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19. In our devices, the gate voltage changes the charge state of the SWNT by approximately 2×10^5 electrons per volt per centimeter of SWNT. This corresponds to a doping level of $\sim 5 \times 10^6$ holes/cm at a gate voltage of -25 V, or a Fermi level of ~ 75 meV referenced to the valence band. For a SWNT 1.4 nm in diameter, this corresponds to a doping level of $\Delta \approx 1.3$ in the terminology of (*17*) and $f \approx 3 \times 10^{-3}$ in the terminology of (*20*).
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Tectonic Implications of U-Pb Zircon Ages of the Himalayan Orogenic Belt in Nepal

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Metasedimentary rocks of the Greater Himalaya are traditionally viewed as Indian shield basement that has been thrust southward onto Lesser Himalayan sedimentary rocks during the Cenozoic collision of India and Eurasia. Ages determined from radioactive decay of uranium to lead in zircon grains from Nepal suggest that Greater Himalayan protoliths were shed from the northern end of the East African orogen during the late Proterozoic pan-African orogenic event. These rocks were accreted onto northern Gondwana and intruded by crustal melts during Cambrian-Ordovician time. Our data suggest that the Main Central thrust may have a large amount of pre-Tertiary displacement, that structural restorations placing Greater Himalayan rocks below Lesser Himalayan rocks at the onset of Cenozoic orogenesis are flawed, and that some metamorphism of Greater Himalayan rocks may have occurred during early Paleozoic time.

The Himalayan orogen includes four tectonostratigraphic units (Fig. 1) that record the tectonic evolution of northern Gondwana and southern central Asia since early Proterozoic time (*1, 2*). The Tibetan Himalaya comprises Cambrian through Eocene sedimentary rocks of the Tethyan succession (*3–5*). South of the Tibetan Himalaya lies the Greater Himalaya, consisting of high-grade metasedimentary rocks (*6–9*) intruded locally by early Paleozoic (*10–12*) and Miocene (*13–17*) granitoids. Greater Himalayan rocks are thrust southward along the Main Central thrust (MCT) on top of the Lesser Himalaya, which includes the ~10- to 12-km-thick Nawakot Group (Proterozoic) and Permian–lower Miocene strata (*18–24*). The Subhimalaya (Fig. 1) consists of Neogene foreland basin deposits. The Greater and Lesser Himalaya are sparsely dated, and their relationships to each other and to the Indian shield remain obscure. Because of their high metamorphic grade, Greater Himalayan rocks are assumed to be Indian shield basement that has been uplifted along the MCT. However, U-Pb ages and Nd isotopic data from Greater and probable Lesser Himalayan rocks in a small area near the MCT in central Nepal suggest that Greater Himalayan rocks may be younger than Lesser Himalayan rocks (*25*).

We conducted U-Pb isotopic analyses on 445 zircon grains (*26*) from 41 samples of the four Himalayan terranes and modern river sediment throughout Nepal (Fig. 1) to determine the ages, provenance, and crustal affinity of Himalayan rocks. Detrital zircons provide maximum depositional age constraints, and minimum depositional ages of some strata are constrained by U-Pb ages of crosscutting intrusive rocks.

Ages of detrital zircons from quartzites in the Nawakot Group of the Lesser Himalaya are generally greater than ~1600 million years ago (Ma), with age distribution peaks at ~1866 and ~1943 Ma (Fig. 2). Because the age of zircons from the intrusive Ulleri augen gneisses is ~1831 Ma, the lower Nawakot Group must have been deposited between ~1866 and 1831 Ma. The detrital zircon ages are consistent with sedimentological data indicating that Lesser Himalayan sediments were derived from the Indian shield (*19, 21, 27*).

Metasedimentary rocks of the Greater Himalaya yield zircon ages of 800 to 1700 Ma,

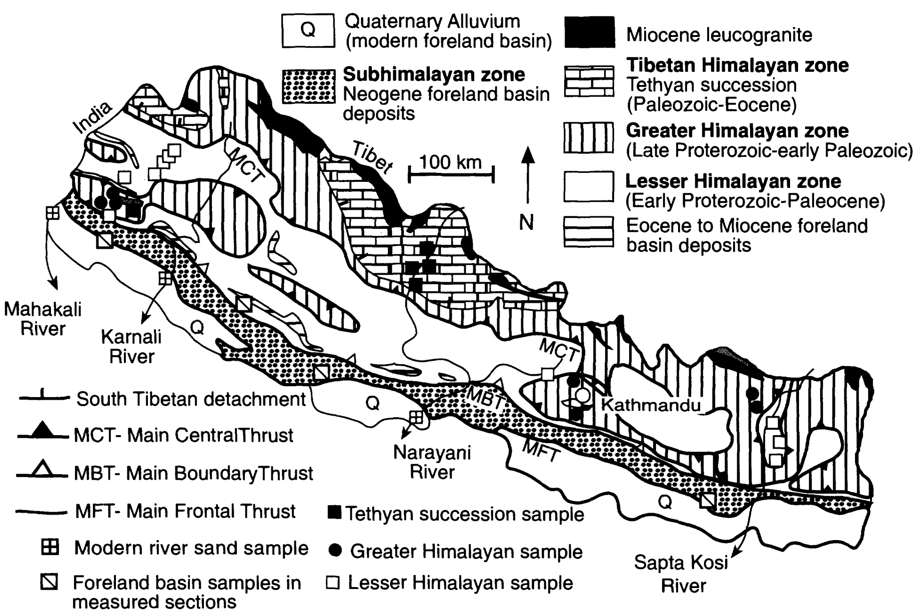

Fig. 1. Geologic map of Nepal, showing locations of samples and regional tectonostratigraphic terranes.

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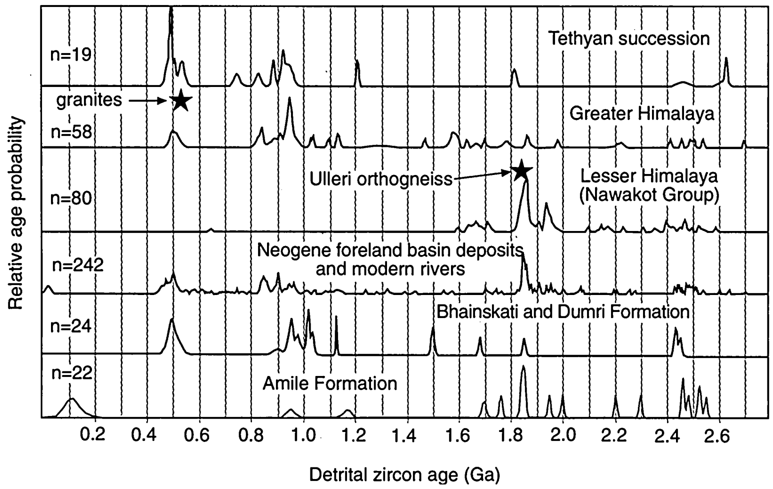

Fig. 2. Age spectra for 445 detrital zircon grains from Tethyan, Greater Himalayan, and Lesser Himalayan (Nawakot Group) rocks and from foreland basin deposits (Ga, 10^3 Ma). Each curve represents the sum of all analyses from a group of samples, normalized such that all curves contain the same area. The number of grains represented by each curve is shown on the left. Stars indicate ages of intrusive bodies. The Amile Formation is the youngest pre-foreland basin unit in the Lesser Himalaya (*23, 24*).

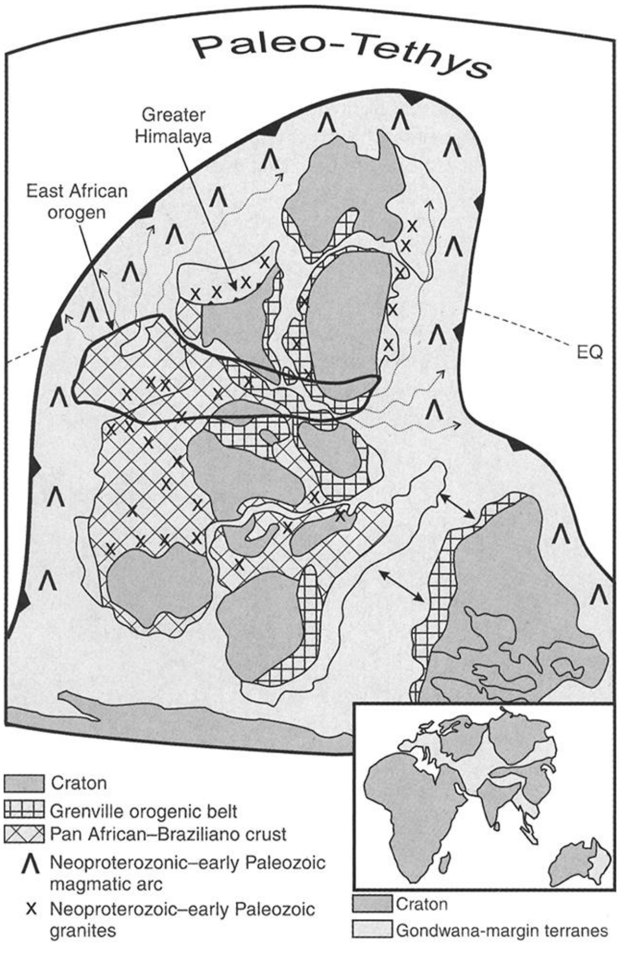

Fig. 3. Paleotectonic map of Gondwana (*33–35*), showing hypothetical sediment dispersal during the pan-African orogenic event. Inset shows distribution of Gondwana margin rocks that underlie accreted terranes in central Asia with protoliths that are probably similar to the Greater Himalayan rocks.

with peaks at ~851 and ~954 Ma (Fig. 2). On the basis of U-Pb ages of zircons from cross-cutting granitic plutons and orthogneisses, the minimum age of Greater Himalayan rocks is ~480 to 500 Ma (*9, 11, 12, 14, 28*). Therefore, the Greater Himalayan protoliths throughout Nepal must have been deposited between ~800 and ~480 Ma.

Qualitative comparisons of the age spectra suggest that Lesser Himalayan rocks are related to India, whereas Greater Himalayan protoliths appear to be younger and exotic to India. Support for this idea comes from Nd isotopic data indicating that Lesser Himalayan rocks have older Nd model ages than Greater Himalayan rocks (*17, 25, 29–32*). The most likely source of the 800- to 1000-Ma zircons in Greater Himalayan rocks is the East African part of the pan-African orogen, which was uplifted during Neoproterozoic time (Fig. 3) (*33–35*).

Tibetan (Tethyan) Himalayan zircon ages resemble those of the Greater Himalaya, with age distribution peaks at ~500 and ~956 Ma and a few older ages similar to those of Lesser Himalayan zircons. Tethyan rocks were deposited nonconformably on Greater Himalayan rocks, explaining the abundant <1700-Ma zircons. Abundant Paleozoic fauna of Indian (as opposed to Eurasian) affinity and the general northward increase in Tethyan paleobathymetry (*4*) suggest that these strata were deposited on Greater Himalayan rocks after they amalgamated with northern India. In northern India and Pakistan, Tethyan rocks rest directly on Lesser Himalayan rocks (*5, 36, 37*). Thus, the older zircons in Tethyan strata may have been derived from Lesser Himalayan rocks or the Indian craton.

The erosional history of the Himalaya can be reconstructed by qualitative comparison of the ages of zircons from the Eocene to modern foreland basin deposits with the ages of zircons in Tibetan, Greater, and Lesser Himalayan terranes (Fig. 2) (*24, 28*). The pre-orogenic, Cretaceous-Paleocene Amile Formation contains zircons with ages similar to those of the Lesser Himalaya. The overlying Bhainskati (Eocene) and Dumri (lower Miocene) Formations contain zircons with a typical Greater Himalayan age distribution, signaling the erosion of Tethyan and Greater Himalayan rocks (Fig. 2). Ages of zircons from Neogene foreland basin deposits and modern river sediments suggest an increase in grains derived from Lesser Himalayan rocks and the persistence of Greater Himalayan and Tethyan sources. The foreland basin sediments were derived from large drainage basins that unroofed the entire orogen, and the apparent similarity of their zircon age peaks to those of the bedrocks suggests that the age patterns are regionally representative of the distinct terranes.

The zircon ages constrain a tectonic model for the assembly of Himalayan terranes from Proterozoic through Cenozoic time. In Early to Middle Proterozoic time, the northern Indian passive margin was buried by Lesser Himalayan sediments. During Late Proterozoic time, Greater Himalayan sediments were dispersed from the East African portion of the pan-African orogen during the assem-

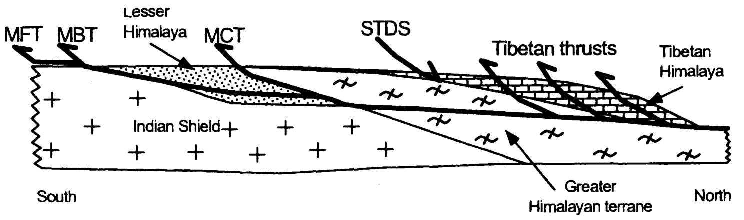

Fig. 4. Schematic north-south cross section depicting the architecture of the northern Indian margin before the Cenozoic Himalayan-Tibetan orogeny. Future trajectories of major Himalayan faults are shown by bold lines and labeled as follows: MFT, Main Frontal thrust; MBT, Main Boundary thrust; MCT, Main Central thrust; and STDS, South Tibetan detachment system.

bly of western Gondwana, and from Neoproterozoic island arcs within and along the margins of the paleo-Tethys ocean (Fig. 3). The island arcs and related basinal strata now constitute much of the Arabian-Nubian shield (*38*) and may underlie tectonic fragments that accreted to central Asia (inset, Fig. 3).

Greater Himalayan rocks may have accreted onto India during Late Cambrian–Early Ordovician time, when the northern margin of Gondwana experienced widespread subduction-related orogenic and igneous activity (*8, 33, 39*). The timing of this tectonic event may be signaled by the transition from Cambrian turbiditic to Early Ordovician synorogenic sedimentation in northern India (*36, 40*). Cambrian-Ordovician granites in the Greater Himalaya that postdate an early phase of metamorphism (*20, 41*) and are interpreted as crustal melts (*10, 14, 17*) may have resulted from this orogenic event. The expected early Paleozoic suture would lie along the MCT and its southern imbricates, which form the boundary between the Greater and Lesser Himalayan terranes.

Throughout the remainder of Paleozoic time, northern India was buried by the Tethyan succession (*5, 40*). Rifting along the northern Gondwana margin began in the late Paleozoic and continued into the Cretaceous (*42*). The Lhasa block, which probably also consists of Neoproterozoic accretionary material, detached from northern India in early Mesozoic time and collided with southern Eurasia in Late Jurassic–Early Cretaceous time (*42, 43*). India detached from Africa, migrated northward, and collided with Eurasia in Eocene time (*3*).

At the onset of Cenozoic orogenesis (~55 Ma), Lesser Himalayan rocks rested on the Indian shield and were separated from the Greater Himalayan terrane by an ancient suture. The Greater Himalayan terrane was overlain by the Tethyan succession (Fig. 4). Thrust faults propagated southward through Tethyan rocks as they entered the subduction zone along the south flank of Eurasia, forming the Tibetan Himalaya and metamorphosing underlying Greater Himalayan rocks during Eocene-Oligocene time (*6, 44*). In the early Miocene (*45*) the basal thrust incorporated Greater Himalayan rocks, and by the middle Miocene, thrusts had propagated into the Lesser Himalaya and Subhimalaya (*24*).

Most reconstructions of the Himalayan thrust belt restore Greater Himalayan rocks below Lesser Himalayan strata (*8, 46*) and are based on the assumption that the Greater Himalayan rocks are Indian shield basement. Our hypothesis that Greater Himalayan rocks were thrust over Lesser Himalayan strata during early Paleozoic time requires a lesser amount of Cenozoic displacement on the MCT. Cenozoic strain in the MCT zone (*9, 47*) may partially or completely overprint the Paleozoic deformation, such that the amounts of both Paleozoic and Cenozoic displacement on the MCT may be inscrutable. Whether a large portion of Greater Himalayan metamorphism occurred during early Paleozoic time is a fundamental question in Himalayan tectonics. The validity of the hypothesis can be tested by searching for evidence of early Paleozoic metamorphism and deformation in Greater Himalayan rocks and syntectonic sedimentation in the Cambrian-Ordovician part of the Tethyan succession in Nepal.

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