U.S. Department of the Interior
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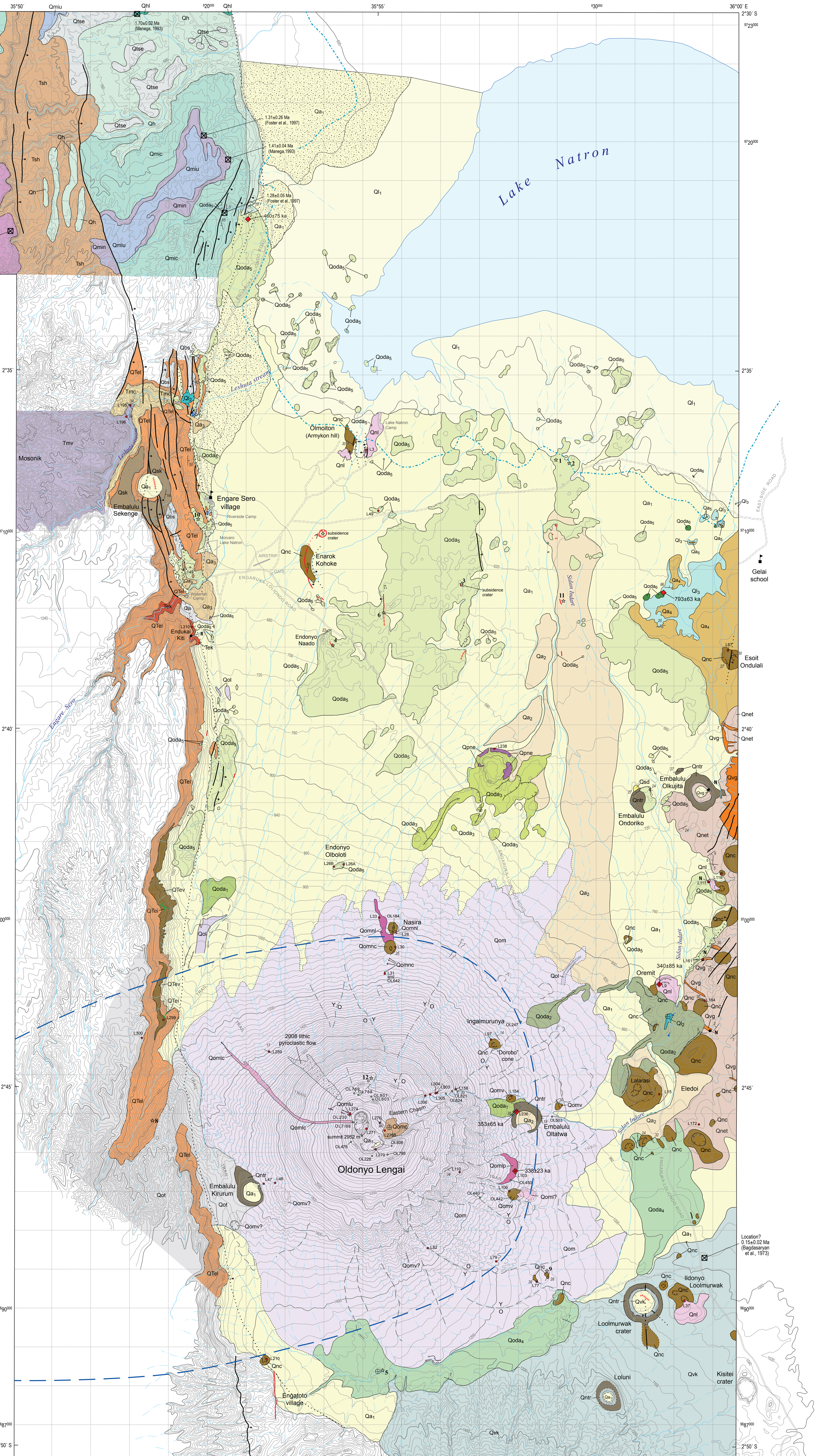
Open-File Report 2013-1306
Pamphlet accompanies map



Base from Surveys and Mapping Division, Ministry of Lands, United Republic of Tanzania. Mosonik (sheet 39/2), 1990; Oldonyo Lengai (sheet 39/4), 1990
Transverse Mercator projection, UTM zone 36.
New (1960) Arc datum

APPROXIMATE MEAN DECLINATION AND UTM GRID CONVERGENCE, 2012

SCALE 1:50 000

CONTOUR INTERVAL 20 METERS
EXCEPT 40-METER INTERVAL BETWEEN 1800- and 2800-METER ALTITUDE ON CONE OF OLDONYO LENGAI
VERTICAL DATUM UNSTATED

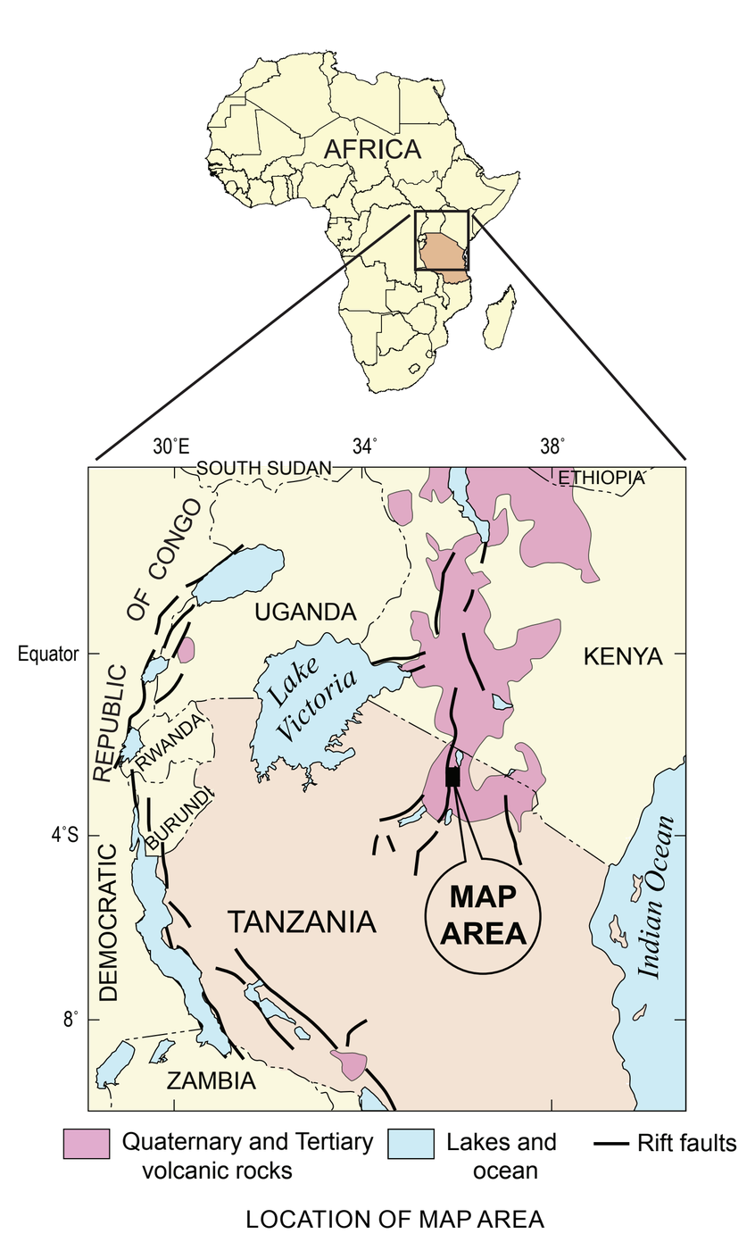
Geology mapped by D. Sherrod, M. Magigita, and S. Kwelwa, February–March 2010.
Assisted by Kisana Mollel and Olemelok Nantatwa

GIS database and digital cartography by D. Sherrod
Edited by Claire Landowski
Manuscript approved for publication Dec. 23, 2013

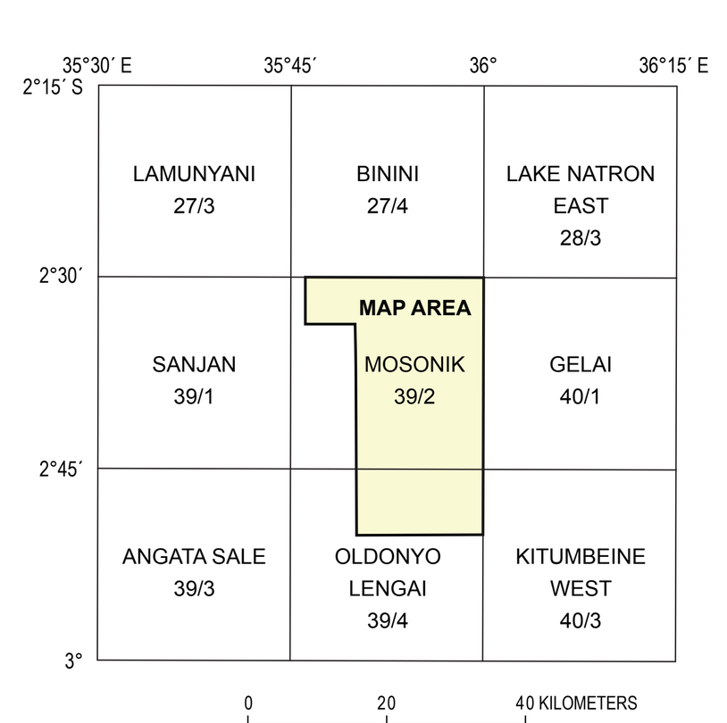
Index to Notable Features

[Shown on map by symbol (☆) and map number. Coordinates (east, north) are UTM zone 36, New Arc (1960) datum]

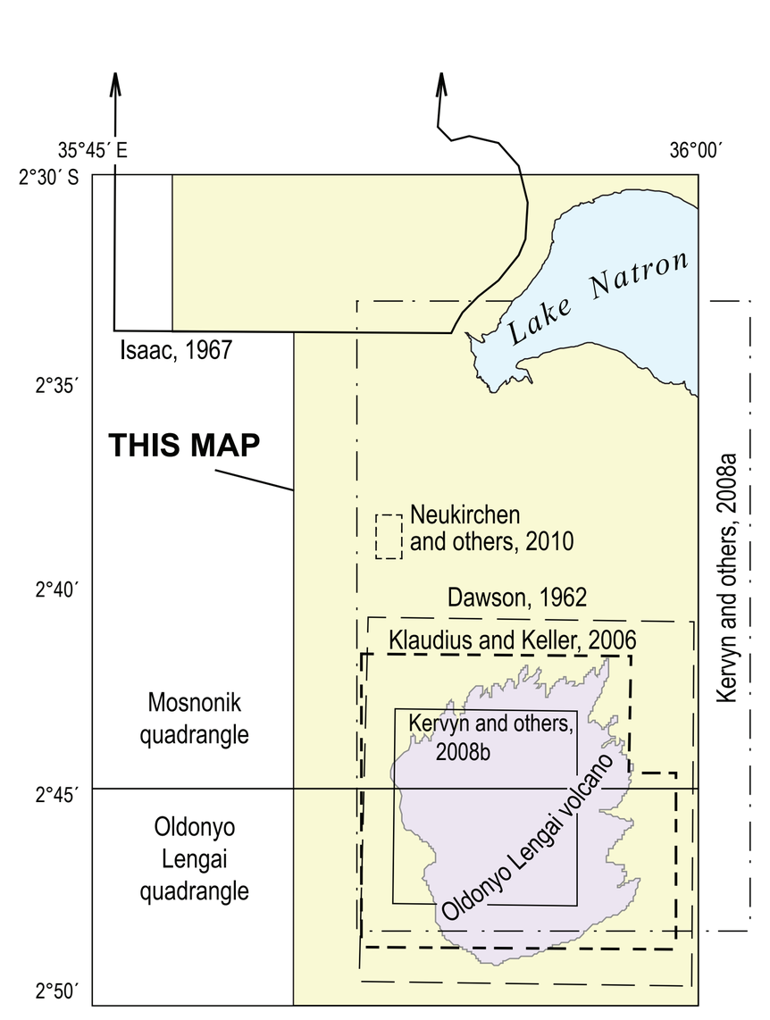
Map No.	Feature	Easting	Northing
1	Ancestral shoreline deposits atop debris avalanche deposits	828963	9711815
2	Ancestral shoreline deposits atop debris avalanche deposits	829307	9711731
3	Sand-and-pebble deposit (sand blow), liquefaction	826541	9708581
4	Sand-and-pebble deposit (sand blow), liquefaction, fig. 38*C* in explanatory pamphlet	823222	9707044
5	Tuff and sandstone between debris-avalanche deposits, fig. 32	824510	9688396
6	Sand-and-pebble deposit (sand blow), liquefaction, fig. 37*D*	824535	9707885
7	Subsidence pit, Holocene faulting, fig. 35*D*	822974	9709915
8	Thick tephra exposure west of Oldonyo Lengai	818623	9694749
9	Ultramafic inclusions in east and west exposures of tephra cone	828741	9690837
10	Good exposures, thickly bedded debris-avalanche deposits	819763	9710281
11	Holocene sag (graben); fig. 36	829053	9708108
12	Explosion(?) crater mapped from air photos	824174	9695877



LOCATION OF MAP AREA

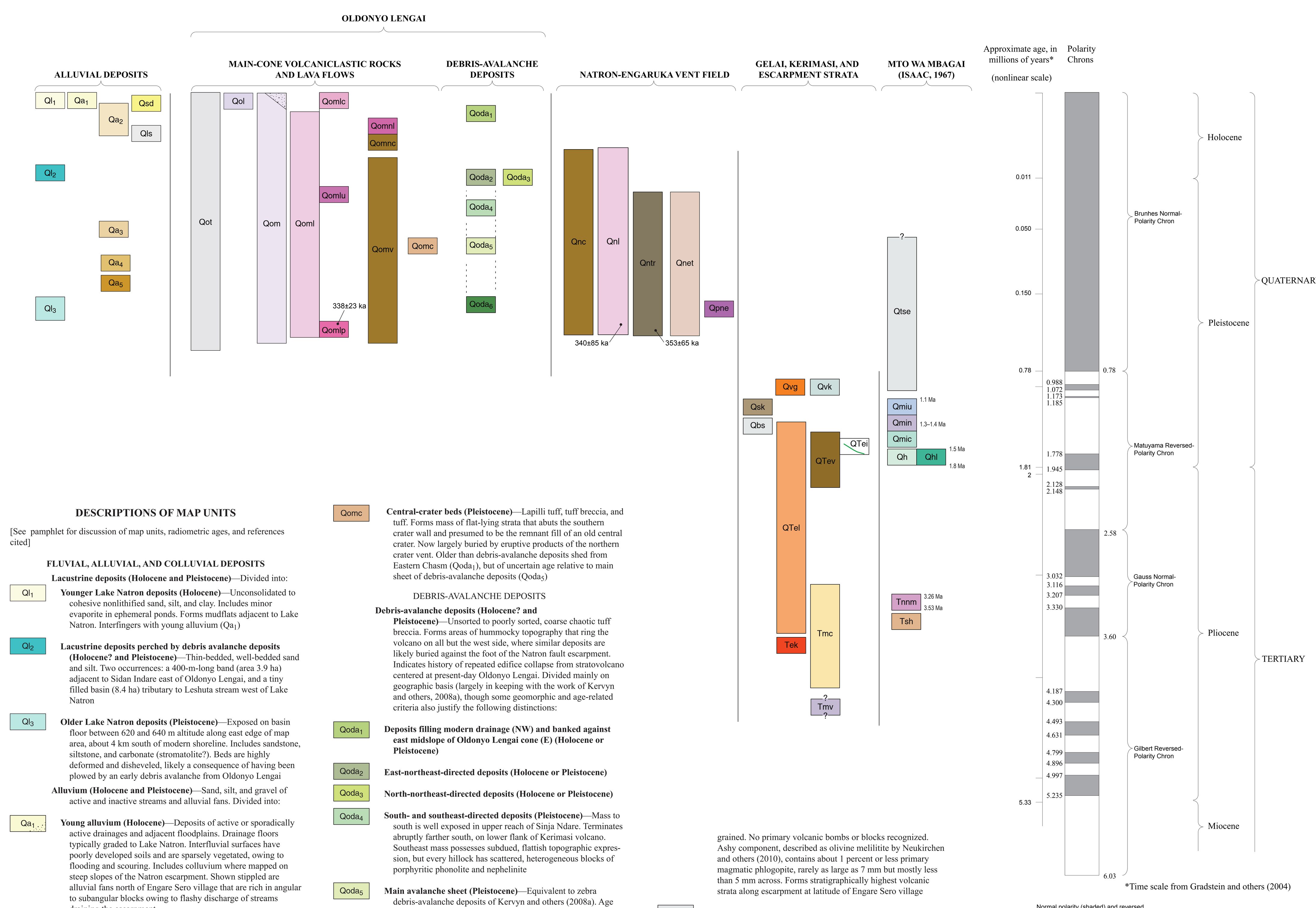


INDEX TO 1:50,000-SCALE TOPOGRAPHIC QUADRANGLE MAPS (NAME AND SHEET NUMBER)



INDEX TO PREVIOUSLY MAPPED AREAS

CORRELATION OF MAP UNITS



*Time scale from Gradstein and others (2004)

Normal polarity (shaded) and reversed polarity (white) shown for subchrons through end of Gilbert time

DESCRIPTIONS OF MAP UNITS

[See pamphlet for discussion of map units, radiometric ages, and references cited]

FLUVIAL, ALLUVIAL, AND COLLUVIAL DEPOSITS

Lacustrine deposits (Holocene and Pleistocene)—Divided into:

Ql_1 **Younger Lake Natron deposits (Holocene)**—Unconsolidated to cohesive nonlithified sand, silt, and clay. Includes minor evaporite in ephemeral ponds. Forms mudflats adjacent to Lake Natron. Interfingers with young alluvium (Qa_1)

Ql_2 **Lacustrine deposits perched by debris avalanche deposits (Holocene? and Pleistocene)**—Thin-bedded, well-bedded sand and silt. Two occurrences: a 400-m-long band (area 3.9 ha) adjacent to Sidan Indare east of Oldonyo Lengai, and a tiny filled basin (8.4 ha) tributary to Leshuta stream west of Lake Natron

Ql_3 **Older Lake Natron deposits (Pleistocene)**—Exposed on basin floor between 620 and 640 m altitude along east edge of map area, about 4 km south of modern shoreline. Includes sandstone, siltstone, and carbonate (stromatolite?). Beds are highly deformed and disheveled, likely a consequence of having been plowed by an early debris avalanche from Oldonyo Lengai

Alluvium (Holocene and Pleistocene)—Sand, silt, and gravel of active and inactive streams and alluvial fans. Divided into:

Qa_1 **Young alluvium (Holocene)**—Deposits of active or sporadically active drainages and adjacent floodplains. Drainage floors typically graded to Lake Natron. Interfluvial surfaces have poorly developed soils and are sparsely vegetated, owing to flooding and scouring. Includes colluvium where mapped on steep slopes of the Natron escarpment. Shown stippled are alluvial fans north of Engare Sero village that are rich in angular to subangular blocks owing to flashy discharge of streams draining the escarpment

Qa_2 **Deposits of areas rarely alluviated in past 200–2,000 years or more (Holocene)**—Lithologically similar to but older than young alluvium (Qa_1) on basis of geomorphic characteristics. Found in areas where stream channelization protects higher-standing areas from frequent stripping

Qa_3 **Perched sand and gravel (Pleistocene)**—Deposits result from the temporary damming and subsequent overflow of Engare Sero and Leshuta streams by Oldonyo Lengai-derived debris-avalanche deposits, upon which they were commonly emplaced. Found on west side of map area

Qa_4 **Gelai sandstone (Pleistocene)**—Light grayish-red sandstone and an overlying basalt-cobble veneer that extends outward from Gelai volcano (east side of map area). The “Gelai fans” overlie older Lake Natron beds (unit Ql_3) and debris-avalanche blocks in ancestral lake deposits (unit $Qoda_6$)

Qa_5 **High-standing alluvial fan (Pleistocene)**—Pebbly sandstone. Forms surface planed onto older Lake Natron beds (Ql_3). Surface topographic gradient projects higher into basin than top of Gelai sandstone (unit Qa_4)

Qsd **Sand dune (Holocene)**—Accumulation of sand on north flank of Embalulu Ondoriko tuff ring near Sidan Indare stream

Qls **Landslide deposit (Holocene or Pleistocene)**—Coarse blocky deposit. Mantles lower flank of escarpment just south of the mouth of Engare Sero stream and extends downslope into gully

ROCKS AND DEPOSITS OF OLDONYO LENGAI VOLCANO

DOWNWIND AND OTHER BEYOND-CONE DEPOSITS

Qot **Tephra (Holocene and Pleistocene)**—Ash beds. Shown only where sufficiently thick to obscure underlying rocks over large areas. Includes young ash that mantles lower west flank of modern cone and a thick tephra blanket that has accumulated downwind to the west atop the Natron escarpment over thousands of years

Qol **Mica-rich lahars (Holocene)**—Fine-grained lahar deposits rich in phlogopite. Located on north and northwest alluvial apron of volcano. Separate exposures may not be age-equivalent deposits

CONE-BUILDING VOLCANICLASTIC ROCKS AND LAVA FLOWS

Qom **Main-cone volcaniclastic rocks and lava flows (Holocene and Pleistocene)**—Stippled on northwest flank where pyroclastic flow(?) deposits of 2007–08 can be delineated from oblique photography. Mapped separately are:

Qoml **Lava flows (Holocene and Pleistocene)**—Chiefly nephelinite and phonolite, but includes recent carbonatite on west flank. Shown are those lava flows for which mapping is sufficient to approximate their extent; other less well-defined flows are contained within the unit of main-cone volcaniclastic rocks and lava flows (Qom). Subdivided into:

Qomlc **Carbonatite lava flows (Holocene)**—Pāhoehoe and ‘a‘ā of 2006 eruption

Qomlu **Nephelinite of upper flanks (Pleistocene)**—Remnants of lava flow, highest part of which is sometimes called “Pearly Gates” for the slot traversed through it by westside climbers’ trail

Qomlp **Phonolite lava flow on lower east-southeast flank (Pleistocene)**

Nasira tephra cones and lava flows (Holocene)—Extrusive volcanic rocks on lower north flank of Oldonyo Lengai. Undated. Divided into:

Qomnc **Tephra cones and spatter mounds**

Qomnl **Lava flows**

Qomv **Flank vent deposits (Holocene and Pleistocene)**—Forms chiefly tephra cones. Several supposed tephra cones are shown queried owing to burial by tephra of past several decades that has thoroughly mantled underlying deposits. Some of these have obvious cone morphology and likely are buried vent deposits; whereas others are more subdued, and their semicircular downslope edges may be underlain instead by the snouts of debris-flow deposits or by landslide or debris-avalanche blocks

Qomc **Central-crater beds (Pleistocene)**—Lapilli tuff, tuff breccia, and tuff. Forms mass of flat-lying strata that abuts the southern crater wall and presumed to be the remnant fill of an old central crater. Now largely buried by eruptive products of the northern crater vent. Older than debris-avalanche deposits shed from Eastern Chasm ($Qoda_1$), but of uncertain age relative to main sheet of debris-avalanche deposits ($Qoda_5$)

DEBRIS-AVALANCHE DEPOSITS

Debris-avalanche deposits (Holocene? and Pleistocene)—Unsorted to poorly sorted, coarse chaotic tuff breccia. Forms areas of hummocky topography that ring the volcano on all but the west side, where similar deposits are likely buried against the foot of the Natron fault escarpment. Indicates history of repeated edifice collapse from stratovolcano centered at present-day Oldonyo Lengai. Divided mainly on geographic basis (largely in keeping with the work of Kervyn and others, 2008a), though some geomorphic and age-related criteria also justify the following distinctions:

$Qoda_1$ **Deposits filling modern drainage (NW) and banked against east midslope of Oldonyo Lengai cone (E) (Holocene or Pleistocene)**

$Qoda_2$ **East-northeast-directed deposits (Holocene or Pleistocene)**

$Qoda_3$ **North-northeast-directed deposits (Holocene or Pleistocene)**

$Qoda_4$ **South- and southeast-directed deposits (Pleistocene)**—Mass to south is well exposed in upper reach of Sinja Ndare. Terminates abruptly farther south, on lower flank of Kerimasi volcano. Southeast mass possesses subdued, flattish topographic expression, but every hillock has scattered, heterogeneous blocks of porphyritic phonolite and nephelinite

$Qoda_5$ **Main avalanche sheet (Pleistocene)**—Equivalent to zebra debris-avalanche deposits of Kervyn and others (2008a). Age older than 10,000 years and possibly older than 50,000 years on basis of stromatolite and beach deposits that overlie it (Hillaire-Marcel and others, 1987)

$Qoda_6$ **Blocks in ancestral lake deposits (Pleistocene)**—Avalanche emplacement age likely in the range 240,000–135,000 years ago, which is a period of Lake Natron highstands estimated from U/Th ages from stromatolite associated with a 655-m-altitude paleoshoreline (Hillaire-Marcel and others, 1987). We presume that lacustrine beds, in which the avalanche blocks are embedded, formed during those highstands

ROCKS OF NATRON-ENGARUKA VOLCANIC FIELD

[Scattered vent deposits and lesser lava flows in the area from Lake Natron south for 40 km to village of Engaruka, as defined by Dawson and Powell (1969). Lithology and emplacement mechanisms discussed in detail by Mattson and Tripoli (2011); geochemistry is described by Keller and others (2006). Tuff rings and fine-grained tephra cones (tuff cones) are common across the length of the area, whereas coarser-grained tephra cones are found mainly in the divide between the modern Lake Natron basin and a large closed topographic depression south of it]

Qnc **Tephra cones (Holocene? and Pleistocene)**—Near-vent fallout tephra that built cone-shaped landforms. Many cones are built chiefly of fine-grained strata (tuff cones), but some are lapilli cones; agglutinate and spatter occur locally

Qnl **Lava flows**—Sparse ‘a‘ā and block flows ranging in composition from olivine melilitite to nephelinite. Issued from tephra cones (unit Qnc). See explanatory pamphlet for chemical analyses and evidence bearing on relative ages

Qntr **Tuff rings (Pleistocene)**—Tuff and lapilli tuff. Commonly fine-grained to very fine-grained, more so than tuff rings from volcanic arcs worldwide. The grain size distinction may arise from a greater role played by CO_2 as an explosive agent (compared to lake water or groundwater in many volcanic arcs) (Mattson and Tripoli, 2011). Age ranges widely, to judge from degree of erosional state, though all are thought to be younger than Gelai and Kerimasi volcanoes and therefore younger than 1 Ma. Phlogopite samples from tuff rings of Loolmurwak and Kisitei craters have K-Ar weighted-mean ages of about 0.37 Ma (Nos. 3 and 4, table 2; data of Macintyre and others, 1974)

Qnet **Extensive tuff deposits (Pleistocene)**—Yellowish gray to light brownish gray tuff and lapilli tuff. Chiefly pyroclastic-flow and debris-flow deposits that originated from tuff cones and rings of the Engaruka-Natron volcanic field. Beds 0.5–3.0 m thick. Includes some thinner fallout lapilli tuff, lapillistone (ash-size content minimal), and fine- to medium-grained sandstone

Qpne **Phonolite lava flow 10 km northeast of summit (Pleistocene)**—Slightly porphyritic lava flow or flat dome. Overtopped by debris-avalanche deposits of unit Qoda3, but age of those deposits poorly known. Relation to Oldonyo Lengai’s magma system unknown: if lava flow from central vent, then sufficiently old that erosion has made it topographically distinct; if peripheral dome, it stands well beyond the 6-km radius that encompasses all other vents associated with that volcano. May be a randomly emplaced rift-basin phonolite or, conceivably, an unusually silicic component of the Natron-Engaruka volcanic field

ROCKS OF THE ESCARPMENT AND GELAI AND KERIMASI VOLCANOES

Qvg **Volcanic rocks of Gelai volcano (Pleistocene)**—Chiefly lava flows and thin interbedded tephra. As described by Dawson (2008), forms shield volcano that ranges in composition from alkali basalt to trachyte, and upper slopes have scattered outcrops of trachyte. Sparse published chemical analyses are basanitic, (table 1, this map; Paslick and others, 1996). Radiometric age is about 1 Ma on basis of two gas extractions from a sample collected on south flank (table 3, No. 5; Evans and others, 1971)

Qvk **Volcanic rocks of Kerimasi volcano (Pleistocene)**—Volcaniclastic beds. Forms southern limit of our mapping; deposits not studied by us. As discussed by Hay (1976, p. 137), age older than 0.37 Ma, the average of several ages from mica-rich tuff of Loolmurwak and Kisitei craters

Qsk **Sekenge tuff ring deposit (Pleistocene)**—Slightly micaceous tuff, lapilli tuff, and tuff breccia. Has more bedrock rubble, including conglomeratic clasts, in its block component than any other tuff ring or tuff cone in the area, most of which are notably fine grained. No primary volcanic bombs or blocks recognized. Ashy component, described as olivine melilitite by Neukirchen and others (2010), contains about 1 percent or less primary magmatic phlogopite, rarely as large as 7 mm but mostly less than 5 mm across. Forms stratigraphically highest volcanic strata along escarpment at latitude of Engare Sero village

Qbs **Basaltic sedimentary strata (Pleistocene)**

Volcanic rocks of the Natron escarpment (Pleistocene and Pliocene)—Chiefly basalt, basanite, and tephrite in composition (Neukirchen and others, 2010). Divided into:

QTel **Lava flows**

QTev **Vent deposits**—Scoriaceous lapilli and ash. Bold lines show dikes

QTei **Dikes**—Broadly basaltic in composition. Intrude vent deposits (QTev) and, locally, underlying lava flows (QTel)

Tek **Lava of Endukai Kiti (Pliocene)**—Thin lava flows and tuff breccia (agglomerate) of very fine-grained basanite. Thickness 60 m, but base not exposed. Includes 20 m of fallout tuff and breccia (probably all near-vent) and an overlying sequence of orange-brown-weathering, moderately bedded volcaniclastic sandstone 6–8 m thick. Corresponds to waterfall sequence of Neukirchen and others (2010). Forms oldest strata exposed along face of Lake Natron escarpment between Leshuta stream and Oldonyo Lengai volcano. Reversed polarity magnetization

Tmc **Mosonik conglomerate (Pliocene)**—Cobble conglomerate rich in volcanic stones, with sparse clasts of volcaniclastic sedimentary rocks. No Precambrian clasts seen. Clast size typically 10–15 cm, rarely to 1.4 m. Unit is 80–100 m thick along north-trending segment of Leshuta stream, where beds dip 2° eastward. Overlies Mosonik volcanic rocks. Late Pliocene and (or) early Pleistocene age on basis of stratigraphic position above Mosonik volcanic beds and apparent discordance with that unit

Tmv **Mosonik volcanic rocks (Pliocene or Miocene)**—Debris-flow or lithic pyroclastic-flow deposits. Clast population varies little among outcrops: typically aphyric in hand sample, with microphenocrysts of clinopyroxene <0.5 mm visible with hand lens. Those samples are phonotephrite on basis of two analyses (table 1). See explanatory pamphlet for discussion of age

AREA OF MTO WA MBAGAI

[Area not mapped by us. Depiction from Isaac (1967) and fitted to the Mosonik topographic map for this map]

Qtse **Tuff and sandstone atop escarpment (Pleistocene)**—Ill-defined stratigraphic unit likely composed of sand and gravel deposited before escarpment had reached its current level of structural offset. Includes distal volcanic ash from unknown sources

Peninj Group (Pleistocene)—Consists of:

Moinik Formation—Lacustrine deposits and lesser interbedded lava flows. Exposed in upthrown block of Natron fault. Age between about 1.1 and 1.5 Ma according to assessment of several radiometric ages from lava flows within and beneath unit (see explanatory pamphlet). Divided by Isaac (1967) into

Qmiu **Upper tuff**

Qmin **Nephelinite lava flow**—Potassium-argon ages of 1.31±0.26 Ma (Foster and others, 1997) and 1.41±0.04 Ma (Manega, 1993)

Qmic **Claystone and tuff**

Qh **Humbu Formation**—Deltaic sandstone and interbedded lava flows. Age between about 1.5 and 1.8 Ma according to assessment of widely scattered radiometric ages from lava flows above, within, and beneath unit. Divided locally to show:

Qhl **Lava flows**

Tnnm **Nephelinite lava north of Mosonik volcano (Pliocene)**—Radiometric ages of 3.26±0.08 Ma (Isaac and Curtis, 1974) and 3.53±0.06 (Manega, 1993)

Tsh **Sambu and Hajaro Basalts (Pliocene)**

EXPLANATION OF MAP SYMBOLS

Contact—Solid where precisely or approximately located; short dashed where inferred; dotted where buried

Internal contact

Lateral margins and snouts of lobate geomorphic features (on Oldonyo Lengai)—Narrow breadths and convex-downslope snouts probably mark the boundaries of debris flows. More extensive areas, including those that open downslope from upslope apices, show sectors of the volcano that are now active depositional slopes that abut slightly higher-standing, less active slopes. Estimated relative age indicated by Y (younger) and O (older)

Fault—Solid where precisely or approximately located; short dashed where inferred; dotted where buried. May show dip. Ball and bar on downthrown side

Fault with known Holocene or latest Pleistocene offset

Fault with Pleistocene offset

Lineament

Gaping crack

Dikes (unit QTei) associated with escarpment vent deposits (QTev)

Crater rims—Enclose intact and breached volcanic craters of small to moderate size. Hachures point into crater. Not shown for major craters, which are portrayed adequately by topographic contours on the map. Rim labeled “subsidence crater” 7 km south of Lake Natron is probably related to liquefaction during a basin earthquake. Another small crater at 2,340-m altitude on north flank of Oldonyo Lengai was recognized in air-photo mapping and distant views but not visited. It seemingly lacks substantial mounding of material around the crater rim and may have formed by minor CO_2 explosions during a summit eruption

Levee in lava flows, lahar deposits, and debris-avalanche deposits—Hachures point into body of flow

Isopach—Showing 5–10-cm thickness limit for 2007–08 explosive deposit

Latest Pleistocene shoreline—Extant between about 13,900 and 11,500 cal yr B.P. (from Hillaire-Marcel and others, 1986, 1987)

Strike and dip of beds

Inclined—Showing dip

Horizontal

Vertical

Notable site—Places likely of interest to future Earth scientists working in the area but not flagged by other symbols. See table (this sheet) for index of features

Paleomagnetic determination—Measured by portable fluxgate magnetometer. Normal-polarity magnetization (N) at three sites along east side of map area thought to be in lava flows from Gelai volcano (unit Qvg) and another site in lava erupted from a vent in Natron-Engaruka volcanic field. Reversed-polarity magnetization (R) from intrusion within Natron escarpment lava of Endukai Kiti (unit Tek)

Sample locations for new radiometric ages and geochemical analyses (this report)

338±23 ka **$^{40}Ar/^{39}Ar$ ages**—Showing age in thousands of years (ka). Complete data in appendix 3 of explanatory pamphlet

L37 **Geochemical analyses**—Showing sample number (short version)

OL184 **Previously analyzed rock samples**—Showing sample number (Klaudius and Keller, 2006)

0.15±0.02 Ma (Bagdasaryan et al., 1973) **Previously dated samples**—Showing age and analytical error, with publication source in parentheses. Sites with “Location?” have large positional uncertainty

Springs—Showing those verified during mapping: (1) in Sidan Indare, (2) near Engare Sero village, (3) near mouth of Leshuta stream

Geologic Map of Oldonyo Lengai Volcano and Surroundings, Arusha Region, United Republic of Tanzania

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2013

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Digital files available at http://pubs.usgs.gov/of/2013/1306

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