0.014)	2.700	55.54	84.41	11.58 $\pm$ 0.54
1350	0.79(0.91)	3.990(0.011)	2.255	62.71	76.66	12.01 $\pm$ 4.19
1550	0.45(0.02)	4.490(0.016)	11.210	98.35	86.63	12.06 $\pm$ 0.11
1925	0.94(0.68)	2.788(0.015)	0.519	100.00	72.28	16.18 $\pm$ 4.47
				Total Gas ⁰		12.14 $\pm$ 1.15

[†]: Numbers in parentheses indicate 2σ errors in individual ratios. ⁺: number of moles of ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. ⁺: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. [#]: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. ^{*}: Uncertainties, quoted at 2σ , include propagated error in the irradiation parameter J . ⁰: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2σ) include the propagated errors in J and isotopic measurements.

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Appendix D: (continued)

L95-116 Muscovite

J value: $3.46\text{E-}03 \pm 1.93\text{E-}06$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) ⁺	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
900	2.15(1.18)	0.697(0.019)	0.062	0.18	36.59	32.51 ± 30.61
1000	2.85(0.63)	0.454(0.004)	0.149	0.60	15.66	21.42 ± 25.46
1050	2.45(0.22)	0.797(0.004)	0.329	1.53	27.56	21.45 ± 5.12
1100	1.53(0.28)	1.903(0.007)	0.994	4.35	54.79	17.89 ± 2.65
1125	1.41(0.21)	2.494(0.007)	1.443	8.43	58.29	14.55 ± 1.58
1150	0.67(0.14)	3.071(0.007)	3.139	17.33	80.04	16.22 ± 0.87
1175	0.41(0.17)	3.613(0.009)	3.838	28.20	87.79	15.13 ± 0.86
1200	0.19(0.15)	3.787(0.009)	4.040	39.65	94.30	15.50 ± 0.73
1225	0.17(0.15)	3.765(0.009)	3.794	50.40	94.80	15.67 ± 0.75
1250	0.31(0.16)	3.675(0.010)	3.085	59.14	90.62	15.35 ± 0.81
1275	0.31(0.11)	3.544(0.010)	2.184	65.33	90.84	15.95 ± 0.59
1300	0.30(0.26)	3.519(0.013)	1.627	69.94	90.99	16.09 ± 1.38
1350	0.26(0.21)	3.545(0.009)	2.546	77.15	92.03	16.16 ± 1.08
1400	0.20(0.12)	3.818(0.009)	3.956	88.36	93.83	15.30 ± 0.59
1450	0.06(0.36)	3.836(0.015)	1.522	92.67	97.98	15.90 ± 1.71
1550	0.12(0.36)	3.836(0.013)	1.295	96.34	96.42	15.65 ± 1.73
1925	0.21(0.44)	3.439(0.012)	1.292	100.00	93.65	16.94 ± 2.34
Total Gas ⁰						15.82 ± 0.58

†: Numbers in parentheses indicate 2σ errors in individual ratios. †: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. †: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. #: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. *: Uncertainties, quoted at 2σ , include propagated error in the irradiation parameter J. □: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2σ) include the propagated errors in J and isotopic measurements.

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Appendix D: (continued)

L95-117 Muscovite

J value: $3.47\text{E-}03 \pm 9.20\text{E-}06$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) [†]	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
950	3.17(0.13)	0.121(0.001)	0.098	0.26	6.27	32.19 ± 19.25
1000	3.30(0.21)	0.140(0.001)	0.174	0.72	2.47	11.04 ± 27.69
1050	3.30(0.11)	0.1470(0.0005)	0.332	1.61	2.42	10.30 ± 13.84
1100	3.04(0.16)	0.395(0.001)	0.634	3.29	10.26	16.22 ± 7.59
1125	2.73(0.17)	0.695(0.002)	0.833	5.51	19.36	17.39 ± 4.61
1150	1.99(0.08)	1.844(0.003)	3.576	15.03	41.15	13.94 ± 0.78
1175	0.98(0.08)	3.324(0.007)	5.445	29.52	70.98	13.35 ± 0.43
1200	0.44(0.08)	4.058(0.010)	7.188	48.64	86.90	13.39 ± 0.38
1225	0.37(0.05)	4.139(0.011)	5.947	64.47	88.85	13.43 ± 0.23
1250	0.45(0.15)	3.948(0.012)	3.907	74.87	86.65	13.73 ± 0.72
1300	1.12(0.11)	3.302(0.008)	3.211	83.41	66.88	12.67 ± 0.65
1350	1.38(0.14)	2.715(0.006)	2.494	90.05	59.19	13.63 ± 0.93
1375	0.34(0.29)	3.790(0.013)	2.043	95.49	89.69	14.79 ± 1.42
1400	0.00(0.78)	4.309(0.023)	1.139	98.52	100.00	14.51 ± 3.31
1450	1.93(2.62)	4.228(0.027)	0.470	99.77	42.90	6.36 ± 11.43
1925	2.41(3.41)	1.628(0.026)	0.087	100.00	28.69	11.02 ± 38.59
Total Gas [□]					13.60 ± 0.84	

[†]: Numbers in parentheses indicate 2σ errors in individual ratios. [†]: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. [†]: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. [#]: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. ^{*}: Uncertainties, quoted at 2σ , include propagated error in the irradiation parameter J . [□]: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2σ) include the propagated errors in J and isotopic measurements.

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Appendix D: (continued)

L95-119 Muscovite

 J value: $3.47\text{E-}03 \pm 9.39\text{E-}06$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) [†]	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
900	1.42(1.45)	0.503(0.018)	0.054	0.10	58.06	70.94 ± 51.32
950	2.40(0.51)	1.077(0.015)	0.116	0.31	28.96	16.77 ± 8.77
1000	2.27(0.55)	0.791(0.005)	0.197	0.67	32.96	25.91 ± 12.77
1050	2.49(1.48)	1.351(0.009)	0.207	1.05	26.56	12.28 ± 20.16
1100	2.42(0.23)	1.259(0.004)	0.921	2.74	28.58	14.17 ± 3.40
1125	2.13(0.19)	1.612(0.003)	2.173	6.72	36.90	14.29 ± 2.21
1150	0.80(0.08)	3.127(0.006)	4.826	15.56	76.28	15.24 ± 0.45
1175	0.32(0.14)	3.785(0.010)	5.840	26.26	90.26	14.90 ± 0.70
1200	0.25(0.12)	4.021(0.010)	6.219	37.65	92.60	14.39 ± 0.54
1225	0.34(0.11)	3.985(0.010)	5.709	48.10	89.80	14.08 ± 0.52
1250	0.43(0.10)	3.845(0.010)	5.285	57.78	87.20	14.17 ± 0.47
1275	0.62(0.14)	3.700(0.010)	3.552	64.29	81.48	13.76 ± 0.71
1300	0.70(0.12)	3.548(0.088)	3.007	69.79	79.25	13.95 ± 0.62
1350	0.46(0.09)	3.791(0.010)	5.651	80.14	86.13	14.19 ± 0.42
1400	0.12(0.09)	4.220(0.011)	5.081	89.45	96.16	14.24 ± 0.41
1450	0.05(0.42)	4.057(0.015)	1.785	92.72	98.39	15.15 ± 1.91
1550	0.18(0.46)	4.014(0.014)	1.791	96.00	94.42	14.70 ± 2.11
1925	0.34(0.16)	3.768(0.009)	2.184	100.00	89.69	14.87 ± 0.78
Total Gas [‡]					14.51 ± 0.91	

[†]: Numbers in parentheses indicate 2σ errors in individual ratios. [‡]: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. ⁺: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. [#]: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. ^{*}: Uncertainties, quoted at 2σ , include propagated error in the irradiation parameter J . [‡]: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2σ) include the propagated errors in J and isotopic measurements.

Appendix D: (continued)

L94-10 Biotite

J value: $3.47\text{E-}03 \pm 9.38\text{E-}06$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) ⁺	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
950	2.32(0.31)	0.623(0.007)	0.278	1.16	31.48	31.36 ± 9.02
1000	1.42(0.17)	1.110(0.003)	0.868	4.77	58.06	32.50 ± 2.76
1050	1.12(0.13)	1.630(0.003)	1.695	11.81	66.93	25.59 ± 1.49
1100	0.79(0.07)	1.780(0.003)	3.014	24.35	76.63	26.74 ± 0.69
1150	0.47(0.07)	2.000(0.003)	2.239	33.66	86.03	26.76 ± 0.66
1200	0.40(0.19)	1.980(0.006)	1.092	38.20	88.24	27.78 ± 1.8
1250	0.42(0.28)	1.920(0.007)	1.038	42.52	87.56	28.33 ± 2.62
1300	0.39(0.06)	2.020(0.004)	2.354	52.30	88.55	27.28 ± 0.55
1350	0.33(0.13)	2.090(0.005)	3.373	66.33	90.16	26.85 ± 1.13
1400	0.26(0.06)	2.080(0.004)	3.925	82.65	92.26	27.57 ± 0.5
1450	0.29(0.07)	2.140(0.004)	3.875	98.77	91.44	26.62 ± 0.63
1550	0.48(1.26)	2.020(0.010)	2.963	100.00	85.75	26.49 ± 11.4
Total Gas [□]						27.22 ± 0.56

[†]: Numbers in parentheses indicate 2σ errors in individual ratios. ⁺: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. ^{*}: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. [#]: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. ^{*}: Uncertainties, quoted at 2σ , include propagated error in the irradiation parameter J . [□]: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2σ) include the propagated errors in J and isotopic measurements.

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Appendix D: (continued)

L95-110 Biotite

J value: $3.46\text{E-}03 \pm 1.93\text{E-}05$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) [†]	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
900	3.30(0.21)	0.348(0.002)	0.233	0.71	2.38	4.28 $\pm$ 11.03
950	2.32(0.40)	0.921(0.004)	0.430	2.02	31.30	21.11 $\pm$ 7.89
1000	2.03(0.32)	0.137(0.001)	1.160	5.56	40.05	18.19 $\pm$ 4.27
1050	1.23(0.17)	2.783(0.005)	3.320	15.68	63.47	14.21 $\pm$ 1.14
1100	0.34(0.13)	3.839(0.009)	5.490	32.40	89.84	14.59 $\pm$ 0.61
1150	0.33(0.38)	3.978(0.012)	4.280	45.44	90.13	14.13 $\pm$ 1.78
1200	0.003(0.314)	3.951(0.011)	2.110	51.87	99.77	15.74 $\pm$ 1.46
1250	0.46(0.16)	3.752(0.010)	1.850	57.51	86.19	14.32 $\pm$ 0.80
1300	0.41(0.21)	3.848(0.010)	2.840	66.18	87.63	14.20 $\pm$ 1.01
1350	0.38(0.13)	3.897(0.010)	5.330	82.42	88.51	14.16 $\pm$ 0.64
1400	0.37(0.25)	3.775(0.010)	3.330	92.56	88.86	14.67 $\pm$ 1.22
1450	0.39(0.33)	3.817(0.010)	1.390	96.81	88.22	14.41 $\pm$ 1.60
1550	0.21(0.95)	3.791(0.016)	0.505	98.35	93.58	15.38 $\pm$ 4.59
1925	0.42(0.66)	3.612(0.027)	0.541	100.00	87.59	15.11 $\pm$ 3.33
Total Gas [‡]						14.61 $\pm$ 0.74

†: Numbers in parentheses indicate 2 σ errors in individual ratios. ‡: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. +: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. #: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. *: Uncertainties, quoted at 2 σ , include propagated error in the irradiation parameter J . ‡: Total gas ages are calculated by summing ^{40}Ar and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2 σ) include the propagated errors in J and isotopic measurements.

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Appendix D: (continued)

L95-116 Biotite

J value: $3.46\text{E-}03 \pm 1.93\text{E-}05$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) ⁺	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
900	3.29(0.24)	0.324(0.001)	0.244	0.59	2.83	5.44 $\pm$ 13.89
950	2.58(0.12)	0.780(0.002)	1.190	3.47	23.77	18.96 $\pm$ 2.82
1000	1.79(0.08)	1.389(0.002)	2.230	8.87	47.01	21.04 $\pm$ 1.08
1050	0.63(0.09)	2.428(0.004)	6.620	24.88	81.38	20.85 $\pm$ 0.69
1100	0.11(0.05)	2.732(0.005)	8.480	45.39	96.62	21.99 $\pm$ 0.36
1125	0.05(0.08)	2.742(0.005)	4.220	55.59	98.31	22.29 $\pm$ 0.58
1150	0.00(0.13)	2.700(0.006)	2.240	61.00	100.00	23.02 $\pm$ 0.92
1175	0.00(0.57)	2.684(0.007)	1.350	64.25	100.00	23.16 $\pm$ 3.90
1200	0.06(0.13)	2.635(0.090)	1.020	66.71	98.04	23.13 $\pm$ 1.21
1225	0.20(0.22)	2.648(0.009)	1.070	69.29	94.03	22.08 $\pm$ 1.51
1250	0.17(0.25)	2.695(0.010)	1.410	72.69	94.81	21.87 $\pm$ 1.68
1275	0.17(0.12)	2.694(0.007)	2.340	78.35	94.79	21.88 $\pm$ 0.80
1300	0.21(0.18)	2.657(0.005)	2.740	84.98	93.62	21.91 $\pm$ 1.23
1350	0.40(0.41)	2.607(0.005)	3.040	92.33	88.02	21.00 $\pm$ 2.87
1400	0.24(0.18)	2.578(0.007)	1.900	96.93	92.77	22.37 $\pm$ 1.26
1450	0.00(0.32)	2.525(0.009)	0.650	98.50	100.00	24.60 $\pm$ 2.29
1550	0.39(1.77)	2.370(0.019)	0.324	99.29	88.33	23.16 $\pm$ 13.60
1925	1.45(1.26)	2.083(0.017)	0.294	100.00	57.01	17.03 $\pm$ 11.08
Total Gas [□]						21.67 $\pm$ 1.58

†: Numbers in parentheses indicate 2σ errors in individual ratios. †: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. +: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. #: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. *: Uncertainties, quoted at 2σ, include propagated error in the irradiation parameter J. □: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2σ) include the propagated errors in J and isotopic measurements.

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Appendix D: (continued)

L95-119 Biotite

J value: $3.46\text{E-}03 \pm 1.93\text{E-}05$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) ⁺	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
900	3.06(0.36)	0.305(0.004)	0.165	0.45	9.46	19.28 $\pm$ 21.41
950	2.98(0.18)	0.6710(0.0009)	0.752	2.49	11.90	11.06 $\pm$ 5.04
1000	2.40(0.11)	1.542(0.002)	1.817	7.42	28.98	11.72 $\pm$ 1.36
1050	0.89(0.06)	3.474(0.053)	3.772	17.65	73.75	13.24 $\pm$ 0.40
1100	0.45(0.11)	4.223(0.010)	6.397	35.01	86.60	12.79 $\pm$ 0.49
1125	0.24(0.11)	4.401(0.014)	3.775	45.26	92.87	13.16 $\pm$ 0.47
1150	0.19(0.50)	4.419(0.014)	2.050	50.82	94.19	13.29 $\pm$ 2.08
1175	0.00(1.54)	4.457(0.020)	1.059	53.69	100.00	13.99 $\pm$ 6.33
1200	0.20(0.30)	4.297(0.020)	1.318	57.27	94.00	13.64 $\pm$ 1.30
1250	0.10(0.37)	4.462(0.019)	1.600	61.61	96.76	13.53 $\pm$ 1.52
1275	0.33(0.11)	4.359(0.012)	3.031	69.84	89.98	12.88 $\pm$ 0.49
1300	0.48(0.15)	4.245(0.011)	5.205	83.96	85.77	12.60 $\pm$ 0.65
1350	0.47(0.16)	3.974(0.010)	3.498	93.45	86.01	13.50 $\pm$ 0.73
1400	0.55(0.38)	4.026(0.014)	1.446	97.38	83.74	12.97 $\pm$ 1.73
1450	0.53(0.84)	4.235(0.026)	0.472	98.66	84.32	12.42 $\pm$ 3.63
1550	0.47(0.84)	4.323(0.043)	0.307	99.49	86.03	12.42 $\pm$ 3.55
1925	0.55(2.36)	3.349(0.014)	0.188	100.00	83.48	15.53 $\pm$ 12.89
Total Gas ^U					13.0 $\pm$ 2.1	

[†]: Numbers in parentheses indicate 2 σ errors in individual ratios. ⁺: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. ⁺: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. [#]: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. ^{*}: Uncertainties, quoted at 2 σ , include propagated error in the irradiation parameter J . ^U: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2 σ) include the propagated errors in J and isotopic measurements.

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Appendix D: (continued)

L95-123 Hornblende (1st aliquot)J value: $3.51\text{E-}03 \pm 8.76\text{E-}06$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) ⁺	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
1100	2.05(0.48)	0.232(0.003)	0.148	1.03	39.34	104.11 $\pm$ 36.68
1125	0.72(1.46)	0.896(0.009)	0.093	1.67	78.74	54.82 $\pm$ 29.63
1150	2.72(1.62)	0.847(0.010)	0.059	2.07	19.54	14.54 $\pm$ 35.46
1200	1.55(1.02)	0.828(0.009)	0.083	2.65	54.06	40.85 $\pm$ 22.43
1250	0.47(0.69)	0.908(0.005)	0.305	4.76	86.16	59.07 $\pm$ 13.70
1275	0.21(0.25)	0.731(0.005)	0.256	6.52	93.80	79.42 $\pm$ 6.05
1300	0.12(0.39)	0.812(0.005)	0.275	8.42	96.51	73.76 $\pm$ 8.59
1350	0.20(0.10)	1.038(0.002)	0.935	14.90	94.07	56.51 $\pm$ 1.80
1375	0.17(0.43)	1.120(0.002)	0.915	21.23	94.87	52.85 $\pm$ 7.06
1400	0.21(0.05)	1.048(0.001)	3.288	43.98	93.72	55.74 $\pm$ 0.94
1425	0.24(0.16)	1.189(0.004)	0.774	49.33	92.83	48.77 $\pm$ 2.41
1450	0.18(0.03)	9.262(0.001)	2.219	64.69	94.57	63.51 $\pm$ 0.60
1475	0.16(0.05)	1.008(0.001)	3.398	88.20	95.18	58.83 $\pm$ 0.93
1525	0.007(0.267)	1.017(0.003)	1.054	95.49	99.76	61.07 $\pm$ 4.76
1600	0.007(0.254)	1.006(0.005)	0.417	98.38	99.75	61.70 $\pm$ 4.57
1923	0.93(0.35)	9.417(0.004)	0.234	100.00	72.49	48.09 $\pm$ 6.80
Total Gas [□]					58.67 $\pm$ 0.46	

†: Numbers in parentheses indicate 2σ errors in individual ratios. †: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. +: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. #: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. *: Uncertainties, quoted at 2σ, include propagated error in the irradiation parameter J. □: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2σ) include the propagated errors in J and isotopic measurements.

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Appendix D: (continued)

L95-123 Hornblende (2nd aliquot)J value: $3.51\text{E-}03 \pm 8.76\text{E-}06$

Temperature (K)	$^{36}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-3}$) [†]	$^{39}\text{Ar}/^{40}\text{Ar}$ ($\times 10^{-1}$) [†]	$^{39}\text{Ar}_K$ ($\times 10^{-13}$ moles) [†]	Cum. $^{39}\text{Ar}_K$ (%) ⁺	$^{40}\text{Ar}^*$ (%) [#]	Age (Ma) [*]
1100	3.01(0.40)	0.207(0.003)	0.112	0.89	11.07	33.56 ± 35.16
1200	1.72(0.63)	0.805(0.008)	0.187	2.39	49.30	38.34 ± 14.23
1250	0.41(0.72)	0.863(0.004)	0.256	4.45	87.80	63.27 ± 15.04
1300	0.78(0.23)	0.847(0.002)	0.546	8.82	76.86	56.54 ± 4.96
1350	0.00(0.17)	1.013(0.004)	0.942	16.38	100.00	61.45 ± 3.07
1375	0.09(0.20)	1.110(0.005)	0.866	23.33	97.36	54.71 ± 3.30
1400	0.10(0.06)	1.077(0.002)	2.949	46.98	97.04	56.17 ± 0.97
1425	0.45(0.70)	1.115(0.009)	0.272	49.16	86.79	48.62 ± 11.51
1450	0.19(0.05)	0.968(0.001)	2.788	71.52	94.46	60.76 ± 0.99
1475	0.10(0.05)	1.048(0.001)	2.439	91.08	96.97	57.66 ± 0.81
1525	0.05(0.13)	0.994(0.004)	0.537	95.39	98.52	61.68 ± 2.44
1600	0.08(0.32)	0.992(0.003)	0.430	98.84	97.57	61.24 ± 5.76
1925	0.44(0.77)	0.895(0.009)	0.145	100.00	87.01	60.53 ± 15.63
Total Gas [□]					57.78 ± 0.46	

[†]: Numbers in parentheses indicate 2σ errors in individual ratios. ⁺: number of moles of K-derived ^{39}Ar ($^{39}\text{Ar}_K$) released during each heating step. ^{*}: cumulative percentage of $^{39}\text{Ar}_K$ after each heating increment. [#]: percentage of radiogenic ^{40}Ar ($^{40}\text{Ar}^*$) in the total ^{40}Ar for each analysis. [□]: Uncertainties, quoted at 2σ, include propagated error in the irradiation parameter J. [□]: Total gas ages are calculated by summing $^{40}\text{Ar}^*$ and $^{39}\text{Ar}_K$ for each increment. Assigned uncertainties (2σ) include the propagated errors in J and isotopic measurements.

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Appendix E. SEM chemical analyses of the samples used for $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology

Sample	Biotite				Muscovite						Hornblende	
	L10	L110	L116	L119	L10	L104	L116	L117	L119	L143	L123	
SiO ₂	36.88	35.91	35.08	34.23	46.60	45.37	47.01	46.08	45.79	43.81	42.94	
Al ₂ O ₃	16.46	16.44	17.02	16.12	30.89	34.24	30.80	29.53	29.32	33.97	12.19	
TiO ₂	2.09	2.95	3.16	3.74	0.91	1.46	0.80	1.09	0.88	0.41	0.34	
Cr ₂ O ₃	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	
FeO	14.23	20.20	23.86	23.50	1.77	0.73	3.38	4.29	4.19	0.70	17.37	
MnO	0.00	0.39	0.67	0.77	0.00	0.00	0.04	0.00	0.05	0.00	0.21	
MgO	13.00	7.82	4.25	3.27	2.31	0.78	1.15	1.87	1.35	0.76	9.33	
CaO	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.81	
K ₂ O	8.59	9.71	9.70	9.35	11.33	11.06	11.08	11.26	10.93	10.21	1.73	
Na ₂ O	0.00	0.00	0.00	0.00	0.14	0.25	0.00	0.00	0.00	0.50	1.23	
Cl	0.00	0.02	0.10	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	
Total	91.63	93.43	93.85	90.98	93.95	93.94	94.25	94.12	92.51	90.36	97.22	

	(22 O basis)				(22 O basis)				(23 O basis)			
	Si	Al	Ti	Cr	Fe	Mn	Mg	Ca	K	Na	Cl	Sum
Si	5.67	5.63	5.59	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63
Al	3.00	3.03	3.20	3.12	3.12	3.12	3.12	3.12	3.12	3.12	3.12	3.12
Ti	0.24	0.35	0.38	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Cr	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	1.83	2.65	3.18	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23
Mn	0.00	0.05	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Mg	2.98	1.83	1.01	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Ca	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	1.68	1.94	1.97	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl	0.00	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	15.46	15.48	15.45	15.32	15.32	15.32	15.32	15.32	15.32	15.32	15.32	15.32
n	2	3	3	3	4	2	3	3	3	3	3	5

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**Map 1. STATION LOCATION MAP OF
THE KALI GANDAKI VALLEY,
ANNAPURNA-DHAULAGIRI
REGION, CENTRAL NEPAL**

Ice and Quaternary sediment distribution from Bordet et al. (1971) and
Colchen et al. (1986). Compiled by Laurent Godin, Ph.D. thesis,
Carleton University, 1999.

- Ice
- Quaternary sediments
- Station location and number

Map legend and scale information:

- Village: Kalopani
- Contour interval 2000 feet
- Major summits (elevation in meters): Annapurna I (8091)
- Scale: 0 to 5 km, scale 1 : 100,000
- Base map: sheet 62/P10, published by the Government of India, 1964.
- Magnetic North vs True North: 1/4° difference
- Magnetic variation from True North about 1/4 degree west in 1960, increasing annually by about 1 degree

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Map 2. GEOLOGIC MAP OF THE KALI GANDAKI VALLEY, ANNAPURNA-DHAULAGIRI REGION, CENTRAL NEPAL

Geology and stratigraphy modified from Bordet et al. (1971), Colchen et al. (1986) and Gradstein et al. (1992). Compiled by Laurent Godin, Ph.D. thesis, Carleton University, 1999.

Neogene	Pliocene	Thakkhola Fm*	hiatus
	(K4)	Dzong unit*	
	(K3)	Muding unit	
	(K2)	Chukh	
	(K1)	Chukh unit	
	(J3)	Lupra Fm	
	(J2)	Bagung Fm	
	(J1)	Jomsom Fm	
	(T)	sandstone	
	(T)	Thini Fm	
	(CP)	Thini Chu Fm	
	(CP)	Lake Tilicho Fm	
	(D)	alternating black shale & limestone	
	(S)	Sombre Formation	
	(S)	gritty dolomite	
	(O)	Nilgiri Fm	
	(Ca)	Annapurna Fm	
	(Es)	Sanctuary Fm	
	(Fm III)	Greater Himalayan metamorphic sequence	
	(Fm II)		
	(Fm I)		
	(LHSS)	Lesser Himalayan sedimentary sequence	

Tethyan sedimentary sequence

* not shown

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**Map 3. STRUCTURAL DATA MAP OF
THE KALI GANDAKI VALLEY,
ANNAPURNA-DHAULAGIRI
REGION, CENTRAL NEPAL**

Structural data collected between 1994 and 1996 by Laurent Godin,
Ph.D. thesis, Carleton University, 1999.

- Strike and dip of bedding
- Strike and dip of foliation (gneissosity, S₁, S₂, S₃, and S₄)
- Trend and plunge of mineral elongation lineation (L_m)
- Trend and plunge of intersection lineation (L₂, L₃)
- Trend and plunge of F₂ minor fold hinge lines (S, Z and symmetric shapes of minor folds viewed down plunge)
- Trend and plunge of F₃ minor fold hinge lines (S, Z, and symmetric shapes of minor folds viewed down plunge)
- Station location

Contour interval 2000 feet

Major summits (elevation in meters)

0 5 km

scale 1 : 100,000

Base map: sheet 62/P10, published by the Government of India, 1964.

Magnetic North
True North
1/4°

Magnetic variation from True North about 1/4 degree west in 1960, increasing annually by about 1 degree