Dating the Indian continental subduction and collisional thickening in the northwest Himalaya: Multichronology of the Tso Morari eclogites

Julia de Sigoyer Institut de Géologie, 11 rue E. Argand, 2007 Neuchâtel, Switzerland
Valérie Chavagnac* Isotopengeologie, Erlachstrasse 9a, 3012 Bern, Switzerland
Janne Blichert-Toft Centre National de la Recherche Scientifique, 69364 Lyon Cedex 07, France
Igor M. Villa Isotopengeologie, Erlachstrasse 9a, 3012 Bern, Switzerland
Béatrice Luais*, Stéphane Guillot — Centre National de la Recherche Scientifique, 69364 Lyon Cedex 07, France
Michael Cosca Institut de Minéralogie et Pétrographie, 1015 Lausanne, Switzerland
Georges Mascle Centre National de la Recherche Scientifique, Institut Dolomieu, 38100 Grenoble, France

ABSTRACT

Multichronometric studies of the low-temperature eclogitic Tso Morari unit (Ladakh, India) place timing constraints on the early evolution of the northwest Himalayan belt. Several isotopic systems have been used to date the eclogitization and the exhumation of the Tso Morari unit: Lu-Hf, Sm-Nd, Rb-Sr, and Ar-Ar. A ca. 55 Ma age for the eclogitization has been obtained by Lu-Hf on garnet, omphacite, and whole rock from mafic eclogite and by Sm-Nd on garnet, glaucophane, and whole rock from high-pressure metapelites. These results agree with a previously reported U-Pb age on allanite, and together these ages constrain the subduction of the Indian continental margin at the Paleocene-Eocene boundary. During exhumation, the Tso Morari rocks underwent thermal relaxation at about 9 ± 3 kbar, characterized by partial recrystallization under amphibolite facies conditions ca. 47 Ma, as dated by Sm-Nd on garnet, calcic amphibole, and whole rock from metabasalt, Rb-Sr on phengite, apatite, and whole rock, and Ar-Ar on medium-Si phengite from metapelites. Ar-Ar analyses of biotite and low-Si muscovite from metapelites, which recrystallized at <5 kbar toward the end of the exhumation, show that the Tso Morari unit was at upper crustal levels ca. 30 Ma. These results indicate variable exhumation rates for the Tso Morari unit, beginning with rapid exhumation while the Indian margin subduction was still active, and later proceeding at a slower pace during the crustal thickening associated with the Himalayan collision.

Keywords: Indian subduction, radiochronology, eclogites, exhumation rate, Himalaya.

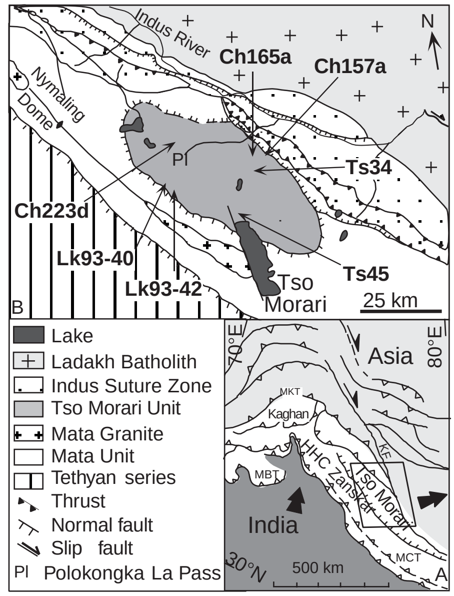

Figure 1. A: Locality map. Box shows studied area. B: Geologic map of Tso Morari area (east Ladakh) showing sample localities. MKT—Main Karakorum thrust, MCT—Main Central thrust, HHC—High Himalayan Crystalline slab, MBT—Main Boundary thrust, KF—Karakoram fault.

INTRODUCTION

The collision between India and Asia has modified not only the motion of lithospheric plates, but has also caused changes in sedimentation, climate, oceanic circulation, and faunal distribution (e.g., Patriat and Achache, 1984; Jaeger et al., 1989). The precise timing of the first contact between these two continents therefore is critical to our understanding of its widespread consequences. Estimates of the age of the onset of the collision in the western part of Himalaya vary from 65 to 45 Ma (e.g., Dewey et al., 1989; Jaeger et al., 1989). This wide range of ages reflects the diverse nonsimultaneous effects of the India-Asia collision. To clarify the timing of the early evolution of the northwest Himalayan orogeny, we here report new multichronological data from the Tso Morari eclogitic massif, which records the timing of the very high-pressure metamorphism related to the Indian margin subduction (de Sigoyer et al., 1997; Guillot et al., 1997). The successive ages of the different assemblages that recrystallized during the subsequent exhumation of the Tso Morari unit help constrain the exhumation processes of these high-pressure–low-temperature (high-*P*–low-*T*) rocks during convergence.

Because a number of difficulties are associated with the dating of eclogitic rocks (Thöni and Jagoutz, 1992), we tested the validity of our results by applying multiple isotopic systems (Lu-Hf, Sm-Nd, Rb-Sr, and Ar-Ar) to specific mineral assemblages, each of which characterizes the tectonic-metamorphic evolution of the Tso Morari massif. We discuss the implications of these new results on the early evolution of the Himalayan orogeny and the Tso Morari exhumation.

GEOLOGIC SETTING AND PETROGRAPHY

The Tso Morari dome is located in the internal part of the northwestern Himalaya (east Ladakh), between the Indus suture zone to the north and the Zanskar sedimentary unit to the south (Fig. 1). The dome is considered to be a distal crystalline block of thinned Indian continental margin (Mascle et al., 1994). Petrological studies have shown that all the lithologies of the Tso Morari unit (metapelites, metabasalts, and orthogneisses) underwent a period of high-*P*–low-*T* metamorphism (≥20 ± 3 kbar, 550 ± 50 °C) during the subduction of the thinned Indian margin below Asia, to a depth of ≥70 km (de Sigoyer et al., 1997; Guillot et al., 1997). The exhumation of the Tso Morari rocks is divided into two main steps: they first recrystallized under blueschist facies conditions (11 ± 2 kbar, 580 ± 50 °C) during a quasiisothermal decompression from a depth of 70 km to 40 km. They then locally underwent extensive recrystalliza-

*Present addresses: Chavagnac—Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA; Luais—Centre National de la Recherche Scientifique, 54501 Vandoeuvre, France.

Data Repository item 200057 contains additional material related to this article.

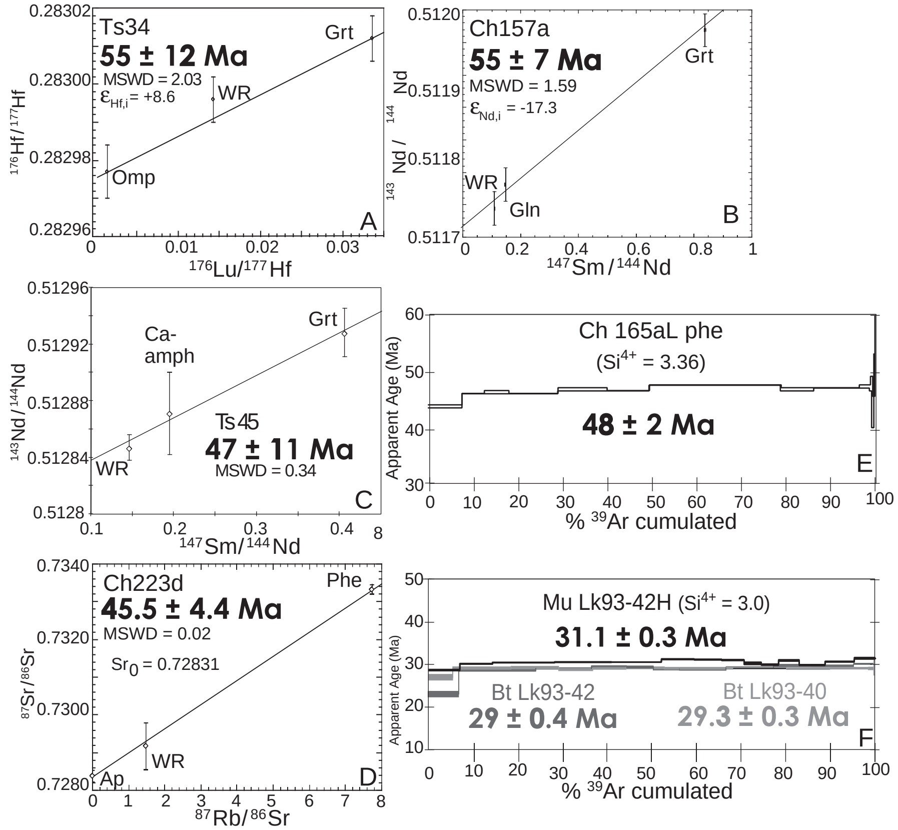

Figure 2. Results of multichronological study. Errors are 2 σ uncertainties. Best-fit regression lines were obtained by using ISOPLOT (Ludwig, 1999). A: Lu-Hf isochron plot (garnet, omphacite, whole rock; Grt, Omp, WR) for Ts34 eclogite. Lu-Hf analyses were carried out with multicollector inductively coupled plasma–mass spectrometry (ICP-MS) Lyon VG Plasma 54. Uncertainties are 1% on Lu/Hf ratio and 30 ppm on Hf isotope composition. B: Sm-Nd isochron (Grt, Gln [glaucophane], WR) for Ch157a high-pressure–low-temperature metapelite done at University of Bern with thermal ionization VG sector mass spectrometer in single-collector mode for Nd and AVCO single-collector thermal ionization mass spectrometer for Sm. Uncertainty on Sm/Nd ratios is <±0.3%. C: Sm-Nd isochron (Grt, Ca-amphibole, WR) for Ts45 recrystallized amphibolite obtained with Plasma 54 in Lyon. Uncertainty on Sm/Nd ratios is ±0.2%, and uncertainty on Nd isotope composition is ±0.001%. D: Rb-Sr isochron (Ap, Phe [apatite, phengite], WR) for Ch223d metapelite recrystallized under amphibolite facies conditions. Rb-Sr analyses were carried out on AVCO at Bern University. Uncertainties are ±2% for Rb and ±0.05% for Sr. E: Ar-Ar spectra for Ch165aL phengite (3.36 Si per formula unit) performed on MAP 215-50B rare-gas spectrometer at Bern. F: Ar-Ar spectra for Lk93-40 Bt, Lk93-42 Bt, and Lk93-42H Mu recrystallized under greenschist facies conditions. Biotite analyses were performed on MAP 215-50 of Lausanne University, whereas muscovite was analyzed in Bern. MSWD—mean square of weighted deviate.

tion under amphibolite facies conditions (9 ± 3 kbar, 610 ± 70 °C). Ductile normal shearing is associated with this thermal relaxation. On the southwestern border of the Tso Morari dome, the deformation continued under greenschist facies conditions, resulting in the recrystallization of micas at pressures ≤5 kbar (Fig. 1).

In order to date the different metamorphic stages (eclogitic, amphibolitic, and greenschist), Lu-Hf, Sm-Nd, Rb-Sr, and Ar-Ar geochronological analyses were carried out on specific mineral assemblages of both metabasaltic and metapelitic rocks. Sample Ts34, from the core of a meter-scale mafic lens (sample locations are shown in Fig. 1), shows a very fresh eclogitic assemblage of garnet I, omphacite, phengite (with 3.56 Si atoms per formula unit [p.f.u.]), glaucophane, quartz, zoisite, and rutile. In contrast, sample Ts45, from the rim of a similar lens, underwent a strong metamorphic recrystallization under amphibolite facies conditions. Calcic amphibole, garnet II, plagioclase, and biotite grew at the expense of omphacite, garnet I, and glaucophane, reflecting the temperature increase during the exhumation at about 30 km depth (de Sigoyer et al., 1997).

Sample Ch157a is an Fe-rich metapelite with a well-preserved eclogitic assemblage of garnet, glaucophane, jadeite, chloritoid, paragonite, phengite, zoisite, and chlorite ± biotite. Samples Ch223d and Ch165a are more deformed metapelites, associated in the field with recrystallized metabasalts (e.g., Ts45). They show a recrystallized association of quartz, white mica with low Si (3.1–3.3 and 3.36 p.f.u., respectively), garnet, apatite, and zoisite ± biotite stable under amphibolite facies conditions (de Sigoyer et al., 1997).

In the most deformed and potassic metapelites (Lk93-40, Lk93-42), sampled near the southwestern border of the dome (Fig. 1), no eclogitic relicts are preserved because of the extensive recrystallization under amphibolite and greenschist facies conditions. The amphibolitic conditions are characterized by the crystallization of kyanite and biotite at the expense of staurolite (Guillot et al., 1997), whereas the greenschist facies conditions are shown by the recrystallization of chlorite, biotite, and muscovite in later normal shearing planes. The Si content of the white micas is 3.0 p.f.u., which indicates low-*P* recrystallization (≤5 kbar), corresponding to a maximum depth of 15 km.

MULTISYSTEM GEOCHRONOLOGY

In order to date the pressure peak, the Lu-Hf and Sm-Nd isotope systems were applied to fresh eclogite facies mineral associations (Ts34, Ch157a), whereas to date the amphibolitic stage, Sm-Nd, Rb-Sr, and Ar-Ar isotope systems were applied to amphibolite facies mineral assemblages (Ts45, Ch223d, Ch165a). In order to date the greenschist facies retrogression, Ar-Ar analyses were carried out on the most deformed samples (Lk93-40, Lk93-42). The results are shown in Figure 2 (and see Tables 1 and 2; Appendix Figure 1[1]). Throughout this paper uncertainties are given as 2 standard deviations. Mineral abbreviations are from Kretz (1983).

Eclogitization Age

A three-point Lu-Hf age of 55 ± 12 Ma was obtained on garnet, omphacite, and whole rock of metabasalt Ts34 (Fig. 2A). The uncertainty on this result is relatively large because of the small spread in Lu/Hf ratios between garnet and omphacite. The positive initial epsilon value value (ε_{Hf}) of +8.6 suggests a mantle contribution resembling the within-plate basalt of the Indian margin, the Panjal Trap (Spencer et al., 1995).

Sm-Nd analyses on garnet, glaucophane, and whole rock from the high-*P*–low-*T* metapelite Ch157a define an isochron age of 55 ± 7 Ma (MSWD [mean square weighted deviate] = 1.59), which is controlled by garnet (Fig. 2B). The large negative initial ε_{Nd} value of –17.3 and the T_{DM} (depleted mantle age) of 3 Ga confirm the ancient Indian crustal origin for the metapelite protolith (cf. Gopalan et al., 1990; Whittington et al., 1999). The low MSWD indicates that garnet, glaucophane, and the whole rock were in isotopic equilibrium at the time of crystallization.

[1]GSA Data Repository item 200057, Tables 1 and 2, and Appendix Figure, tabulated isotopic results and Ar-Ar isochrons, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2000.htm.

The temperature throughout the history of the Tso Morari unit was insufficient to cause the loss of radiogenic daughter isotopes from the garnets after their crystallization (Thöni and Jagoutz, 1992). We therefore interpret the concordant Lu-Hf and Sm-Nd ages as the time of eclogite crystallization.

Timing of Exhumation: Age of the Amphibolite and Greenschist Facies Recrystallization

The temperature increase recorded during exhumation of the Tso Morari unit is estimated by dating the assemblages that recrystallized under amphibolite facies conditions. A three-point (garnet, calcic-amphibole, and whole rock) Sm-Nd age of 47 ± 11 Ma was obtained (Fig. 2C) on the Ts45 amphibolite facies metabasalt. The complete reequilibration under amphibolite facies is attested to by the low MSWD value of 0.34 of the isochron. The high uncertainty associated with this age is due to a small spread in Sm/Nd ratios, which may be caused by the presence of cogenetic low Sm/Nd inclusions in the garnet, bringing its Sm/Nd value closer to that of the whole rock.

The metapelite Ch223d contains recrystallized phengite (3.1–3.3 Si p.f.u.), corresponding to a minimum pressure of 7–10 kbar (Guillot et al., 1997). An Rb-Sr isochron on phengite, apatite, and whole rock gives an age of 45 ± 4 Ma (MSWD = 0.02) (Fig. 2D).

For ^{39}Ar-^{40}Ar analyses we selected the metapelite Ch165a, in which only one single phengite generation is present, with an Si content of 3.36 p.f.u., typical of medium-pressure conditions. Step heating yielded a constant Cl/K ratio for 92% of the ^{39}Ar released, confirming the presence of a single generation of micas (Villa et al., 1997). The ages of these steps vary from 47.5 to 49.4 Ma (Fig. 2E), with an average of 48 ± 2 Ma. As reviewed by Villa (1998), phengite is known to retain most, or all, of its Ar below 550–580 °C in the absence of subsequent greenschist facies recrystallization. Even if the medium-Si phengite had not been completely closed to Ar loss during the thermal peak, its ^{39}Ar-^{40}Ar age is indistinguishable from the Rb-Sr and Sm-Nd ages on the other amphibolite facies samples, and it therefore quite closely approximates the age of amphibolite crystallization. These three ages suggest that the Tso Morari unit had been exhumed to a depth of 30 km by the middle Eocene, ca. 47 ± 2 Ma.

Subsequent exhumation is dated by ^{39}Ar-^{40}Ar on recrystallized muscovite and biotite from the most deformed metapelites (LK93-40, Lk93-42). Their Cl/K ratios are all uniform, and age spectra are flat (Fig. 2F). An age of 31.1 ± 0.3 Ma is calculated from 70% of the ^{39}Ar released from the homogeneous low-Si muscovite (~3.0 p.f.u.) of sample Lk93-42H. A slightly younger age at 29.3 ± 0.3 Ma is obtained on 58% of ^{39}Ar released from biotite Lk93-40. For biotite Lk93-42, an age of 29 ± 0.4 Ma was obtained on 63% of the ^{39}Ar release. The results are consistent for the three samples and allow us to propose a geologically meaningful age of ca. 30 Ma. The ca. 30 Ma ages cannot be interpreted as cooling ages, because phengite Ch165a started retaining its Ar ca. 48 Ma. Instead, these ^{39}Ar-^{40}Ar ages date the recrystallization under greenschist facies conditions. In the deformed metapelites, low-Si muscovite and biotite recrystallized at the end of decompression at ~5–3 kbar. This indicates that by Oligocene time the Tso Morari unit had reached a crustal level of ~10–15 km, i.e., was almost completely exhumed.

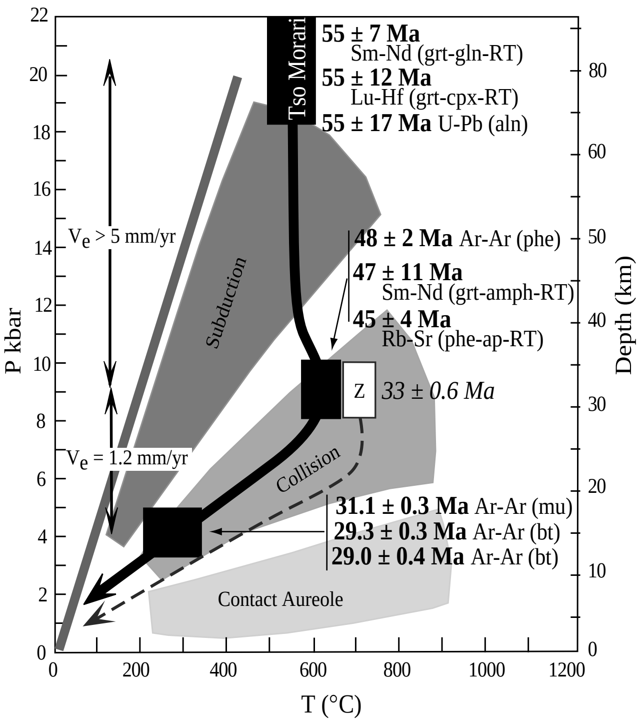

Figure 3. Pressure-temperature-time path of Tso Morari eclogitic unit (in black). Black boxes represent metamorphic stages dated in this study. V_e = estimated vertical exhumation rates. U-Pb age on allanite at 55 ± 17 Ma is from de Sigoyer et al. (1999). First stage of Tso Morari exhumation took place in context of continental subduction, whereas end stage took place in collisional context. White box, labeled Z, and dotted path represent metamorphic evolution of High Himalayan Crystalline unit in Zanskar; its temperature peak is dated as 33 ± 0.6 Ma (Sm-Nd on garnet; Vance and Harris, 1999). Comparison between metamorphic evolution of Tso Morari eclogitic unit and High Himalayan Crystalline unit shows that Tso Morari was partly exhumed when High Himalayan Crystalline slab was at its maximum depth.

DISCUSSION

The ages we obtained on eclogitic mineral assemblages (Lu-Hf 55 ± 12 Ma, Sm-Nd 55 ± 7 Ma) are substantiated by a U-Pb age of 55 ± 17 Ma on eclogitic allanite (de Sigoyer et al., 1999). Together, these three ages date the eclogitization of the Indian margin as 55 ± 6 Ma. This age is indistinguishable from that of the Kaghan eclogites in northwestern Pakistan (Tonarini et al., 1993). At the Paleocene-Eocene boundary (55 ± 0.5 Ma according to Berggren et al., 1995), the Indian margin recorded its first Asian deposits and the formation of foreland basins, interpreted as the initial India-Asia contact (Garzanti et al., 1987; Pivnik and Wells, 1996). Paleomagnetic data from the Indian oceanic floor also support an initial India-Asia contact at 55 Ma in northwest Himalaya (Klootwijk et al., 1992). Because the convergence velocity between India and Asia was high at this time (Klootwijk et al., 1992), the Indian margin was probably subducted down to a depth of 70 km in only 1 ± 0.5 m.y. (for a Benioff plane dip angle of 15°–30°). Our results in conjunction with biostratigraphic and paleomagnetic data suggest that the onset of Indian continental subduction below Asia occurred ca. 55 Ma. The older age of 65 Ma based on terrestrial fauna exchange (Jaeger et al., 1989) could be interpreted, as first suggested by Treloar and Izatt (1993), as an early Paleocene collision between the Kabul block and India.

The low-temperature metamorphic conditions preserved by the Tso Morari eclogites suggest that their exhumation began quickly after burial. In addition, their quasiisothermal decompression from a depth of 70 km to 40 km (Fig. 3) suggests a rapid exhumation rate. This rapid exhumation began in a continental subduction context (Fig. 3), when the Indian-Asian convergence was still fast (Patriat and Achache, 1984; Klootwijk et al., 1992).

When the Tso Morari unit was reaching a depth of ~30 km, temperature increased, as shown by the recrystallization of rocks under amphibolite facies conditions. The temperature peak is dated by recrystallized minerals as 47 ± 2 Ma; by Rb-Sr as 45 ± 4 Ma; by Sm-Nd as 47 ± 11 Ma; and by Ar-Ar as 48 ± 2 Ma. Although when taking analytical errors into account, the age of the amphibolite facies thermal peak overlaps with that of eclogitization, the textural sequence observed in these rocks clearly indicates that the amphibolite facies minerals are younger than the eclogitic assemblage. From the age and depth of eclogitization (55 Ma, 70 km), to the age and depth of amphibolitization (47 Ma, 30 km), a minimum exhumation rate of 5 mm/yr is estimated (Fig. 3).

The end of the Tso Morari exhumation is dated as ca. 30 Ma on greenschist facies micas. Therefore a vertical exhumation rate of about 1.2 mm/yr is estimated for the unit's rise from a depth of 30 km to 10 km (Fig. 3). The second stage of the exhumation was therefore slower than the first stage.

The changes in exhumation rate and metamorphic conditions recorded by the Tso Morari unit coincide with the variations of the Indian-Asian convergence rate. Actually, since middle Eocene time (after 50 Ma), the Indian-Asian convergence rate strongly decreased (from 10 to 4.5 cm/yr) (Patriat and Achache, 1984). At the same time, the episutural sea basins between the two plates disappeared, and the sedimentation became continental, reflecting the erosion of the first Himalayan relief (Garzanti et al., 1987; Pivnik and Wells, 1996; Rowley, 1996). All of these phenomena recorded since the middle Eocene are related to the thickening of the orogenic Himalayan wedge. As first suggested by Treloar et al. (1989), we propose that the Himalayan wedge was strongly thickened when the High Himalayan Crystalline slab was underthrust into the orogenic wedge, from 50 to 40 Ma in the northwest Himalaya. As a consequence of the thickening, since about 33 Ma, the High Himalayan Crystalline unit of Zanskar, located south of the Tso Morari, underwent temperature relaxation after its burial, under Barrovian conditions (8–10 kbar, 660–720 °C) typical of a collisional context (Fig. 3) (Vance and Harris, 1999). The Tso Morari unit was in the middle crustal level (30 km) since ca. 47 Ma, and, rising at a slow exhumation rate, its temperature increase could also be due to thermal relaxation related to the thickening of the Himalayan wedge.

The present work has succeeded in dating eclogite formation and therefore the time of the onset of the Indian-Asian contact in the northwest Himalaya at 55 ± 6 Ma. Furthermore, our results show that the exhumation rate of the high-*P*–low-*T* Tso Morari eclogitic massif was variable, related to changes in geodynamic processes on a lithospheric scale. The exhumation began in the early Eocene and was initially proceeding rapidly, when the continental subduction of the Indian margin was still active. Since the middle Eocene, exhumation continued at a slower rate in a collisional regime, while crustal thickening occurred within the Himalayan wedge. Similar variations in the exhumation rate of high-*P* rocks have been observed in other modern and Paleozoic mountain belts (Duchêne et al., 1997), suggesting that different processes control the successive exhumation stages from great depths to the surface.

ACKNOWLEDGMENTS

This work was supported by the CNRS-INSU program IDYL-HIMALAYA. Isotope research in Bern is partly funded by Suisse National Fonds grant 20-47157.96. We thank J.P. Burg for helpful discussions. Constructive reviews by J. Dewey and an anonymous reader are gratefully acknowledged.

REFERENCES CITED

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.P., 1995, A revised Cenozoic geochronology and chronostratigraphy, *in* Berggren, W.A., et al., eds., Geochronology time scales and global stratigraphic correlation: SEPM (Society for Sedimentary Geology) Special Publication 54, p. 129–212.

de Sigoyer, J., Guillot, S., Lardeaux, J.M., and Mascle, G., 1997, Glaucophane-bearing eclogites in the Tso Morari dome (eastern Ladakh, NW Himalaya): European Journal of Mineralogy, v. 9, p. 1073–1083.

de Sigoyer, J., Chavagnac, V., Baldwin, J., Luais, B., Blichert-Toft, J., Villa, I., and Guillot, S., 1999, Timing of the HP-LT Tso Morari evolution: From continental subduction to collision in NW Himalaya: Terra Nostra, v. 99, p. 141.

Dewey, J.F., Cande, S., and Pitman, W.C., 1989, Tectonic evolution of the India-Eurasia collision zone: Eclogae Geologicae Helveticae, v. 82, p. 717–734.

Duchêne, S., Lardeaux, J.M., and Albarède, F., 1997, Exhumation of eclogites: Insights from retrograde depth-time path analysis: Tectonophysics, v. 280, p. 125–140.

Garzanti, E., Baud, A., and Mascle, G., 1987, Sedimentary record of the northward flight of India and its collision with Eurasia (Ladakh Himalaya, India): Geodynamica Acta, v. 1, p. 297–312.

Gopalan, K., Macdougall, J.D., Roy, A.B., and Murali, A.V., 1990, Sm-Nd evidence for 3.3 Ga old rocks in Rajastan, northwestern India: Precambrian Research, v. 48, p. 287–297.

Guillot, S., de Sigoyer, J., Lardeaux, J.M., and Mascle, G., 1997, Eclogitic metasediments from the Tso Morari area (Ladakh, Himalaya): Evidence for continental subduction during India-Asia convergence: Contributions to Mineralogy and Petrology, v. 128, p. 197–212.

Jaeger, J.J., Courtillot, V., and Tapponnier, P., 1989, Paleontological view of the ages of the Deccan Traps, the Cretaceous-Tertiary boundary, and the India-Asia collision: Geology, v. 17, p. 316–319.

Klootwijk, C.T., Gee, J.S., Peirce, J.W., Smith, G.M., and McFadden, P.L., 1992, An early India-Asia contact: Paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121: Geology, v. 20, p. 395–398.

Kretz, R., 1983, Symbols for rock-forming minerals: American Mineralogist, v. 68, p. 277–279.

Ludwig, K.R., 1999, User's manual for Isoplot/Ex version 2.2, A. Geochronological toolkit for Microsoft Excel: Berkeley Geochronology Center Special Publication 1a, 53 p.

Mascle, G., Colchen, M., Guillot, S., and Delaygue, G., 1994, Preliminary results on the metamorphic evolution of the Tso Morari dome: Consequences for the geodynamic evolution of the Indian margin during Himalayan collision: Nepal Geological Society Journal, v. 10, p. 85–86.

Patriat, P., and Achache, J., 1984, India-Eurasia collision chronology has implications for crustal shortening and driving mechanisms of plates: Nature, v. 311, p. 615–621.

Pivnik, D.A., and Wells, N.A., 1996, The transition from Tethys to the Himalaya as recorded in northwest Pakistan: Geological Society of America Bulletin, v. 108, p. 1295–1313.

Rowley, D.B., 1996, Age of initiation of collision between India and Asia: A review of stratigraphic data: Earth and Planetary Science Letters, v. 145, p. 1–13.

Spencer, D.A., Tonarini, S., and Pognante, U., 1995, Geochemical and Sr-Nd isotopic characterisation of Higher Himalayan eclogites (and associated metabasites): European Journal of Mineralogy, v. 7, p. 89–102.

Thöni, M., and Jagoutz, E., 1992, Some new aspects of dating eclogites in orogenic belts: Sm-Nd, Rb-Sr, and Pb-Pb isotopic results from the Austroalpine Saualpe and Koralpe type-locality (Carinthia/Styria, southeastern Austria): Geochimica et Cosmochimica Acta, v. 56, p. 347–368.

Tonarini, S., Villa, I.M., Oberli, M., Meier, F., Spencer, D.A., Pognante, U., and Ramsay, J.G., 1993, Eocene age of eclogite metamorphism in Pakistan Himalaya: Implications for India-Eurasia collision: Terra Nova, v. 5, p. 13–20.

Treloar, P.J., and Izatt, C.N., 1993, Tectonics of the Himalayan collision between the India plate and the Afghan block: A synthesis, *in* Treloar, P.J., and Searle, M.P., eds., Himalayan tectonics: Geological Society [London] Special Publication 74, p. 69–87.

Treloar, P.J., Rex, D.C., Guise, P.G., Coward, M.P., Searle, M.P., Windley, B.F., Petterson, M.G., Jan, M.Q., and Luff, I.W., 1989, K-Ar and Ar-Ar geochronology of the Himalayan collision in NW Pakistan: Constraints on the timing of suturing, deformation, metamorphism and uplift: Tectonics, v. 8, p. 881–909.

Vance, D., and Harris, N., 1999, Timing of prograde metamorphism in the Zanskar Himalaya: Geology, v. 27, p. 395–398.

Villa, I.M., 1998, Isotopic closure: Terra Nova, v. 10, p. 42–47.

Villa, I.M., Ruggieri, G., and Puxeddu, M., 1997, Petrological and geochronological discrimination of two white-mica generations in a granite cored from the Larderello-Travale geothermal field (Italy): European Journal of Mineralogy, v. 9, p. 563–568.

Whittington, A., Foster, G., Harris, N., Vance, D., and Ayres, M., 1999, Lithostratigraphic correlations in the western Himalaya—An isotopic approach: Geology, v. 27, p. 585–588.

Manuscript received October 13, 1999
Revised manuscript received February 28, 2000
Manuscript accepted March 9, 2000