plate tectonic history, geological timing, and laboratory modelling to reconstruct the subduction history and the evolution of the central Mediterranean over the last 80 Myrs. We find that the dynamic evolution of the subducting oceanic lithosphere can reconcile the rapid, episodic back-arc migration with the slow African convergence, but only if the subduction process is restricted to the upper mantle.

T51F MC: 309 Friday 0830h

Raising Plateaus I *(joint with G, GP, S, V)*

Presiding: **M Edwards,** Technixche Universitaet Bergakadamie**; P Tapponnier,** Institut de Physique du Globe de Paris

T51F-01 0830h INVITED

Project INDEPTH and the Deep Structure of the Tibet Plateau

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Since 1992 the multinational consortium known as INDEPTH has collected a variety of geophysical and geological data along an approximately north-south transect across the Himalaya/Tibet Plateau collision zone. The most recent work (INDEPTH III) has focused on the central Tibet Plateau in order to, among other things, test the hypothesis of wide-spread partial melt in the deep Tibetan crust and probe the nature of the postulated "mantle suture" of Indian and Asian lithosphere at depth. The core of the latest field work is a 400 km corridor across the northern Lhasa Block and southern Qiangtang terrane within which an integrated active-passive seismic experiment and regional magnetotelluric (MT) profiles were recorded in 1998-1999. Additional MT surveys across the Kunlun and geologic field mapping in the central Qiangtang complemented the core effort. Although high conductivities and low seismic velocities at depth support the suggestion that partial melt continues to be present beneath both central and northern Tibet, the more prominent mid-crustal anomalies found during INDEPTH II and attributed to specific magma accumulations beneath the southern Lhasa block (e.g. seismic "bright spots", a distinct mid-crustal low velocity zones, ultrahigh conductivity pockets) are absent or less obvious to the north. Moreover, the depth to the top of high conductivity and relatively lower S velocity appears to deepen northward and are found in the lower crust beneath the Qiangtang. Crustal seismic refraction results indicate a decrease in crustal thickness from south (ca 62 km) to north (ca 57 km), and receiver functions indicate distinct changes in Moho character both and north of the Bangong Suture, which is the surface expression of the boundary between the Lhasa and Qiangtang terranes. Small-scale seismic reflection tests indicate a thick zone of reflective lamination (ductilely thickened crust?) that corresponds with an increase in seismic velocity at depth beneath the Lhasa block, with reflectivity terminating at the Moho. Local seismicity was found to be substantial, and is now being analyzed to improve crustal velocity models and further search for magma in the crust. Shear wave splitting studies indicate a pronounced contrast in anisotropy between southern and north Tibet. The Lhasa block shows little anisotropy until the Karakoram-Jiali fault system (well south of the Bangong suture), then strong anisotropy with rapid lateral variations that correlate with surface morphology well into the Qiangtang. New Pn results continue to support the suggestion of relatively fast (cold?) mantle beneath the Lhasa terrane in contrast to slower (hot?) mantle beneath the Qiangtang. At greater mantle depths (below 180 km), teleseismic tomography suggests a zone of high velocity dipping vertically beneath the northernmost Lhasa block, a possible remnant of subducted Indian lithosphere. Thus while results generally bolster the concepts of underthrust Indian mantle (beneath the Lhasa terrane) and widespread partial melt in the Tibetan crust (pointing to ductile flow for plateau uplift), they reveal important new lateral variations that presumably mark a more heterogeneous lithospheric response to regional collision.

URL: http://www.geo.cornell.edu/geology/indepth/indepth.html

T51F-02 0845h

Crustal and mantle structure of Northern Tibet imaged by magnetotelluric data

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Magnetotelluric (MT) data collected on the Tibetan plateau in 1995 and 1998 showed that an anomalously conductive middle and lower crust extended from the vicinity of the Yarlung Zangbo suture northward into Central Tibet. The most recent MT data collected in 1999 have extended this coverage northward to the Qaidam basin. In this presentation we will describe the results obtained from the combined broadband and long period magnetotelluric data. This combination allows both shallow crustal structure and deeper features to be resolved.

The resistivity models derived from the MT data show that the anomalously conductive crust continues northward almost to the Kunlun Shan. When combined with MT data to the south in the Lhasa and Qiangtang terranes, a symmetric pattern is observed. The highest conductances are observed close to the north and south margins of the anomalous zone and the conductance exceeds 10,000 Siemens. In between, a region with conductance of 3000-5000 S is observed. This conductance can be explained on the basis of either saline aqueous fluids or partial melt.

The conductivity structure also exhibits an inherent asymmetry. In the south between 29°N and 31 °N (Lhasa terrane) the high conductivity appears to be confined to the mid-crust. Here a combination of partial melt and saline fluids can explain the anomalous structure. The distribution of geothermal phenomena also shows a significant correlation with the north-south variation in crustal conductance. In contrast, to the north the high conductance centered at 34°N may extend through the entire crust. At these greater depths partial melt is more realistic explanation and the range of permissible melt fractions will be presented. This conductive feature may represent processes in the mantle that are actively underplating the crust and responsible for the Plio-Pleistocene volcanics found in Northern Tibet.

High conductivities have also been observed in the crust and mantle beneath the Altiplano. The depth to the top of the conductive zone is comparable to that detected in Tibet and similar lateral variations are also observed. However, the total conductance observed at several locations beneath the Altiplano is a factor of 3-5 greater than beneath Tibet. If fluids are responsible for both the high conductivity beneath the two locations, then the fluid layer thickness and/or porosity beneath the Altiplano must be significantly higher than beneath Tibet.

T51F-03 0900h INVITED

The Geologic Evolution of the Himalayan-Tibetan Orogen: Constraints and Models

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The >1400 km of N-S shortening absorbed by the Himalayan-Tibetan orogen since the onset of collision at ∼70 Ma is manifested in two ways: 1) discrete thrust belts with relatively narrow zones of contraction or regional decollement (e.g., MCT, Qimen Tagh-North Kunlun thrust system), and 2) distributed shortening over a wide region involving basement rocks (e.g., Nan Shan and western Kunlun thrust belts). This crustal shortening began synchronously in the early Paleogene in both the Tethyan Himalaya and Nan Shan, some 1400 km to the north suggesting that the plateau began to constructed between the northern margin of India and the Qilian suture zone simultaneously, and not through sequential propagation from south to north. Paleozoic and Mesozoic tectonic histories have exerted strong control on the Cenozoic strain distribution and history during development of the plateau (e.g., Cenozoic thrust belts developed along pre-existing sutures; the Triassic flysch complex spatially correlated with Cenozoic volcanism and thrusting; basement-involved thrusts in the Nan Shan and Kunlun Shan follow pre-Cenozoic tectonic belts). Also, the Early Cenozoic tectonic history of the orogen guided the Late Cenozoic strain distribution and petrogenesis in the Himalaya. The main strike-slip faults in the orogen are transfer faults linking either major thrust belts (e.g., Altyn Tagh system) or extensional systems (e.g., Karakorum fault).

At least five mechanisms appear to have contributed to the generation of syn-collisional igneous activty: 1) early crustal thickening folowed by slip along a shallow decollement (e.g., Himalayan leucogranites), 2) Paleogene slab break-off (e.g., Linzizong volcanics), 3) continental subduction in southern and central Tibet (e.g., <40 Ma calc-alkaline magmatism), 4) formation of releasing bends and pull-apart structures (e.g., Neogene-Quaternary volcanics along the Altyn Tagh), and 5) viscous dissipation in the upper mantle and subduction of flysch complexes to mantle depths (e.g., widespread Cenozoic magmatism across Tibet). Extensive Cretaceous crustal shortening in the Lhasa block led to this terrane behaving in a rigid fashion during the Indo-Asian collision. Mid-crustal exposures indicate that Late Cretaceous-Paleocene shortening of the Lhasa block was thin skinned.

Models assuming both strong (underthrusting of Tibet by India, N-directed continental subduction under northern Tibet, continental subduction during transpressional faulting) and weak (distributed shortening across Tibet, continuous accretion and erosion in a stable wedge, diffuse assimilation of Indian crust into the Tibetan lower crust) lithosphere have been proposed to explain the tectonic and petrologic evolution of the Himalayan-Tibetan orogen. The observations summarized above are generally consistent with variants of the strong crust models, but differ sharply from predictions of models assuming weak crust.

T51F-04 0915h

Role of pre-existing weaknesses in the pre-collisional "Andean Margin" (S. Lhasa Block) of the Tibet Plateau

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The Transhimalaya (the Gangdese Arc) represents the Andean margin of the southern Lhasa block active up until 70-80 Ma as collision began. An understanding of the pre-collisional condition of the Lhasa Block (and the other Tibetan terranes) is needed to study crustal evolution following continental collision. To this, a comparison of the arc/hinterland of the present day Andes and the pre-collisional Gangdese is of interest. Despite significant "post"-collisional shortening in the Lhasa Block (Linzizong, >25%; Eocene h.w. conglomerates >20%) and an extensive marine environment in the Upper Cretaceous, significant highlands existed (c.f. Gansser 1981; Murphy et al. 1997). It is likely that pre-collision features acted as mechanical instabilities hence foci for development of present day major structures in the Lhasa Block, including the Nyainqentanghla (NQTL) and the Damxung-Gulu Shear Zone (DGSZ). From NE NQTL, we introduce the DGSZ, a major (>70 km x >10 km) sinistral shear zone that pre- and post-dates (and has influenced the emplacement of) the main NQTL granite/gneiss. Significant fault zone weakening (shallowing of the frictional/viscous creep transition) and varying styles of deformation indicate multiple periods of DGSZ activity. Typically, DGSZ fabric is truncated-intruded by one of the various multistage granitic bodies that form the plutonic complex of the NQTL. Analyses of fault plane slip, ductile-brittle and Neotectonic features show that portions of the DGSZ have additionally experienced significant post-plutonism sinistral displacement requiring either DGSZ reactivation (separated by a period of plutonism) or protracted DGSZ activity (with a probable syn-kinematic (pull-apart?) environment for pluton emplacement). Consistent fault slip planes measurements were obtained throughout including within steep to overturned Eocene conglomerates N of the main DGSZ. Together with highly deformed (Linzizong) volcaniclastics in the DGSZ, these overturned Eocene rocks indicate large amounts of Cenozoic strain. East of the Gulu rift, an apparent eastern continuation of the DGSZ (the Jiali SZ) is dextral but with strikingly similar features (Armijo et al. 1989). We suggest that this is reactivation (and shear sense reversal) of an older portion of a much larger "proto-DGSZ". From our observations we suggest that the low-angle (8 Ma E-W extension) granitic mylonite (Pan + Kidd 1992, Harrison etal. 1995) is minor late plutonism and a widespread partially molten middle crust is not required. Our new data are consistent with analogue modelling of Tapponnier et al (1982), which generated one or two long, suitably oriented sinistral shear zones, parts of which tended to dextral reactivation as "escape" faults. On the DGSZ N. margin, 150 Ma (Ar/Ar-mu) gnt-staur schist (Copeland, 1990) suggests a pre-collision structure in the Lhasa Block. In aggregate, the DGSZ has played a central role in the accommodation of collisional shortening, escape, plateau collapse, protracted plutonism, and the switching between these mechanisms. It is likely located upon in a previous (strike slip) structure that was present in the old "Andean" hinterland. The DGSZ is further evidence that throughout Tibet, strike-slip faults are deep-seated, long lasting structures which influenced plateau evolution during "Andean" and "Tibetan" times.

T51F-05 0930h INVITED

Tectonic Rotations in the Central Andes: Implications for the Geodynamic Evolution of the Altiplano-Puna Plateau

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Several authors have suggested that the pattern of rotations and the curved shape of the Central Andes are related to oroclinal bending during the formation of the Altiplano-Puna high Plateau. Numerous additional paleomagnetic results have been obtained recently within the forearc regions and the Altiplano-Puna. The same pattern is observed in both areas. Rotations are clockwise to the south and counterclockwise to the north of the Arica bend. However, these rotations do not occur at the same time across the Andean chain. Within the forearc region: Paleomagnetic results (223 sites) obtained along the forearc of Northern Chile define a complex pattern of clockwise rotations. At some localities, clockwise rotations are greater than 45° and are related to local and regional deformation that occurred from the Late Cretaceous until the Oligocene. There is no evidence for rotation of the forearc area since the Miocene. Margin-parallel shear driven by oblique subduction and shortening during the Incaic phase of deformation may have played a major role in shaping the deformation and associated rotations within the forearc prior to the Neogene. The curved shape of the actual margin is partly inherited and partly the consequence of the Early to Middle Tertiary deformation, especially a counterclockwise rotation of southern Peru. Within the Altiplano-Puna: Paleomagnetic results indicate that rotations do occur at various scales and that the largest rotations are usually associated to local structures. Rotations are also found in Miocene rocks and are contemporaneous with the Andean deformation. Paleomagnetic and Anisotropy of Magnetic Susceptibility data indicate that 50 to 70% of the deviation in the orientation of the structural trends from north to south are accounted by rotation. Direction of contraction determined by fault kinematic data should be interpreted with caution and corrected for local tectonic block rotations. Oroclinal bending driven by propagating shortening on the eastern side of the Andes would provide the largest rotations within the forearc because the forearc should integrate all increments of Neogene rotation. This is not observed in the paleomagnetic data. There is also a lack of geological evidence for a bending of the forearc by an amount equivalent to the relative rotations recorded east of the western Cordillera. Thus, rotations found in the Altiplano domain cannot be explained by oroclinal bending of the whole margin during the Miocene. Shallowing of subduction around 25 Ma and the eastward shift of the volcanic arc contributed to a cooling and increase in the rigidity of the forearc region. We propose that the indentation of the Altiplano by the curved forearc induces counterclockwise rotations in the northern Altiplano and clockwise rotation in the southern Altiplano.

T51F-06 0945h

Temporal and Spatial Constraints on the Construction of the Andean Chain via Neogene Paleomagnetism from Peru

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Paleomagnetic data accumulated over the past thirty years rather consistently show that magnetic declinations roughly parallel structural trends for some 3000 km along strike of the Andean Mountain chain. Paleomagnetic declinations north of the Bolivian orocline trend northwest, whereas south of it, they point towards the northeast. Such a pattern of rotations, which is historically based mostly on Cretaceous data, has initiated the idea of a global mechanism for the flexure of the Andes and the building of the Altiplano. However, the relationship between the spatial and temporal development of the orogenic belt and its geometry remains loosely constrained, and controversy persists regarding the length scale and timing of the rotations. For this reason we performed a paleomagnetic study in Peru on ~700 samples (80 sites) of primarily lacustrine sediments from intermountain basins, the Sub-Andean belt, and along the coast. The formations we sampled are well constrained in age, ranging between 3 Ma and 20 Ma. Together they comprise among the youngest rocks sampled for Andean paleomagnetism. We concentrated our efforts in Peru because structural trends there are consistent over long distances. Our results obtained after stepwise thermal and alternating field demagnetization demonstrate positive fold and reversals tests. Site mean directions show rotations ranging between -25° and 0°. Interestingly, rotation magnitudes of the Neogene strata often equal those of the Cretaceous, suggesting that most of the counterclockwise rotational component is a recent phenomenon. Our results are highly compatible with a continuum strain partitioning model derived from relative plate motion trajectories and earthquake moment tensor solutions and much less compatible with models evoking partitioned vertical axis block rotations. This is probably the main distinction between orogenesis in Asia, where the limits of rotated fault blocks are well defined, compared to Peru, where the limits are more ambiguous. The Peruvian data also suggest that deformation occurs in discrete pulses lasting less than 2 million years and that the deformation would be too fast and too young to alone explain the origin of the Altiplano.

T51F-07 1030h

Formation of Topographic Barriers and Filling of Sedimentary Basins, a Mechanism for the Growth of the Tibetan Plateau. Examples of Northeastern Tibet : the Tanghenan Shan and Qinghainan Shan.

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The mechanisms, timing of uplift and thickening of the crust of the Tibet Plateau are still debated. Growth of the Tanghenan and Qinghainan ranges, in northeastern Tibet, are attested by kilometer-wide folds as well as the existence of seismic scarps indicating, respectively, northward and southward propagation of the seismic thrusts. These NW-SE trending ranges, about 250 km long, have the structure of anticlines growing upon thrust ramps of crustal scale.

Total station levelling and topographic map profiles were used to determine the geometry of different folded and uplifted alluvial levels. Along the Tanghenan Shan, 4 main terrace levels, with vertical heights above active stream beds of up to 120 m have 26Al-10Be cosmogenic surface exposure ages ranging from 2000 to 200,000 yrs, implying a vertical uplift rate of about 0.5-0.6 mm/yr. Six main levels are identified along the Qinghainan Shan with heights above the Chaka salt-lake base-level ranging from a few to 500 meters. Regional paleoclimatic data and a radiocarbon age of 3057+/-53 yr BP constrain the ages of the most recent terraces which were emplaced after the Last Glacial Maximum. The vertical offsets of T0 (12+/-3ka) at two sites (5+/-1m and 7.5+/-1.0m) define a vertical uplift rate of 0.4+/-0.2mm/yr and 0.6+/-0.3mm/yr. The ages of the higher terrace levels (T1 to T5) are obtained by correlating terrace emplacement with the spikes of the d18O curve from the Gulyia glacier ice core (Western Kunlun). The best correlation (rms=0.01) imply that the main levels T0 and T4 were emplaced during post-glacial warming stages 1 and 5e, respectively. Other levels correlate with interstadials at 37, 55 and 77 ka. The long term uplift rates obtained at the two sites are thus 0.78 and 0.55 mm/yr, consistent with the Holocene rates. Such rates, and the structural cross-sections, imply a shortening rate between 0.5 and 2 mm/yr and an age between 1 and 4 Ma for initiation of shortening along these ranges.

The eastern extremity of the Qinghainan range is cut and incised by the Huang He which has abandoned a set of terraces during its entrenchment through the Gonghe Basin. The terraces, which appear to be younger than 150 kyrs and the 600 m incision have recorded rapid downcutting of the Huang He after it was temporarily dammed by uplift of the Qinghainan Shan, at times drier than present. Such damming of the Gonghe Basin has led to deposition of about 1200 m of Quaternary sediments and to a present day elevation of 3000 m a.s.l. of the basin floor. The building of the northern Tibet plateau probably results from localized range growth leading to basin closure. Such a mechanism accounts well for emplacement of the Gonghe terraces and canyon incision west of Lanzhou. At the scale of Tibet, the maxima of the hypsographic curve are associated with high, elevated plains and probably result from a similar mechanism. Internal drainage within the plateau thus probably played an essential role in smoothing topographic gradients, leading to planation, hence plateau building.

T51F-08 1045h

Paleogene Syn-contractional Sedimentary Basins in the Eastern Tibetan Plateau

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Paleogene sedimentary basins within the interior of the Tibetan Plateau may record the early uplift history of the plateau related to the Indo-Asian collision. A sedimentologic-stratigraphic investigation of Paleogene strata in the northeastern Qiangtang terrane, eastern Tibetan Plateau, indicates lacustrine and alluvial-fan sedimentation in basins developed during regional NE-SW shortening. The Nangqian, Xialaxiu, and Shanglaxiu basins (96-97E, 32-33N) contain up to 3-km-thick successions of fine-grained lacustrine strata (mudrock, sandstone, and minor carbonate facies) and coarse-grained alluvial-fan and fan-delta deposits (conglomerate and sandstone facies). There are numerous examples of growth strata associated with fold-thrust structures in both fan and lacustrine deposits, indicating contractional deformation synchronous with sedimentation. Shortening in the fold-thrust system exceeded 18 km and likely induced crustal thickening and surface uplift. A Paleogene age for shortening and basin development is based on: 1) 33-36 Ma ages (^{40}Ar/^{39}Ar and U-Pb methods) for both interbedded volcanic horizons within the uppermost strata of the Nangqian basin as well as shallow-level intrusions which cut lower Nangqian strata; and 2) a lack of marine facies common in Cretaceous rocks of the Tibetan Plateau. Paleocurrent data and conglomerate/sandstone compositional analyses show that basins were fed from several directions by local sediment source areas composed of Carboniferous to Triassic carbonate and sandstone. The existence of numerous local sediment sources and the lack of a continuous regional stratigraphy for the different Paleogene basins suggest that each basin evolved independently and was probably fed by relatively small drainage networks. These basins may be analogous to late Tertiary hinterland basins developed in the retro-arc region of the Altiplano plateau of the Central Andes. Possible activation of numerous fold-thrust structures across the eastern Tibet plateau may have inhibited the development of a single, integrated foreland basin with a large

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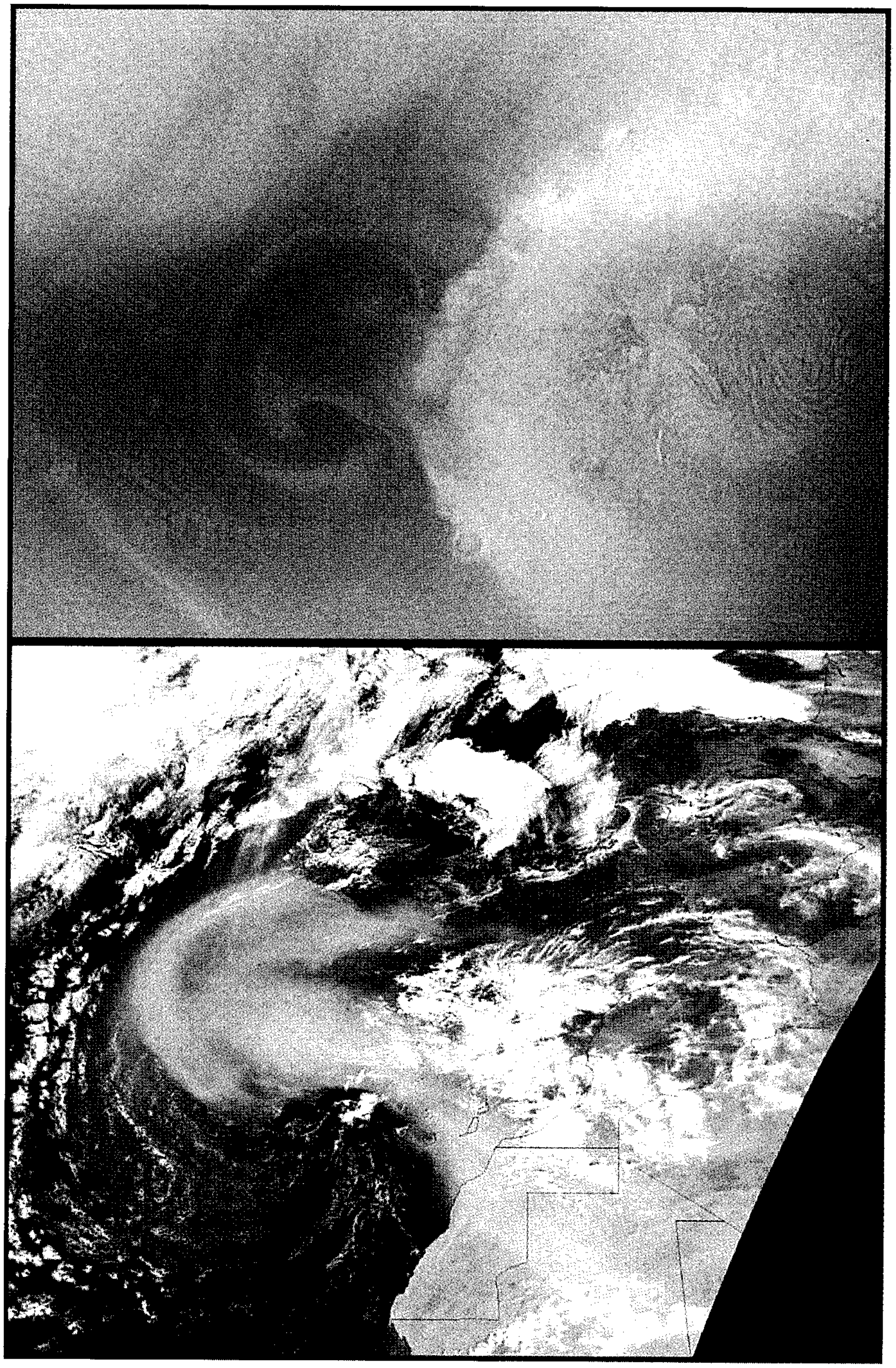

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