of the AYF, and throughout the overlying Ordovician Nilgiri Limestone there are multiple high-angle NW-dipping brittle normal faults (D_4). Cumulative extensional displacement accomodated by D_2-D_4 structures is unknown but thought to be significant.

09:00 AM Ryerson, F. J.

THE NEOGENE THRUST, UPLIFT AND DENUDATION HISTORY OF SOUTHERN TIBET

HARRISON, T.M., YIN, An, CHEN, W., Dept. Earth & Space Sci., UCLA, Los Angeles, CA 90024; RYERSON, F.J., Lawrence Livermore Nat. Lab., Livermore, CA 94550; KIDD, W.S.F., Dept. Geol. Sci., SUNY, Albany, NY 12222; COPELAND, P., Dept. Geosci., Univ. Houston, TX 77204

A growing body of evidence links changes in local, and possibly global climate to evolution of the Himalayan-Tibetan mountain system. Knowledge of the timing of mountain building and decay is pivotal to fully evaluating this relationship, but is incompletely known. For example, it has been proposed that motion on the Main Central thrust (MCT), generally thought to be the earliest of the crustal-scale thrusts in the collision zone, is responsible for development of the Northern Himalayan normal fault (NHF). However, the timing of movement on the MCT is poorly understood. We have recently documented two previously unrecognized thrust systems, the north-dipping Gangdese system (GTS) and the younger south-dipping Renbu-Zedong system (RZT), that have implications for both the orographic history of southern Tibet and timing of the MCT. West of Lhasa, the GTS juxtaposes the Late Cretaceous Xigaze Group (XG) over Tethyan rocks, whereas east of Lhasa, the fault juxtaposes the Late Cretaceous-Eocene Gangdese batholith (GB) over Tethyan rocks. Near Zedong, the GT is marked by a >200-m-thick mylonitic shear zone. Based on $^{40}Ar/^{39}Ar$ thermochronology, the age of the GT is constrained to between 27 and ~24 Ma with a minimum slip rate of 7±3 mm/yr. Displacement of at least 50 km is suggested from the length scale of rocks to the north uplifted during the early Miocene. The early Miocene rapid cooling previously observed in the northern and central GB very likely reflects the onset of rapid denudation following crustal thickening at these locations. Northwest of Xigaze, a major south-dipping backthrust in the hanging wall of the Gangdese thrust puts the XG over Tertiary conglomerates and the GB. A N-S dyke that cross-cuts the backthrust places a lower bound of 17.8±0.8 Ma on the age of the GTS, and may indicate modest E-W extension associated with this early thickening phase. In places, the younger RZT is thrust over the trace of the GT and unconsolidated sediments suggesting it may locally be active. Because the sequence of thrust development on the southern edge of the collision zone has been younging southward, the age of the GT may provide an upper age limit of 24 Ma for the initiation of movement on the MCT. This is consistent with the argument derived from thermobarometry and cooling ages that tectonism was in progress at 20.9±0.3 Ma, and with the oldest established age of anatectic material thought to be related to MCT activity of 24 Ma. Geochronological results permit the possibility that the MCT, the NHF, and the RZT are coeval and related products of the same evolving mechanical system.

09:15 AM Harrison, T. Mark

THE NYAINQENTANGHLA RANGE, SOUTHERN TIBET: TIMING OF THE ATTAINMENT OF A LARGE, HIGH PLATEAU AND IMPLICATIONS FOR DEVELOPMENT OF THE ASIAN MONSOON

COPELAND, Peter, Dept. of Geosci., Univ. of Houston, Houston, TX 77204-5503, T. Mark HARRISON, Earth and Space Sci., UCLA, Los Angeles, CA 90024

The Nyainqentanghla mountain range in southern Tibet (~80 km NW of Lhasa) provides an opportunity to study the crustal thickening history of the Tibetan Plateau by quantifying the time and magnitude of motion on the major range-bounding faults. This range is a NE-SW trending structure adjacent to the ~ 150 km long Yaingbaijain graben , one of a series of grabens interpreted to have accommodated E-W extension due to gravitational collapse of the Tibetan Plateau. The Nyainqentanghla consists of granitic igneous rocks and schsits and gneisses; metamorphic assemblages in these rocks suggest peak conditions of ~5 kbar and 600 °C (Harris *et al.*, 1988).

The boundary between the basin and range is a ~100 m thick mylonitic shear zone with a clearly normal sense of motion (down to the SE). Thermochronologic data have been obtained from within this shear zone as well as the core of the mountain range: A U-Pb age on two fractions of sphene from a leucocratic dike that cross-cuts the metamorphic and deformational fabric of the shear zone in the south-central section of the range indicate an age of 11.1 ± 0.2 Ma (Tc ≃ 600°C); $^{40}Ar/^{39}Ar$ analysis of hornblende and K-feldspar from an outcrop of amphibolite 2 m away yield an age of 6.5 ± 0.9 Ma (Tc ≃ 550°C)and a minimum age of 4.0 ± 0.2 Ma (Tc ≃ 200°C), respectively. These U-Pb data constrain the timing of peak metamorphism to pre-11 Ma while the $^{40}Ar/^{39}Ar$ data suggest very rapid cooling in the interval 7 to 4 Ma., which we interpret to be the result of normal faulting. Other thermochronologic and paleomagnetic data from the shear zone and the interior of the range constrain the unroofing and structural development of the Nyainqentanghla and are consistent with initial formation of the Yaingbaijain graben in the late Miocene.

If, as has been suggested, the formation of the grabens in southern Tibet is the result of the Tibetan Plateau reaching a maximum sustainable elevation, then these data from the Nyainqentanghla indicated a high plateau since ca. 7-6 Ma. This is consistent with data which indicate a change in climate (intensification of the Asian monsoon) at about 6.9 Ma in central Nepal (Harrison *et al.*, 1993), 7.4-7.0 Ma in northern Pakistan (Quade *et al.*, 1989) and *ca.* 8.0 Ma in the Arabian Sea (Murray and Prell, 1991)

09:45 AM Kerrick, Derrill M.

PALEOCLIMATIC CONSEQUENCES OF CO_2 RELEASED DURING REGIONAL METAMORPHISM IN THE HIMALAYAN OROGEN

KERRICK, Derrill M. and CALDEIRA, Ken, Earth System Science Center and Geosciences Dept., Penn State University, University Park, PA 16802

Extensive portions of the Tethyan orogen underwent regional metamorphism that may have been contemporaneous with the Paleocene/Eocene global warming. The amount of metamorphic CO_2 produced at depth in the Himalayan orogen was computed from the duration of prograde metamorphism, and the proportions and bulk compositions of metamorphic CO_2 source rocks. If CO_2 was generated at a constant rate during the prograde event, we estimate that $10^{18}-10^{19}$ moles/Ma of metamorphic CO_2 were produced at depth. However, because extensive decarbonation occurs during progradation through the lower greenschist facies, CO_2 production may have been two to three times more rapid than this estimate.

In addition to the Himalayan orogen, a large portion of the Mediterranean Tethys underwent Eocene regional metamorphism. The total estimated Eocene metamorphic CO_2 production from the Mediterranean Tethys is approximately 10^{18} moles/Myr.

Escape of metamorphic CO_2 to the atmosphere is indicated by the global correlation between the distribution of major zones of seismicity and carbon dioxide discharged from hot springs. In light of large fluid/rock ratios, significant expulsion of CO_2 to the atmosphere may have occurred by focused fluid flow along shear zones such as the extensive Main Central Thrust in the Himalayan orogen. Calculations of CO_2 consumption by silicate weathering show that CO_2 fluxes to the atmosphere of ca. 10^{18}/Ma could account for inferred Eocene atmospheric CO_2 contents and, thus, have contributed to Eocene warming. If a significant fraction of this CO_2 escaped to the Earth's surface, then the India/Asia collision would have contributed to greenhouse warming in the early to mid Cenozoic.

Raymo and Ruddiman proposed that the India/Asia collision, and the consequent uplift of the Himalayas and Tibet, produced a cooling trend in the late Cenozoic. We add that the India/Asia collision may have been responsible for both early to mid Cenozoic warmth and late Cenozoic global cooling.

10:00 AM Derry, Louis A.

CARBON CYCLING AND O_2 LEVELS DURING NEOGENE TIME: IMPACT OF HIMALAYAN UNROOFING AND EROSION

DERRY, Louis A., Hartwick College, Department of Chemistry, Oneonta, NY 13820, (derryl@newton.hartwick.edu); FRANCE-LANORD, Christian, CNRS/CRPG, BP. 20, 54501 Vandoeuvre-les-Nancy, France

Geochronological evidence from the Himalaya and sedimentary evidence from the Indian Ocean shows that erosion rates in the Himalayan region accelerated markedly in latest Oligocene or Early Miocene time. Rapid tectonic unroofing (Hodges et al., 1992) and ersosion appear to have led directly to the subariel exposure of the High Himalayan Crystalline Complex (HHC) before 18 Ma. Erosion of this narrow belt of mid-crustal rocks has dominated the particulate flux into the Bay of Bengal since. Based on Nd-Sr isotopic mass balance, we estimate that the HHC presently accounts for *ca.* 5% of global suspended sediment, while only covering 0.03% of the land surface. Work in progress should allow us to define more precisely the Oligocene-Early Miocene erosional history of the Himalaya.

The flux of sediment into the Bengal Fan traps a large quantity of organic carbon of mostly terrestrial origin. The present day C_{org} burial flux in the Bengal Fan is approximately 8×10^{11} mol/yr, or *ca.* 20% of the global total. This demonstrates the ability of large fluxes of terrigineous sediment to perturb the global carbon cycle. Model calculations using geochemical proxies for erosion rates (Sr and Nd isotopes) show a large increase in erosion rate in Early Miocene time, coincident with rapid erosion of the Himalaya. When these rates are combined with the carbon isotope mass balance, we can make quantitative estimates of the rate of C_{org} burial as a function of time. C_{org} burial rates increase in Early Miocene time, and vary but remain high throughout the Neogene.

Marine $\delta^{13}C$ values fell after 14 Ma, interpreted to imply a decrease in *fractional* organic carbon burial and decreasing PO_2 levels in late Neogene time (Shackleton, 1987). However, we find that *total* burial rates remained high as C_{org} burial shifted increasingly to terrigineous clastic sediments. This shift was aided by increasing oxygenation of ocean deep water. A recycling model that considers variable isotopic fractionation between HCO_3 and C_{org} suggests that decreasing $\delta^{13}C$ in late Neogene carbonate does not require that PO_2 levels dropped. Stable or increasing Neogene PO_2 is consistent with independent evidence.

am TUE

10:15 AM Quade, J.

MAJOR SHIFTS IN THE $^{87}Sr/^{86}Sr$ RATIOS OF LARGE PALEORIVERS DRAINING THE HIMALAYAS OF CENTRAL NEPAL OVER THE PAST 10 MA.

QUADE, J., Dept. of Geosciences, University of Arizona, Tucson, AZ 85721

The contribution of rivers draining the Himalayas to changes in the Sr isotopic composition of the oceans over the past 20 Ma is widely recognized, and yet little direct information on variations through time in the $^{87}Sr/^{86}Sr$ ratios of Himalayan paleorivers exists. Such information potentially resides in thick sequences of fluvial sediments (the Siwalik Group) deposited in the Himalayan foreland of the Indian sub-continent by large rivers tributary the paleo-Ganges. We measured the $^{87}Sr/^{86}Sr$ ratios of aquatic shell and soil carbonate spanning the last ~10 Ma from sediments of the Siwalik Group in Nepal. The shell data suggests that paleorivers in central Nepal varied between 0.728 to 0.744 over this period, while soil carbonate values varied between 0.727 and 0.752 in a nearby section. These large $^{87}Sr/^{86}Sr$ variations probably reflect changes due to erosion and/or tectonism of available bedrock in watersheds . The high $^{87}Sr/^{86}Sr$ ratios values, which peak at ~ 6 to 4 Ma, are similar to those of rivers draining Higher Himalayan Crystallines today. Lower ratios likely reflect a greater contribution to riverine Sr from the varied lithologies of the Lesser Himalayan Series. Our results suggest that the changes in the marine $^{87}Sr/^{86}Sr$ ratios in the last 20 Ma may in part result from shifts in the $^{87}Sr/^{86}Sr$ ratios of the Himalayan rivers themselves, and not wholly from changes in riverine Sr fluxes.

provenance signatures. This, along with observed on-strike facies changes, may indicate that basin bottom topography (possibly caused by syn-depositional faulting) led to intrabasinal sediment reworking.

Two possible models are proposed for the origin of the CBF basin:

1) The mapped Antler thrust fault on the southwestern edge of the CBF trough (B. Skipp, 1993, GSA Abs., v. 25, no. 5, p. 147) coupled with observed cannibalization of already deposited limestone turbidites suggests that a sinistral transpressional orogenic system caused syn-depositional Late Kinderhookian faulting and abrupt basin subsidence;

2) Rates of sedimentation and basin subsidence are similar to the loaded *and* normal faulted Pennsylvanian Atoka Formation in the Arkoma foreland basin of the Ouachita region of Oklahoma and Texas.

11:45 AM DeCelles, P. G.

THE CANYON RANGE CULMINATION, CENTRAL UTAH SEVIER THRUST BELT: LONGTERM CONTROL ON SYNOROGENIC SEDIMENTATION IN CORDILLERAN FORELAND BASIN

DeCELLES, P.G., Dept. of Geosciences, Univ. of Arizona, Tucson AZ 85721; MITRA, G., Dept. of Geological Sci., Univ. of Rochester, Rochester NY 14627; and LAWTON, T.F., Dept. of Geology, New Mexico State Univ., Las Cruces NM 88003.

The Canyon Range thrust (CRT) in central Utah juxtaposes a several-km-thick sheet of Precambrian and Cambrian quartzite and limestone with Cambrian through Devonian carbonate and siliciclastic rocks and Cretaceous synorogenic conglomerate. The CRT is folded into an eastward-verging, overturned antiform-synform pair, owing to uplift over a large footwall imbricate fan in the Cambrian Tintic quartzite. The imbricate fan probably is associated with a major ramp in the Pavant thrust, and produced the Canyon Range culmination in the western Canyon Range. The structure was reactivated during displacements on thrusts that are younger and structurally lower than the CRT.

The CRT is overlapped by the Canyon Range Formation (CRF), a thick (>1 km) synorogenic, alluvial-fan and fan-delta conglomerate. The CRF comprises 8 mappable units of alternating carbonate- and quartzite-clast conglomerate. The lowest two conglomerate units are present only in the hinge of the synformal CRT sheet. The next three units are present in both limbs of the CRT synform, as well as in the proximal footwall of the CRT (i.e., they are cut by the CRT). The top three conglomerate units overlap the CRT, extend across both limbs of the synform, and are incorporated into a growth fault-propagation anticline above the frontal tip of the CRT. Progressive unconformities in the CRF indicate deposition during folding of the CRT sheet and minor, out-of-the-syncline displacement along the frontal CRT.

All of the conglomerate was shed eastward from both limbs of the synformal CRT sheet and from the core of the Canyon Range culmination. The carbonate conglomerates indicate Cambrian through Devonian sources and quartzite conglomerates were derived from Precambrian through Cambrian quartzites. An overall upsection increase (to ~90%) in Tintic clasts indicates progressive erosion of the CRT sheet and eventual breaching of the footwall imbricate fan. Age dates from the CRF are not available, but the presence of marine facies in one of the lower carbonate conglomerates suggests a Turonian or Coniacian age for the lower part of the conglomerate. We tentatively correlate the upper several hundred meters of quartzite conglomerate with the Paleocene North Horn Formation of the Gunnison Plateau to the east. If correct, these correlations imply that the Canyon Range culmination was the dominant sediment producer in the central Utah Sevier thrust belt for roughly 30 Myr during Late Cretaceous-Paleocene time. This period of uplift in the culmination and minor reactivation of the CRT *post-dated the main phase* of displacement on the CRT, which probably took place during Early Cretaceous time. Thus, the CRT and Canyon Range culmination may have dominated sediment production for >50 Myr in the central Cordilleran foreland basin.

SESSION 65, 08:00 AM

Tuesday, October 26, 1993

T14. International Division: Evolution and Global Consequences of the Himalayan Orogenic System (Part II)

HCC 309

08:00 AM Macfarlane, Allison M.

TIMING CONSTRAINTS ON THE TECTONIC EVENTS IN THE CRYSTALLINE CORE OF THE HIMALAYA, LANGTANG NATIONAL PARK, CENTRAL NEPAL.

MACFARLANE, Allison M., Department of Geography and Earth Systems Science, George Mason University, Fairfax, VA 22030-4444.

In Oligocene to Pliocene times, significant shortening in the hinterland of the Himalayan orogen occurred within Indian plate rocks. Two major faults that outcrop in the Nepal Himalaya, the Main Central Thrust (MCT) and the Main Boundary Thrust (MBT), accommodated much of this compression. Recent $^{40}Ar/^{39}Ar$ geochronologic data on units from the MCT zone and its hanging wall at Langtang National Park indicate a complex history for both of these major faults. Detailed mapping revealed two distinct periods of motion associated with the MCT: an early syn-metamorphic ductile phase of motion and a late brittle phase of thrust motion. Brittle reactivation of the MCT zone occurred at 2.3 Ma, based on $^{40}Ar/^{39}Ar$ dating of neoblastic muscovites from the brittle fault zones, in response to transport over a ramp in the MBT. Thus, the still-active MBT is constrained to have been active in Pliocene times at Langtang. Ductile deformation on the MCT is constrained by $^{40}Ar/^{39}Ar$ dating of mylonitic muscovites to have occurred prior to 5.5 Ma. Similarly young $^{40}Ar/^{39}Ar$ ages from micas within the hanging wall (4.6-9.7 Ma) contrast with U-Pb dates of 16-20.5 Ma from metamorphic monazites and zircons from hanging wall units (Parrish et al., 1992), suggesting that the majority of the hanging wall experienced relatively slow cooling in Miocene time. A $^{40}Ar/^{39}Ar$ age of 19.3 Ma for a biotite from an uppermost hanging wall gneiss, when compared with late Miocene U-Pb ages for a nearby granite, suggests rapid cooling, perhaps in response to unroofing along the South Tibetan detachment system, outcropping to the north.

08:15 AM Sorkhabi, Rasoul B.

FISSION-TRACK THERMOCHRONOLOGY IN THE HIMALAYA: PROGRESS, PROBLEMS, AND PROSPECTS

SORKHABI, Rasoul B, and STUMP, Edmund, Department of Geology, Arizona State University, Tempe, AZ 85287.

Fission-track dating appeared 30 years ago with Price and Walker's development of a procedure to use chemically etched fission tracks in uranium-bearing minerals for age determination. With the realization that fission tracks are sensitive to relatively lower-temperature thermal events and hence their potential in unraveling the recent evolution of orogenic belts, such as the Himalaya, the FT technique underwent something of a renaissance. In the past two decades, several FT studies have been carried out in the Himalaya, especially in the Trans-Himalayan Batholith and the Higher Himalayan Crystalline rocks in Pakistan and India. After a critical overview of these studies, we will touch on some of the problems associated with the FT thermochronology such as precision and accuracy of the ages with special emphasis on the Himalaya. We will then highlight some of the developments in FT thermochronology such as track-length measurements and how they can be of use in Himalayan studies. Using FT experiences from the Himalaya as well as from other orogenic belts, various strategies for reconstructing thermotectonic histories of igneous rocks, metamorphic belts, and sedimentary basins will be discussed in order to demonstrate their prospects in tackling geological problems in the Himalaya. Particular attention will be paid to geological interpretation of FT data within the overall framework of thermochronology and in relation to landscape development.

08:30 AM Parrish, Randall R.

MIOCENE (22±1) Ma METAMORPHISM AND TWO STAGE THRUSTING IN THE GREATER HIMALAYAN SEQUENCE, ANNAPURNA SANCTUARY, NEPAL

PARRISH, RANDALL R., Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8, and HODGES, K. V., Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139

We have used U-Pb dating of zircon and monazite to determine the chronology of structural events within the Greater Himalayan sequence above the Main Central Thrust along the Modi Khola transect of Nepal. The Lesser Himalayan sequence, including the Ulleri augen gneiss, is separated at this longitude from the kyanite grade sheared Greater Himalayan metamorphic sequence by a retrogressed brittle thrust zone. Deformed kyanite grade migmatitic segregations within Formation I above the MCT zone are interpreted to be 22.5 Ma old and they contain inherited monazite. Undeformed post-kinematic pegmatite which cross cuts Formation II calc-silicate gneiss has zircons 22±1 Ma old and lacks inheritance. Formation III, previously thought to be granitic gneiss of Paleozoic age, has 35±1 Ma monazite as well as inherited zircon 620 Ma and older and appears to be a deformed Oligocene leucogranite. The Annapurna Formation, which lies above Formation III, has south directed ductile kinematic indicators and appears to be structurally conformable with the underlying Greater Himalyan sequence. A normal fault was not recognized at this contact. Highly sheared allanite-bearing pegmatites within calc-silicate schist of Annapurna Formation also are 22.0±0.5 Ma old and indicate that south directed thrusting is younger than 22 Ma and may have formed out of sequence with respect to the ductile MCT. A brittle normal fault separates the Annapurna Formation from overlying unmetamorphosed rocks of the Tibetan sedimentary sequence and constitutes the main metamorphic break in this area. It may be a branch of the South Tibetan Detachment.

08:45 AM Coleman, M. E.

WEST-DIRECTED EXTENSIONAL DEFORMATION IN THE NORTH MARSYANDI RIVER REGION, WEST-CENTRAL NEPAL HIMALAYA.

COLEMAN, M.E., Department of EAPS, Massachusetts Institute of Technology, Cambridge MA 02139-4307.

Orogen parallel, syn-compressional normal faults have been identified in several parts of the Himalayan orogen, and it has been suggested that extensional tectonism has been episodic during the convergent evolution of the range. New research in the upper Marsyandi valley, west-central Nepal, provides direct evidence for three generations of west-directed extensional structures. The lower tectonostratigraphy of the study area consists of a 12 km-thick section of high-grade metasedimentary rocks of the Greater Himalayan sequence (GHS). Throughout the GHS compositional layering (S_0) has been transposed by F_1 isoclinal folds into parallelism with the predominant S_1 foliation (NE strike, 25°-45° dip to NW). At the top of the GHS a northwesterly dipping ductile shear zone, the Chame detachment (D_2), places a > 4 km-thick section of medium-grade marbles of the Cambrian Annapurna Yellow Formation (AYF) on the GHS. The detachment dips 25° - 30° NW, subparallel to S_1 foliation in the footwall. S_2 foliation is well developed within the shear zone. Mineral and stretching lineations(L_2) are oriented E-W, shallowly plunging to the west. D_2 kinematic indicators in the footwall, including S-C fabrics and west-verging F_2 folds, consistently indicate a sense of shear with top to the west, obliquely down dip of the detachment. S_2 persists into the hanging wall, where sheared-off, preserved F_2 folds are oriented at a consistent angle to S_0, indicating west-directed shearing. Tourmaline pegmatites, both concordant and discordant to the S_2 foliation are abundant in the hanging wall and footwall. A second zone of mylonites (D_3) in a 200-300 m-thick section of AYF is located 3 km up-section from the base of the AYF, and is interpreted to be younger than the Chame detachment because all pegmatite dikes are transposed into parallelism with S_3 mylonitic fabrics within the upper detachment zone. D_3 S-C fabrics and asymmetric west-vergent folds indicate movement with top to the west (obliquely down dip of the D_3 detachment). In the upper part

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ABSTRACTS WITH PROGRAMS

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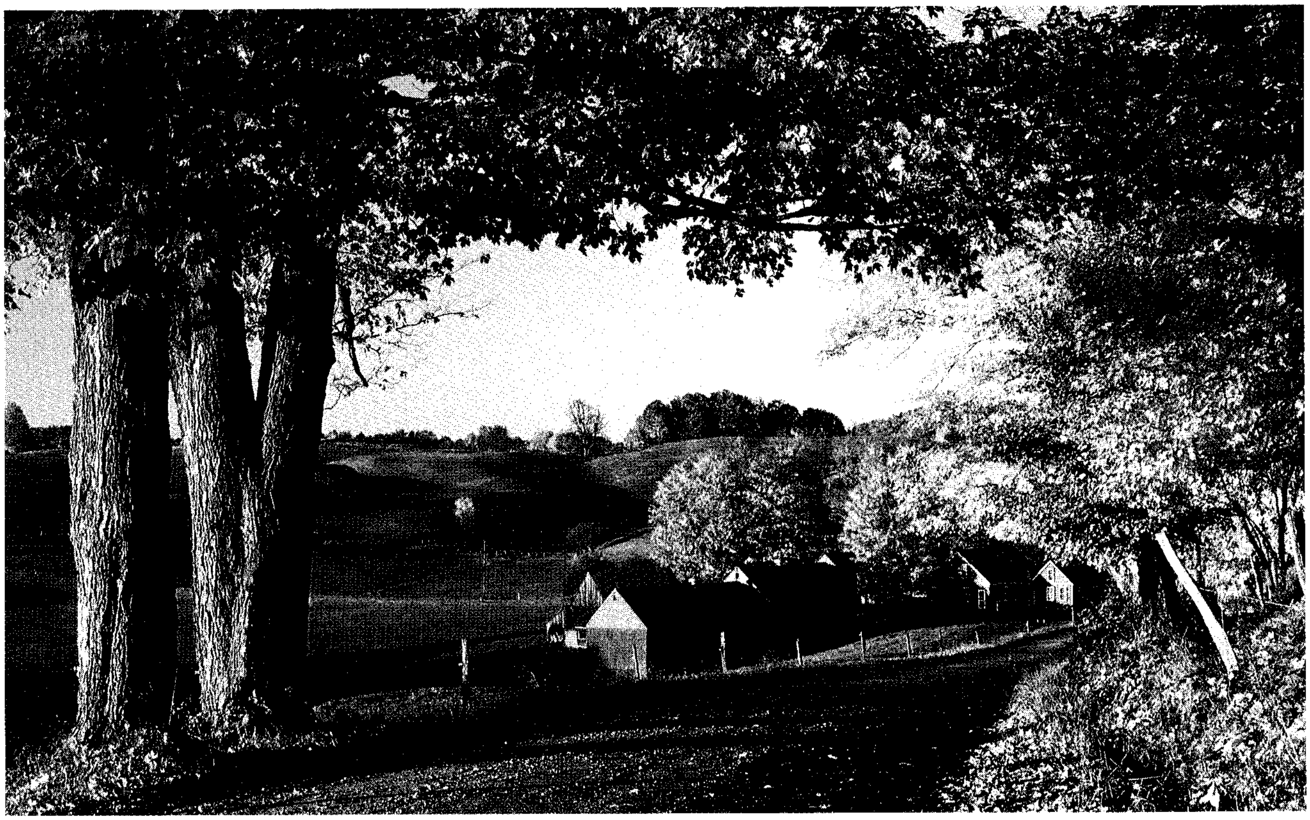

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