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Lithostratigraphy of the Late Miocene to Early Pleistocene, hominid-bearing Galili Formation, Southern Afar Depression, Ethiopia

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Abstract

The Horn of Africa is yields famous Miocene to Pleistocene fossil sites including hominid remains. The fossiliferous sediments were deposited in fluvio-deltaic to lacustrine environments. The basin development is mainly controlled by the tectonic development of the Afar Depression. The Galili research area represents a new fossil site in the southern Afar Depression, Ethiopia. The exposed sediments and volcanics have been organized in the 230 m thick Galili Formation that consists in ascending stratigraphic order of the Lasdanan, Dhidinley, Godiray, Lower and Upper Shabeley Laag, Dhagax and Caashacado Members. The individual members are defined by volcanic layers like basalts, ignimbrites and tuffs. Feldspars separated from several volcanic layers have been dated using $^{40}Ar/^{39}Ar$. The Lasdanan Member (>5.37 - 4.43 Ma) comprises thick basalt flows with intervening fluvial and lacustrine deposits. The Dhidinley Member (4.43 - 3.94 Ma) is characterized by thick lacustrine mudstones erosively overlain by fluviodeltaic sandy sediments capped by a widespread grey ignimbrite. The Godiray Member (<3.94) represents a short fluvial interval with adjacent floodplain mudstones and calcretes topped by a whitish lapilli tuff. The Shabeley Laag Member (<3.94->3.87 Ma) has been subdivided into a lower and upper member. The lower Shabeley Laag Member starts with shallow lacustrine mudstones that are followed by bluish-grey fluvio-deltaic sandstones. A pillow basalt flow defines the upper boundary of the lower Shabeley Laag Member. The upper Shabeley Laag Member shows a similar development and is capped by thick basalt flows with intervening paleosol horizons. The stacked basalt flows are either overlain by the deposits of the Dhagax (>2.335 Ma) or the Caashacado Member (<2.335 Ma). Both members consist of shallow lacustrine mudstones, fluvial sandy deposits, tuffs and ignimbrite layers. The eruption of the thick basalt flows on top of the Shabeley Laag Member is considered as reason for the recorded pause in sedimentation. Abundant mammal fossils have been recovered from fluvio-deltaic sands and lacustrine-floodplain mudstones of the Lasdanan, Dhidinley and Shabeley Laag Members including several hominid fossils. The most prominent hominid fossil site within the Dhidinley Member yielded a well preserved hominid femur. The deposits of the Galili Formation are partly time-equivalent with the sediments of the Adu-Asa, Sagantole, Hadar and Busidima Formations exposed at Middle Awash, Gona, Hadar and Woranso-Mille.

Das Horn von Afrika ist weithin bekannt für seine miozänen bis pleistozänen, hominidenführenden Fossilfundstellen. Das Untersuchungsgebiet um den Galili stellt eine neue Fossilfundstelle in der südlichen Afarsenke, Äthiopien dar. Die Aufschlüsse der Galili Formation befinden sich in der zentralen Übergangszone zwischen dem nördlichen Ast des Äthiopischen Riftsystems und dem südlichen Afar Rift. Die Sediment- und Vulkanitlagen des Untersuchungsgebietes sind in der 230 m mächtigen Galili Formation zusammengefasst. Diese setzt sich in stratigraphischer Reihenfolge aus den Lasdanan, Dhidinely, Godiray, Unteren und Oberen Shabeley Laag, Dhagax sowie der Caashacado Subformationen zusammen. Die einzelnen Subformationen sind durch Basalt-, Ignimbrit- und Tufflagen definiert. Feldspäte aus diesen Lagen wurden mittels $^{40}Ar/^{39}Ar$ radiometrisch datiert. Die Lasdanan Subformation (<5.37 - 4.43 Ma) setzt sich aus mächtigen Basaltlagen mit eingeschalteten lakustrinen Ton- und Siltsteinen und fluvial-deltaischen Sanden zusammen. Die Dhidinley Subformation (4.43 - 3.94 Ma) besteht aus feinkörnigen, lakustrinen Sedimenten, in die erosiv fluviatil-deltaische Sande eingreifen. Die obere Grenze ist durch eine weitflächig aufgeschlossene, graue Ignimbritlage definiert. Die überlagernde Godiray Subformation (<3.94 Ma) repräsentiert ein kurzes fluviatiles Intervall mit weitverbreiteten Ton- und Siltsteinen des Überschwemmungsgebiet. Pedogene Karbonatlagen sind in die feinkörnigen Ablagerungen des Überschwemmungsgebietes eingeschaltet. Ein weißlicher Lapillituff stellt die obere Grenze der Godiray Subformation dar. Die Shabeley Laag Subformation (<3.94 - >3.87 Ma) ist in eine untere und eine obere Einheit unterteilt. Die Untere Shabeley Laag Subformation beginnt mit bunten, feinkörnigen lakustrinen Sedimenten, die erosiv von blau-grauen fluviatil-deltaischen Sanden und Sandsteinen überlagert werden. Die Grenze zwischen Unterer und Oberer Shabeley Laag Subformation ist durch eine Basaltlage definiert, die Kissenstrukturen aufweist. Die Obere Shabeley Laag Subformation ist ähnlich entwickelt wie die Untere Subformation und wird von mächtigen Basaltlagen, die teilweise durch Paläoböden getrennt sind, überlagert. Die Basalte werden von den Abfolgen der Dhagax (>2.335 Ma) und der Caashacado Subformation überlagert, wobei die Sedimente beider Subformation die Basaltlagen direkt überlagern können. Beide Subformationen setzen sich aus lakustrinen Ton- und Siltsteinen, fluviatilen sandigen Ablagerungen sowie Tuffen und Ignimbriten zusammen. Die Eruption der dicken Basaltlagen, die die Obergrenze des Shabeley Laag Members bilden, wird als Grund für die Unterbrechung der Sedimentation angesehen. Zahlreiche Fossilien wurden in den fluviatil-deltaischen Sanden und den Ton-Siltsteinen der lakustrinen und Überschwemmungsgebietfazies der Lasdanan-, Dhidinely und Shabeley Laag Subformationen gefunden, darunter auch Hominiden. Die bedeutendste Hominidenfundstelle liegt stratigraphisch innerhalb der Dhidinley Subformation und ergab einen gut erhaltenen Hominidenfemur. Die Sedimentation der Galili Formation erfolgte teilweise zeitgleich mit der Ablagerung der Adu-Asa-, Sagantole-, Hadar- und Busidima Formationen in der Middle Awash Region sowie in den Gebieten von Gona, Hadar und Woranso-Mille.

1. Introduction

The Horn of Africa, especially the Main Ethiopian Rift (MER) and the Afar region, is well known for its geological strata which produced an outstanding fossil record from the Miocene to the Pleistocene (Tiercelin, 1986; Woldegabriel et al., 2000, 2001; Quade and Wynn, 2008 and references within). Geological and paleontological research in the Afar region started in the 1970´s with studies in the Hadar area (Taieb et al., 1972, 1974, 1976; Johanson, 1976) and the Rift Valley Research Mission led by Jon Kalb (Kalb et al., 1982), and continues until today.

The Paleo Anthropological Research (PAR) team began its research studies in the Galili area (Mulu basin) in February 2000. Eight further field seasons followed since then producing ~2100 fossils including nine hominid teeth and three other hominid fossils; one of them a proximal hominid femur (Kullmer et al., 2008). Together with the fossils, abundant stone tools made of petrified wood, silica and basalt were collected. The unique geographic position and geological situation of the exposed deposits compared to other known fossil sites within the Afar Depression argued for the organization of the exposed deposits in a new lithostratigraphic unit in the rank of a formation. This new unit was named Galili Formation (GF; Urbanek et al., 2005) after the Somali name "Galili" for the hill that constitutes the most prominent geographic feature within the research area. In official maps, this hill is named Serkoma. The Somali-name was chosen to express the gratitude for the support of the local Somali people during the field-seasons.

A first paper dealing with the geology and paleontology of the GF was published by Urbanek et al. (2005). The Lasdanan Member was not defined in this first version of the GF due to the unclear stratigraphic position of the exposures. Kullmer et al. (2008) presented a comprehensive study of the recovered elephantoids and suid fossils. The GF presented in Kullmer et al., (2008) was described including six members. The stratigraphic data obtained from elephantoid and pig molars allowed setting of a first time range for deposition between 4.5 to 3.5 Ma. Both publications suffered from the lack of reliable absolute age data. $^{40}Ar/^{39}Ar$ ages from most volcanic marker horizons became available in 2010. The results of $^{40}Ar/^{39}Ar$ dating and the findings of the field-seasons in 2008 and 2009 called for a revision of the lithostratigraphy of the GF presented in Kullmer et al. (2008).

This publication presents a revised and comprehensive description of the lithostratigraphy of the Galili Formation and ist fossil-sites together with a time-frame based upon the new radioisotope data. A magnetostratigraphic record based on polarity chrons is in preparation.

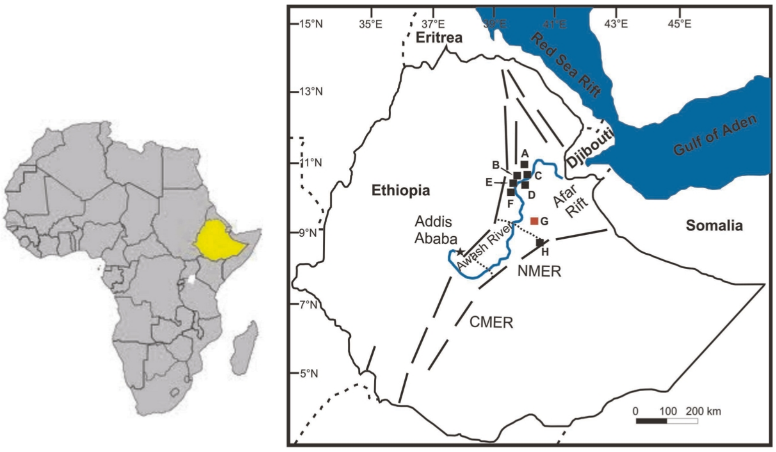
2. Geographic and geological setting

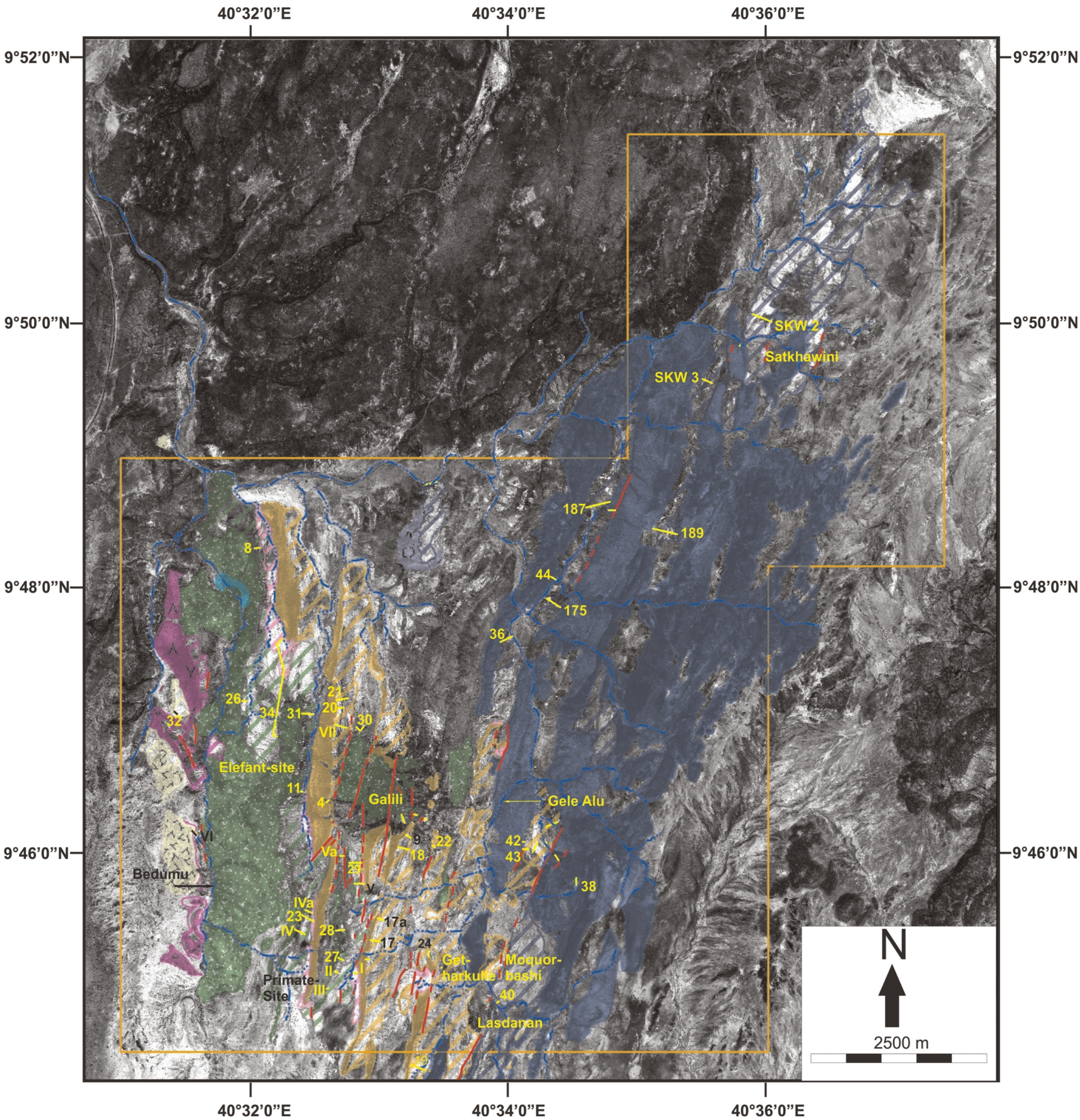
The Galili research area lies 212 km NE from the Ethiopian capital Addis Adaba within the West Harerge Administrative Region. It is situated 100 km NNE of the Awash station, 7 km east of the village of Gedamaytu and 35 km east of the Awash River (Fig. 1). In contrast, most of the other prominent fossil sites of the Afar Depression crop out along the Awash River or at the western escarpment. Only the Chorora fossil site is located more to the east along the southeastern escarpment (Fig. 1a).

The research area is a approx. 9-15 km long and 6 km wide basin, bounded by steep plateaus in the north and the west. Recent alluvial plains and volcanic plateau mark the eastern boundary. Towards the south the basin is covered by alluvial plains. The steep plateau in the north and west are considered to have developed by fault activity and erosion of ephemeral rivers. The course of the larger ephemeral river beds follows the strike of the faults. Based on the official map of the region (Meteka, 0940 B1 1:50 000, Ethiopian Mapping Authority, 1990), the easternmost ephemeral river bed is called "Koda Gelealu", whereas the westernmost river bed is named "Bedumu". The most prominent geomorphological feature is the 865 m high hill "Serkoma" situated in the central part of the research area. The Somali name Galili ("White Hill") instead of "Serkoma" is used in this publication.

The research area is mainly dominated by W to NW tilted blocks capped by volcanic rocks which are bounded by N-S striking faults exhibiting nearly vertical fault planes. Observed throws are in the range of 10 to several tens of meters.

Figure 1: 1a. The location map shows the Galili (G) research area, the Afar and the Northern Main Ethiopian Rift and additional paleoanthropological research areas within the southwestern part of the Afar Rift, including Woranso-Mille (A), Hadar (B), Ledi-Geraru (C), Dikika (D), Gona (E), Middle Awash (F), Chorora (H). Map modified from Woldegabriel et al. (2013).1b. Geological map of the research area based on IKONOS satellite image. Solid colors represent volcanic layers whereas dashed lines refer to sediment and thin tuff exposures. Blue: Lasdanan Member, Orange: Dhidinley Member, Pink: Godiray Member, Green: Shabeley Laag Member, Violet: Dhagax Member, Yellow: Caashacado Member. Yellow lines: measured sections, Red lines: Faults. Important fossil sites are marked on the map. Gelealu and Bedumu river beds are marked by arrows.


15°N
35°E
37°E
43°E
45°E
13°N
11°N
9°N
7°N
5°N
Eritrea
Red Sea Rift
Gulf of Aden
Djibouti
Ethiopia
Afar Rift
Somalia
Addis Ababa
Awash River
NMER
CMER
A
B
C
D
E
F
G
H
0 100 200 km


40°32'0"E
40°34'0"E
40°36'0"E
9°52'0"N
9°50'0"N
9°48'0"N
9°46'0"N
SKW 2
Satkhawini
SKW 3
187
189
44
175
36
8
26
34
31
21
20
30
VII
32
Elefant-site
11
4
Galili
Gele Alu
VI
Bedumu
Va
9
18
22
42
43
38
29
V
IVa
23
IV
28
17a
17
24
27
II
I
III
Primate-Site
Get-harkulle
Moquor-bashi
40
Lasdanan
N
2500 m

In a regional geological context, the volcano-sedimentary successions of the Galili Formation are exposed in the transition zone between the Northern Main Ethiopian Rift (NMER) and the Southern Afar Rift (fig. 1).

The tectonic history of this area is governed by the development of the "Afar Triple Junction" that consists of the Afar, the Red Sea and Gulf of Aden rifts (Wolfenden et al., 2004, 2005; Ring, 2014). The tectonic development of the triple junction from the late Eocene (40 Ma) onwards is considered to be controlled by the rise of one or two mantle plumes to the base of the lithosphere (Redfield et al., 2003). Crustal thinning in the Red Sea rift started 30 Ma ago (Eagles et al., 2002) whereas the major rifting phase took place between the late Oligocene (28 Ma) and the early Miocene (16 Ma; Ghebraeb et al., 1998). Beginning of extension in the Gulf of Aden rift can be constrained between Oligocene to Miocene (Fantozzi, 1996). The development of oceanic crust started in the Red Sea between 10 – 12 Ma and in the Gulf of Aden at 10.3 Ma ago (Cande and Kent, 1992; 1995). The NE-directed sea-floor spreading in the Gulf of Aden is propagating westwards since 16 Ma into the Afar Depression (Wolfenden et al., 2004). Deformation in the NMER and the Southern Afar started in the late Miocene 11 Ma ago (Wolfenden et al., 2004). Early rift-flank uplift and sedimentation on the SE flank of the NMER is evident at 11-10 Ma and caused deposition of the fossiliferous Chorora Formation (Geraads et al., 2002). Larger scale initiation of sedimentation on the western flank of the NMER is considered to have started later at 8 Ma (White et al., 1993; WoldeGabriel et al., 1994; White at el., 2006). The data indicates that no triple junction developed in the Afar Depression before 11 Ma. The period between 8 and 4 Ma in the Southern Afar Rift is characterized by development of only small sedimentary basins represented by thin sediment accumulation attributed to the Adu Asa and Sagantole Formations that are intercalated within basalts in the western margin at Gona and Awash (Wynn et al., 2008). The time-equivalent volcanic deposits in this area are represented by the "Dahla Series" (8-4 Ma; Audin et al., 2004) consisting of 800 m thick basalts with thin intercalations of ignimbrites (Varet, 1978). These Dahla-basalts correlate roughly with basalts within the Adu Asa and Sagantole Formations in the western margin of the Awash River Valley at Gona (Quade et al., 2008; Kleinsasser et al., 2008). The "Dahla Series" are strongly eroded and unconformably overlain by the "Afar Stratoid Series" (Varet, 1978).

The period between 4 and 3 Ma was marked by major reorganization of the triple junction and changes in the tectonic patterns throughout the Afar region. Wolfenden et al. (2004) dated fault patterns in the Adama basin that indicate a shift in extension in the NMER from 130/310° to the modern extension direction of 105°/285°. This shift is consistent with global plate kinematic models (Calais et al., 2003) and is roughly coincident with the initiation of sea-floor spreading in the Red Sea Rift system and the flood basalt eruption of the "Afar Stratoid Series" (mostly <3.5 Ma; Kidane et al., 2003), as well as the predicted increase in extension rates in the Afar region between 4 and 3 Ma from plate kinematics (Eagles et al., 2002). These tectonic events were likely the regional response to larger-scale tectonic patterns such as propagation of the Red Sea and Gulf of Aden Rift Systems into the Afar and the readjustment of plate boundaries (Audin et al., 2004; Lahitte et al., 2003a, 2003b; Manighetti et al., 1997).

The "Afar Stratoid Series" and the associated acidic volcanics cover 2/3 of the Afar Depression and reach a maximum thickness of 1500 m (Varet, 1978). These volcanic series consist of individual, 1-6 m thick flows and are further subdivided into a "lower and an "upper" part (Varet, 1978; Tefera, 1996). They are strongly cut by faults. Silicic central volcanoes grew locally on the upper part of the "Stratoid Series" (Lahitte et al., 2003a). The recent extension in the Main Ethiopian Rift is constrained to <20 km wide, N-S directed, Quaternary rift segments that are bounded by acidic volcanic structures (e. g. Ayelu-Aabida volcano, Bilham et al., 1999). These Quaternary segments developed 1.8 Ma ago and are characterized by "en-echelon" faults and fissures (Boccaletti et al., 1999; Ebinger and Casey, 2001) associated to the Wonji Fault Belt (e. g. Corti, 2009). The Wonji Fault Belt reveals a change in deformation style from the rift margins where extension is accommodated in few widely-spaced faults with large vertical displacements to the rift floor where extension occurs through dense fault swarms (Ebinger and Casey, 2001; Casey et al., 2006). The progressive thinning of the continental lithosphere under constant, prolonged oblique rifting conditions may have been controlled by the migration of deformation and the resulting Quaternary volcano-tectonic segmentation (Corti, 2009). This shift is concomitant with a focusing of Quaternary volcanic activity within the rift depression along the Wonji faults, giving rise to the nowadays magmatic segments with only minor activity outside the en-echelon deformation belt (Corti, 2009). Field observations and geophysical data in the NMER indicate that the large-offset boundary faults are no longer active and most of the deformation is accommodated within the oblique fault segments (Corti, 2009).

3. Methods

IKONOS satellite images with a resolution of 1 m were used as basis for geological mapping due to the lack of detailed topographical maps. Description of the sedimentary and volcanic successions is based on 40 measured sections mainly measured along the N-S striking ridges and exposures along ephemeral streams (fig. 1). Volcanic layers were used as key horizons to subdivide the exposed deposits into members as done with other fossiliferous deposits in the Horn of Africa (e.g., Kalb et al., 1982; Woldegabriel et al., 2000). The member nomenclature originates from local Somali names, and is explained in the beginning of each member description. For descriptive purposes, some of the valleys between fault-blocks have been arbitrarily named. The valley directly south of the Galili is called "Central-Valley", the valley west of it "Godiray Valley". The names of important fossil-sites are marked on Figure 1b.

3.1 $^{40}Ar/^{39}Ar$ Geochronology

Volcanic ash layers were carefully sampled in the field. Bulk samples were crushed, washed and sieved. Finally, mineral fractions were separated by hand-picking under a microscope. Geochronological dating was done at the Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, The Netherlands.

The samples were wrapped in 6ID Al-foil packages with the Drachenfels in-house standard between each set of 4 unknowns and at top and bottom positions. Samples U11 and W78 were irradiated in irradiation batch VU75 for 10 hours and samples U51, 09/16A, 09/16, 09/29, 09/32, W133/2 were irradiated in irradiation batch VU82 for 12 hours both in the High Flux Reactor in Petten, The Netherlands in the rotating Cd-shielded position P3. After irradiation, samples and standards were loaded in 2 mm diameter holes of a copper tray and placed in an ultra-high vacuum extraction line.

Single crystal $^{40}Ar/^{39}Ar$ fusion experiments on the 500-1000 µm fractions and multiple grain fusion experiments on the smaller grain sizes were performed at the Vrije Universiteit Amsterdam, The Netherlands using a Synrad 48-5 CO_2 laser and custom made beam delivery system. Samples were purified in an in-house designed sample clean-up line and analyzed on a MAP 215-50 noble gas mass spectrometer fitted with a Balzers SEV217 detector. Mass discrimination was monitored by 3 replicate runs of air pipettes every 12 hours and blanks were run every 3-4 unknowns.

Ages are calculated using the in-house developed ArArCalc software (Koppers, 2002) with Steiger and Jäger (1977) decay constants. The age for the Drachenfels standard is 25.52±0.08 Ma (note that this age is based on the 24.99±0.07 Ma reported in Wijbrans et al., 1995 relative to Taylor Creek Rhyolite of 27.92 Ma). Using the intercalibration factor 1.0112±0.0010 of Renne et al. (1998) and the recommended age of Kuiper et al. (2008) for FCs of 28.198±0.023 Ma this converts to 25.52±0.08 Ma. Note that Kuiper et al. (2008) reports 28.201 Ma using decay constants of Min et al. (2000), which converts to 28.198 Ma using Steiger and Jäger (1977). The atmospheric $^{40}Ar/^{36}Ar$ value of 295.5 (Nier, 1950) is used in the age calcu-

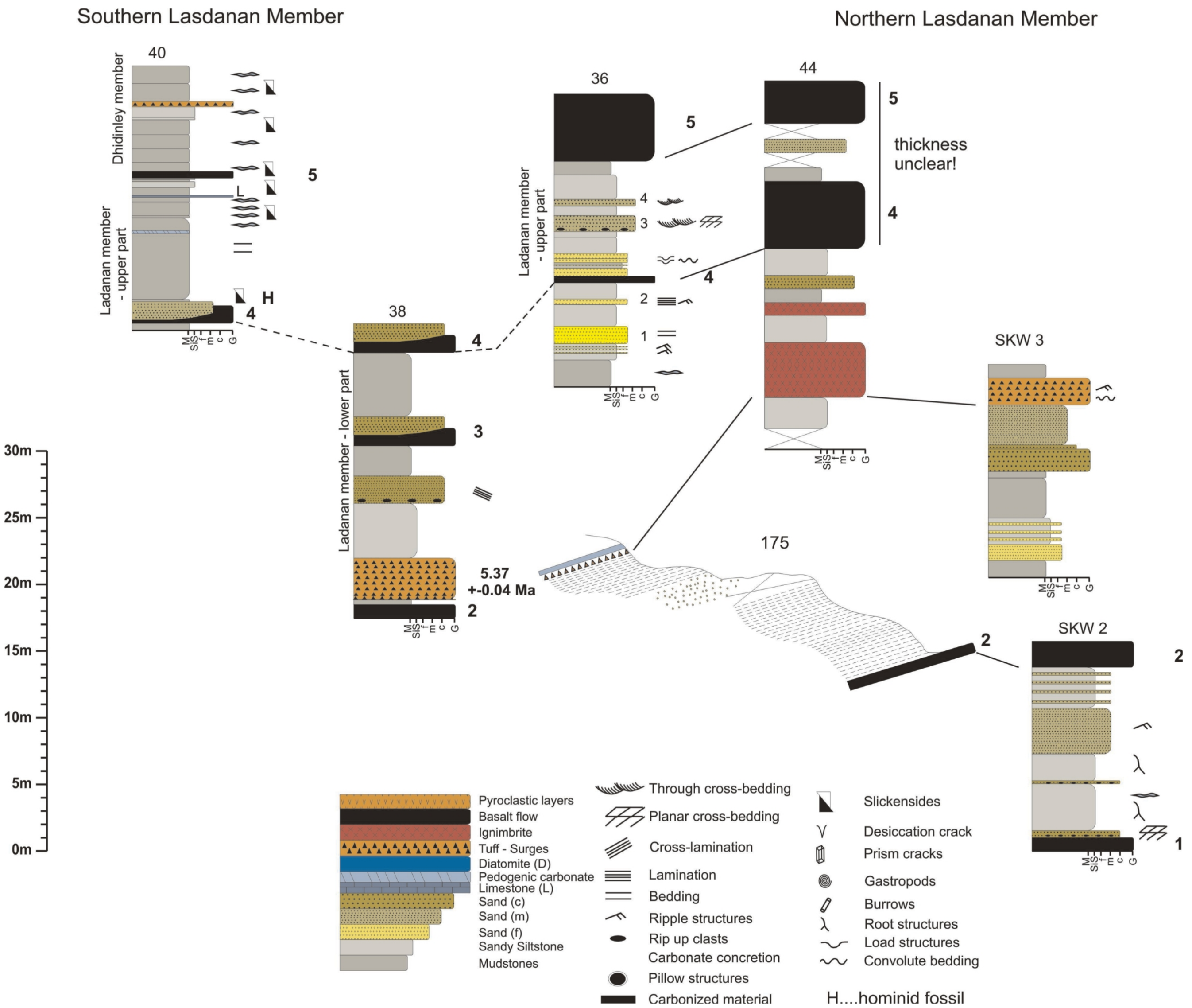


Figure 2: Representative profiles of the Lasdanan Member. Position of individual sections is shown on Figure 1.

lations. Errors are quoted at the 1σ level. Correction factors for neutron interference reactions are (2.65±0.08)×10-4 for (^{36}Ar/^{37}Ar) Ca, (7.33±0.35)×10-4 for (^{39}Ar/^{37}Ar)Ca, (1.139±0.003)× 10-2 for (^{38}Ar/^{39}Ar)κ and (13.4±7.9)×10-4 for (^{40}Ar/^{39}Ar)κ. The ^{40}Ar/^{36}Ar ratio of 298.56±0.31 of Lee et al. (2006) is used in the calculations. Outliers are identified by comparing MSWD with the T-student distributions. The summary of the ^{40}Ar/^{39}Ar results is given in table 1. Full analytical data is provided in the Supplementary Data.

4. Results

4.1 Lithostratigraphic description of the Galili Formation

The Galili Formation (GF) encompasses 230 m of sedimentary and volcanic rocks and consists in ascending stratigraphic order of the Lasdanan, Dhidinley, Godiray, Shabeley Laag, Dhagax and Caashacado Members (Fig. 6). The member boundaries are defined by volcanic marker layers. The Shabeley Laag Member is further subdivided into a lower and upper submember. The lithostratigraphy of each member is described in the following chapters and summarized on table 1.

4.2 Lasdanan Member

The name "Lasdanan" describes the locality where the deposits have been studied first (Fig 1b). For the local Issa nomads, the term Lasdanan means "water when you dig" because the nomads of this area use to dig holes into the alluvial beds of the ephemeral river. Outcrops are mainly found east of the ephemeral Koda Gelealu river bed. The Lasdanan Member is defined as the strata below the fissure basalt flow capped by basal Dhidinley deposits (Fig. 2). Stratigraphic control of this member is hardened by the fact that it consists of several weathered basalt flows with intervening sedimentary successions. These successions are heterogeneous and pinch out laterally resulting in direct stratigraphic contact of basalt flows. Therefore, no fixed lower boundary can be provided for this member. The weathering of the basalt flows and faulting makes it almost impossible to correlate individual flows based on field observations only (similar to the situation at Gona, see Kleinsasser et al., 2008). For these reasons, the overall thickness of the Lasdanan Member is strongly variable. Based on lithological correlations between profiles (fig. 2), a minimum thickness of 60-80 m seems to be plausible. At least 5 basalt horizons (1-5), most of them consisting of several flows, have been observed. Due to the outcrop situation, the most prominent outcrops of the Lasdanan Member are described in detail instead of presenting a summarized description.

The northernmost outcrop of the Lasdanan Member is exposed in the Satkhawini area (SKW) (Figs. 1, 2) and consists of 17 m of muddy and sandy deposits encased between basalt horizons 1 and 2 (cross-section SKW 2, Fig. 2). The basal

MEMBER	AGE (Ma)	THICKNESS (M)	LITHOLOGY
Lasdanan	5.37±0.04 to >4.43	~60-80	Thick basalt horizons consisting of several flows with intercalated mudstones,sandstones and locally ignimbrites-tuffs and limestones, sedimentary successions pinch out laterally resulting in direct contact of basalt horizons, complete succession capped by thick basalt horizon
Dhidinley	<4.43 to >3.94	~18-70	Basal muddy-sandy to tuff-tuffitic deposits overlain by thick mudstones with intercalated carbonate, diatomite and sandstone layers; mudstones erosive cut by bluish-greyish to greenish-greyish, partly tuffitic sands; top of member comprise greyish ignimbrite layer
Godiray	<3.94	~5	Multi-colored mudstones containing calcite concretions to calcrete layers and greenish-greyish, fine- to coarse-grained sandstones, top of member characterized by whitish lapilli tuff
Shabeley Laag	3.97±0.03 to <3.87±0.02	~35-70	*Lower Shabeley Laag Submember:* multi-colored mudstones with intercalated sandstone, limestone and gastropod limestone layers overlain by bluish-greyish, fine-coarse-grained sandstones that grade laterally in brownish mudstones; top of succession comprise greyish mudstone and whitish diatomite overlain by discontinuous basalt flow *Upper Shabeley Laag Submember* : multi-colored mudstones with intercalated limestone, diatomite and tuff layers overlain by coarse-fine-grained sandstones and siltstones exhibiting calcrete layers to concretions, capped by thick basalt horizon consisting of several flows
Dhagax	>3.87±0.02 to 2.355±0.01	~17	Multi-colored mudstones with intercalated limestone layer cut by medium-coasre-grained sandy deposits that are overlain by fine-grained bluish, greyihs pumice tuff, top of member consists of a reddish ignimbrite
Caashacado	<2.355±0.01	~9-25	Intercalation of sandstones and mudstones with bivalve- and gastropod-bearing horizons, top consists of two pyroclastic layers

Table 1: Summarized lithology of Galili Formation

part of the exposed succession comprises brownish mudstones and medium-coarse-grained, planar cross-bedded orange-colored sands to calcite-cemented sandstones that locally erode down to the lower basalt. The sandy deposits yielded abundant mammal fossils. The orange-colored sandstones are overlain by horizontally bedded, brownish silty mudstones containing carbonate concretions. The muddy sequence is erosively overlain by a 3 to 5 m thick, lenticular sand-body consisting of fine- to medium-grained indurated sandstone layers that show small-scale cross-bedding to ripple-and climbing ripple cross-lamination. A 3 m thick interbedding of dm-thick siltstone and fine-grained sandstone layers constitute the uppermost part of the sequence. The sedimentary succession pinches out laterally towards the north and the basalt horizons 1 and 2 are coming in direct contact and form a broadly SW-NE trending basalt ridge.

The deposits overlying the basalt ridge are exposed in the next valley towards the west (profile 175, profiles SKW 3 and 44, fig. 2). The exposed succession is at least 25 m thick and consists of sediments and acidic volcanics. In the south (profile 175), the basal sediments comprise 6-8 m of multi-colored mudstones overlain by a 1-2 m thick, fine-grained horizontal laminated sandstone. The sandy interval is again followed by multi-colored mudstones that are capped by a thin, fine-grained pinkish tuff and a pedogenic carbonate layer. The northern succession (cross-section SKW 3) starts with 1 m grey mudstones overlain by 1 m thick fine-grained sandstones. The sandstone layer fines upward into 2 m thick interbedded reddish-brownish muddy siltstones and fine-grained silty sandstones. The sandy-silty interval is followed by 3.5 m of grey and reddish mudstones. The fine-grained lower part is sharply overlain by 2 m of pebbly sandstones to sandy conglomerates that fineupwards into 2 m thick medium-grained sandy deposits. A primate tooth has been recovered from the basal pebbly sandstone whereas a *Hippopotamus* tooth has been found in the overlying medium-grained sands. The sandy deposits are followed by a 2 m thick, whitish tuff exhibiting slump and ripple structures and lapilli clasts. The top of the succession consists of a grey mudstone. The thin tuff layer grades northwards into a 4 m thick, weathered reddish ignimbrite layer (cross-section 44). The acidic volcanic layer contains cm-sized clasts and the top is strongly calcite-cemented. The ignimbrite layer is overlain by 2 m of brownish silts and another, 1 m thick strongly weathered ignimbrite layer that is topped by a 1 m thick greenish-brownish mudstone. Medium-coarse-grained sands exhibiting granules at the base and calcite concretions cut into the mudstone. The sandy deposits are followed by 2 m of poorly exposed brownish silt- to mudstones. The upper part of the muddy to silty deposits is covered by vegetation and weathered basalt cobbles. The top of the succession consists of a basalt horizon couplet (4, 5) that is separated by poorly exposed sandy and muddy sediments.

Basalts 4 and 5 can be traced more than 800 m towards SW (cross-section 36), where a completely different sedimentary succession is exposed below and between the basalts. The lowermost deposits comprise 2 m of multi-colored mudstones characterized by dm-sized carbonate concretions. The basal mudstones are overlain by a 5.7 m thick sequence of brownish-grey sandy siltstones and fine-grained, orange-colored calcite-cemented sandstones. Individual layer thickness ranges between 0.4 and 1.5 m. The sandstones exhibit horizontal lamination and current to climbing ripples. The silty-sandy succession is topped by a 0.5 m thick porphyric basalt flow that can be correlated with the lower basalt (Basalt 4) at cross-section 44. Towards the south, the basalt flow pinches out whereas the flow strongly increases in thickness towards the north. The lower basalt flow is capped by 9 m of silty to sandy deposits. The sandstones are fine- to medium-coarse-grained, show erosive bases and planar to trough cross-bedding. The siltstones contain synsedimentary deformation and root structures. Dark-grey basalt flows (Basalt 5) mark the top of the exposed succession. Detailed thickness measurements could not performed due to the outcrop situation but GPS-based observations indicate a thickness of 25-30 m. The sedimentary succession decreases in thickness northwards until the lower and upper basalt are in direct contact. Approximately 1 km towards the south, the upper basalt flow is overlain by basal deposits of the Dhidinley Member.

The basal sedimentary succession of the Lasdanan Member in the southern exposures (3.2 km south of section 38) starts with a whitish, 3 m thick coarse- to medium-grained tuff layer with a thin basal lapilli tuff. The tuff is followed by 4 m of greenish, light purple to brownish mudstones to silty mudstones and coarse-grained, cross-bedded sands to sandstones. The sandy deposits are overlain and grade laterally into 2 m thick brownish mudstones. The top of the succession is a strongly weathered basalt showing pillow structures at its base. A thin reddish contact zone is present at the top of the brownish mudstones underneath the basalt flow. Again, the sedimentary package pinches out laterally and the upper basalt flow rests directly on the lower flow. The basalt flow is topped by a 2-3 m thick sedimentary succession consisting of basal conglomerates to coarse-medium-grained, cross-bedded sands overlain by multi-colored mud- to siltstones capped by a strongly weathered basalt flow. This succession increases in thickness towards the south where the uppermost basalt flow is strongly eroded by bluish-grey sandy deposits of the Moquorbashi fossil site (Figs. 2, 6). The fossiliferous deposits consists of several stacked fining-upwards cycles starting from pebbly, planar cross-bedded sandstones and ending with fine-grained, current-rippled sands. A hominid tooth has been found within the pebbly sandstones.

At the Lasdanan area (cross-section 40, Fig. 2), a dark-grey mudstone is overlain and partly baked by a pillow basalt flow. The basalt flow is erosively followed by pebbly- to coarse-grained, strongly fossiliferous (>200 fossils including a hominid tooth) orange colored sands to calcite-cemented sandstones. The sandy deposits pinch out laterally and are overlain by a 10 m succession of multi-colored mudstones. Calcite concretion and layers are intercalated with the muddy deposits. A limestone layer showing gastropod imprints is exposed in the uppermost part. The top of this sequence is marked by a thin, brick-red silty mudstone overlain by a vesicular basalt layer (time-equivalent to basalt 5) that strongly increases in thickness towards the south where it locally exhibits pahoehoe-like flow structures.

Cross-section 38 (N 9°45.782220 E 40°34.507020) is defined as holostratotype for the Lasdanan Member because it contains the only radioisotope dated tuff horizon. The contact to the overlying Dhidinley Member is exposed in cross-section 40 (N 9°44.902620 E 40°33.8488209), therefore this section constitutes the parastratotype of the southern exposures. The basalt topping the succession described by cross-section 36 (N 9°47.638200 E 40°34.015320) is also overlain by basal Dhidinley deposits and constitutes therefore the parastratotype for the northern exposures.

4.3 Dhidinley Member

The Dhidinley Member is defined as the strata between the top of the uppermost Lasdanan basalt layer 5 and the top of the grey ignimbrite of the Dhidinley Member (Fig. 3). The member is well exposed along the N-S striking ridges in the central and eastern parts of the research area and also north of the Galili (Fig. 1). The term Dhidinley Member originates from a ridge northeast of the Galili and is derived from the name of a tree.

The thickness of this member varies between 18 m in the south (measured section 19, 24), 45 m north of Galili (measured sections 20, 21) and 70 m in the east (measured-section 42-43) of the research area. The deposits of the Dhidinley Member exhibit a broad fivefold subdivision: basal muddy-sandy deposits, a basal tuff complex, multi-colored mudstones with intercalated carbonate, diatomite and sandstone layers, bluish-grey to greenish sandy deposits and an ignimbrite layer.

The basal muddy deposits of the Dhidinley Member consist of <1m thick, brownish, grey to reddish-colored mudstones exhibiting root-structures, prism-cracks and carbonate concretions. This basal muddy facies is found in most outcrops of the Dhidinley Member and is overlain by the tuff complex, sandy deposits or thick lacustrine mudstones. The tuff complex occurs only in the southernmost exposures of the Dhidinley Member (measured sections 19, 24). It consists of 2 m of alternating bluish-grey to whitish, dm-thick, fine- to coarse-grained, locally trough cross-bedded tuff layers. The basal sandy deposits are 1-3 m thick, bluish-grey to orange-colored, fine- to coarse-grained sands to sandstones that overlie or erode the basal muddy facies and rest partly on the uppermost Lasdanan basalt flow (profiles 42-43, 9, 22, VII). Physical sedimentary structures identified in the sandy deposits comprise horizontal to low-angle cross-lamination, current ripple structures and trough cross-bedding. Fining-upward cycles are common. Abundant large mammal fossils were recovered from orange-colored, coarse-grained sands to sandstones exposed at the base of cross-section VII (Fig. 3).

These basal sediments are overlain in almost all outcrops by multi-colored mudstones that generally increase in thickness from 5 m in the south (profiles 16-19, 24-39) to more than 25 m in the north (measured sections 20, 22). The muddy deposits exhibit greenish, reddish, brownish, and grey to purple colors. Sedimentary structures could only be observed locally, and consist of horizontal lamination-bedding and root structures. Slickensides and carbonate concretions are mainly present in the lower part of the sequence whereas the latter are also found in the uppermost parts. The fine-grained deposits yield abundant fish, crocodile and *Hippopotamus* fossils. Several up to 0.1 m thick carbonate and diatomite layers are intercalated within the muddy sediments. The most prominent limestone layer exhibits locally desiccation cracks, reaches a maximum thickness of up to 0.3 m and can be traced 3.5 km from section I to section VII. Thin, fine- to coarse-grained sandstone layers are intercalated within the mudstones (measured sections 19, 24, I, 17, 17a). At cross-section 24-39, these sandy deposits constitute the GetHarkulle fossil-site that yielded abundant mammal fossils including a well-preserved hominid femur.

A 55 m thick mudstone sequence is exposed in the eastern parts of the research area (cross-section 42-43). Here the basal sandy deposits are overlain by a 14 m thick succession of reddish to brownish mud- to siltstones exhibiting root structures, prism cracks and carbonate concretions to layers. A brownish mudstone exposed in the middle of the succession contains coal pieces with iron oxide rims and septarian nodu-les. A 0.8 m thick, coarse-grained lapilli tuff caps the muddy deposits. The volcanic layer is overlain by 11 m of predomi-nately reddish-purple to greenish-brownish mudstones and siltstones with two intercalated, whitish diatomite layers. The mudstones show locally root structures and greenish mott-ling whereas the siltstones exhibit horizontal lamination. The upper diatomite layer is up to 0.5 m thick and is followed by 22 m of brownish and partly multi-colored mudstones and siltstones. A thin limestone layer containing gastropods is in-tercalated within the fine-grained deposits. Above this lime-stone layer, the muddy-silty sediments contain carbonate concretion, root structures and locally sand-filled, V-shaped desiccation cracks.

The upper half of the Dhidinley Member is generally more sandy and characterized by an up to 12 m thick sandy succession with minor intercalated brownish mud- to siltstones (sections 9, 22, VII, 21, 20, 42-43). The base consists of up to 9 m thick, greenish-grey, coarse-medium-grained friable sands to calcite-cemented sandstones (profiles 9, 22, 21, 20). The sandy deposits exhibit an erosive base with muddy rip-up clasts and show low-angle cross-stratification to horizontal lamination and trough to planar cross-bedding. In most outcrops, the greenish-grey sands are overlain by a dm-thick, very fine-grained whitish tuff layer that is followed by bluish-grey, fine-grained tuffitic sandstones characterized by planar lamination, climbing current ripple bedding and convolute lamination. Lenticular, 1 m thick medium-coarse-grained sand bo-

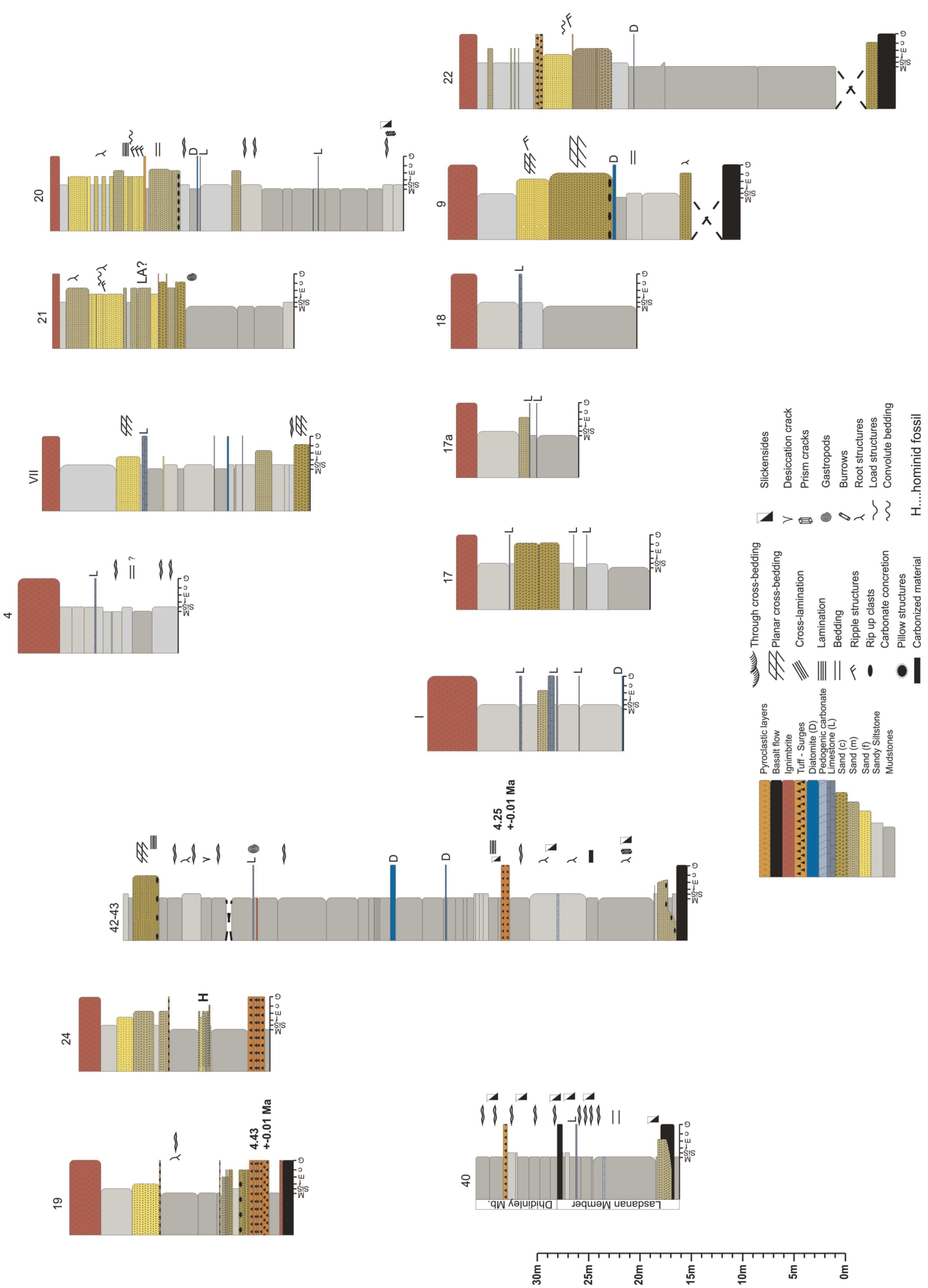


Figure 3: Representative profiles of the Dhidinley Member. Position of individual sections is shown on Figure 1.

dies are cutting into the fine-grained tuffitic sandstones. Sedimentary structures within these bodies comprise planar cross-bedding and lateral accretion surfaces.

The thick fine-grained mudstone sequence described by cross-section 42-43 is erosively overlain by 2.5 m thick, greenish-brownish sands to sandstones exhibiting planar cross-bedding and basal muddy rip-up clasts. The sandstones are locally eroding down to the level of the whitish diatomite layer. Several mammal fossils including remnants of horses and suids were recovered from these sands.

The uppermost deposits of the Dhidinley Member comprise 3-5 m thick brownish siltstones to silty sandstones that exhibit root structures. The top of the Dhidinley Member is marked by a grey ignimbrite that contains abundant dm-sized fiamme structures. The thickness of this ignimbrite layer reaches its maximum with 4 m in the southern and central parts of the research are (profiles I, 4) and thins to 0.5 m towards the northern parts (cross-section 20).

The holostratotype of this member is represented by cross-section 20 (N 9°47.169480 E 40°32.713620). Apart from the basal tuff complex, this section encompasses the complete lithostratigraphy of the Dhidinley Member. Cross-section 19 (N 9°45.285660 E 40°33.480960) describes the complete sequence from the deposits overlying the uppermost basalt of the Lasdanan Member to the top of the grey ignimbrite as is therefore chosen as parastratotype.

4.4 Godiray Member

The Godiray Member includes the strata between the top of the grey ignimbrite and the top of the white Lapilli tuff. Godiray is the Somali word for the Oryx-antelope and also the local name for the valley where the best exposures of this member have been found.

Sediments of the approximately 5 m thick Godiray Member are described by measured sections V, 11, 29, IV, 23, 11, 31, and 25-34. (fig. 4).

The sediments of the Godiray Member consists of sandy, muddy-silty and tuffitic deposits. The sandy deposits comprise coarse-medium- to fine-grained, greenish-grey sands that are in erosive contact with the reddish ignimbrite layer on top of the Dhidinley Member (measured sections 25-34, 31). A basal pebble layer and thin sets of planar cross-bedding to low-angle cross-lamination are common sedimentary features. Root structures are observed locally.

Lateral to the sandy deposits, grey, brownish to reddish mud- to siltstones are exposed (profiles I, V, 29, IV, 23). The fine-grained sediments are characterized by prism-cracks, root-structures, burrows and nodular carbonate concretions and dm-thick, strongly cemented carbonate layers. The top of the Godiray member is marked by a 1 m thick whitish Lapilli tuff. The tuff is build up by two layers with different grain size. The basal layer is 10 to 15 cm thick and consists of fine-grained matrix with granule-sized volcanic clasts. The upper layer is characterized by cm-sized clasts in a whitish, clayey matrix. The clasts have been almost completely replaced by clay minerals. In outcrops where the tuff layer is not exposed, the uppermost carbonate layer marks the top of the Godiray Member.

Cross-section 25-34 (from N 9°47.572200 E 40°32.194800 to N 9°46.884900 E 40°32.184540) is defined as holostratotype because it includes the complete lithostratigraphic sequence of the Godiray Member.

4.5 Shabeley Laag Member

The Shabeley Laag Member encompasses the sedimentary and volcanic strata between the top of the whitish Lapilli Tuff and the top of the uppermost basalt horizon capping this member. The name Shabeley Laag originates from the Somali term of a basalt-capped ridge west of the Galili. The thickness of the Shabeley Laag Member varies between 35 and 70 m (Fig. 4). The Shabeley Laag Member is subdivded into a lower and an upper submember. The boundary between the two submembers is defined by the lower basalt flow. Where the lower basalt flow is not developed because of pinching out or erosion, the top of a gastropod limestone layer or the bluish-grey sandstones are defined as the upper boundary of the lower Shabeley Laag submember.

4.5.1 Lower Shabeley Laag Submember

The lower Shabeley Laag Submember encompasses the sediments between the top of the whitish Lapilli Tuff and the top of the lower basalt flow. It starts with 10 m thick interval of multi-colored mudstones and siltstones with thin interbedded layers of fine- to medium-grained sandstone, limestone and gastropod limestone (measured sections V, 29, IV, 23, 14, 30). The mudstones exhibit greenish, dark to light purple, grey and brownish colors. No sedimentary structures could be identified. Carbonate concretions were found within the mudstones at several outcrops. Fossils recovered from the mudstones comprise Hippopotamus, crocodiles, turtles and abundant fish scales. The interbedded siltstones to silty sands are brownish to grey in color and exhibit horizontal bedding composed of cm-thick dark and light brown layers. Like in the mudstones carbonate concretions were also found within the silty sediments. Thin (<1 dm thick) limestone and gastropod limestone layers are intercalated within the mudstones. Casts of Bellamya sp., Melanoides sp. and Cleopatra sp. have been identified (Frank, 2002). The gastropod limestones are locally intercalated with medium-grained, bluish-grey sandstones.

The fine-grained deposits of the lower Shabeley Laag Member are erosively overlain by up to 5 m thick, coarse-medium-grained bluish-grey friable sandstones (measured sections III, II, 28, V, 29, IV, 23). The bluish-grey sandy deposits exhibit stacked sets of high-angle (>15°) planar and trough cross-bedding that grade upwards into fine-grained, ripple-bedded sandstones. Several large mammal fossils, mainly elephants and trunks of silicified wood have been found within these deposits. Laterally, the bluish-grey sandy deposits grade into interbedded brownish siltstones and minor calcite-cemented sandstones (profiles Va, IVa, 12). Carbonate concretions and layers occur frequently within the silty deposits. A well pre-

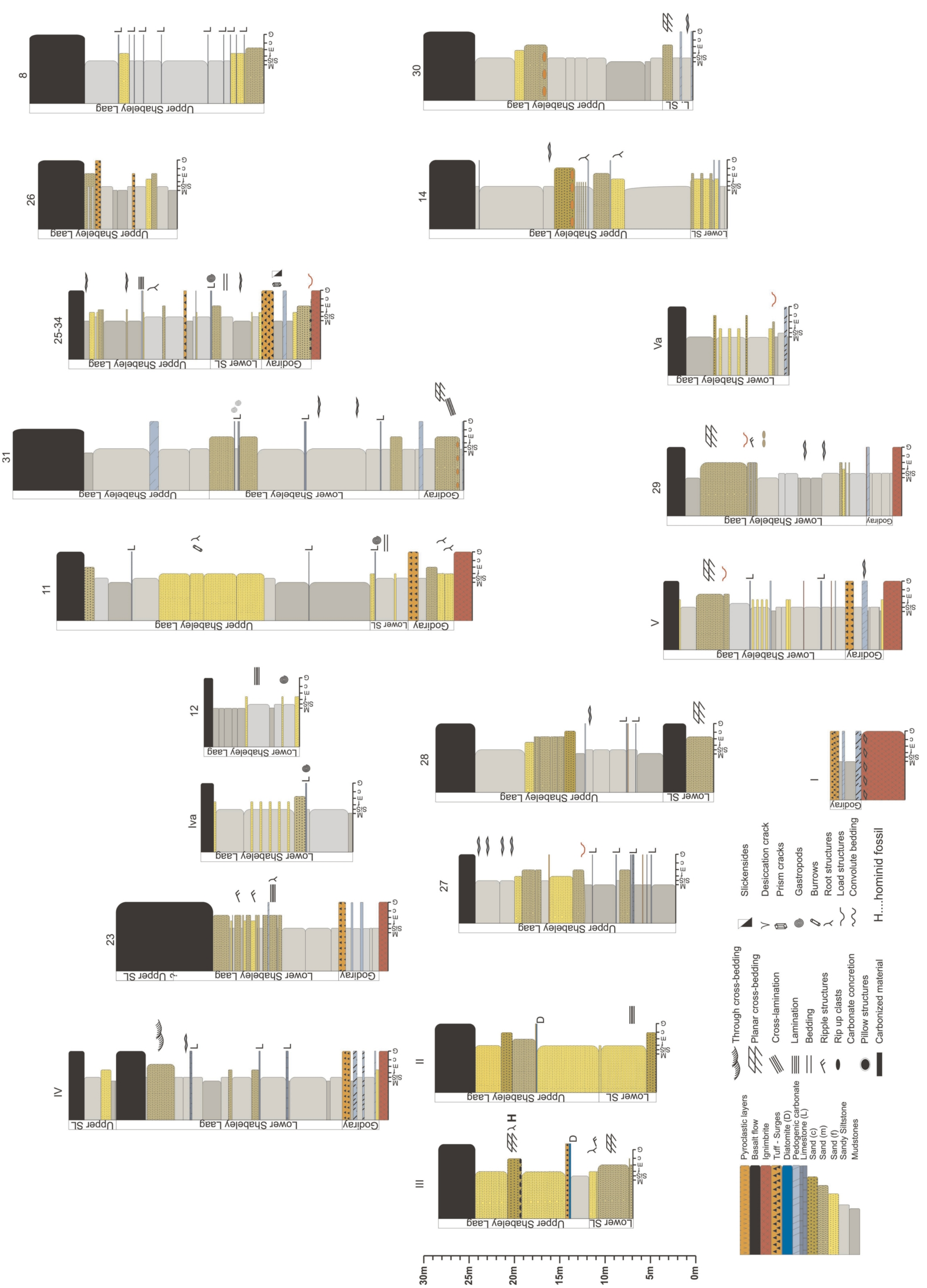


Figure 4: Representative sections of the Godiray and Shabeley Laag Members. Position of sections is shown on Figure 1.

served monkey skull has been recovered from such a carbonate layer at cross-section Va.

The bluish-grey sands are overlain and locally intercalated with white diatomites and grey mudstones (north of cross-section IV). The top of the Lower Shabeley Laag Member is marked by the lower basalt flow that is characterized by pillow structures. This flow has only been encountered in the middle part of the Central Valley (profiles 28, V, 29 and Va) and in the southern parts of the Godiray Valley (measured sections IV, 23, IVa and 12). In outcrops where the lower basalt flow is missing, the bluish-grey sands or the gastropod-limestones are considered as upper boundaries for the Lower Shabeley Laag Member (measured sections III, II, 14, 30, 11, 31, 25-34).

4.5.2 Upper Shabeley Laag Submember

The Upper Shabeley Laag Submember comprises the deposits between the top of the lower submember and the top of the upper basalt horizon. It's thickness varies between 20 and 30 m. The lower part in the Central Valley (profiles 27, 28) comprises 10 m of multi-colored mudstones intercalated with thin, whitish limestone layers. Similar deposits are also present in the sedimentary sequence exposed below the Galili and in the central part of the Godiray Valley (cross-section 11, 31). Carbonate concretions have been found within more silty layers. Abundant fish, Hippopotamus and crocodile fossils have been recovered from the muddy sediments.

The upper part of the Upper Shabeley Laag Submember is characterized by sandy deposits. In the southernmost outcrops of the Central Valley (cross-section III, II), the sandy deposits rest on a tuff/diatomite couplet that can be traced 1.5 km northwards (cross-section 27). The couplet is overlain by 5 of fine-medium-grained, tuffitic sands to sandstones characterized by horizontal lamination. The fine sands are followed by coarse-grained, trough- to planar cross-bedded sands to sandstones that fine upwards into 5 m of fine-grained, silty sands characterized by abundant root-structures. A thin gravel layer at the base of the coarse sandstones yielded one hominid and several primate teeth ("primate-site", cross-section III,).

The upper part of the Shabeley Laag Submember in the middle of the Central Valley comprises one to two, 3-5 m thick, bluish-grey to greenish-grey, erosive sand packages that show fining-upward cycles from coarse-medium- to fine-grained sands to calcite-cemented sandstones. The sandy packages fine-upward into brownish siltstones that contain carbonate concretions. Similar fining-upward sequences have been observed at the Galili outcrops (profiles 14, 30). In the Godiray Valley, thick sandy deposits assigned to the upper Shabeley Laag Member are only described by cross-section 11 where 11 m of fine-medium-grained tuffitic sands to calcite-cemented sandstones are exposed. The latter are characterized by a dense network of roots and burrows. A lower crocodile jaw has been found at the base of the cemented sandstones. The sandy sequence is overlain by 7 m of brownish-grey mudstones with a thin, intercalated limestone.

The deposits of the Upper Shabeley Laag Submember exposed in the northern Godiray Valley (cross-section 31) and in the "Elephant-Site" (cross-section 25-34, 26, 8) comprise 10 to 15 m thick brownish-grey mudstones with intercalated thin fine-medium-grained sand to calcite-cemented sandstones. Carbonate concretions to layers and root structures occur frequently. Two tuff layers are present that can be correlated across the "Elephant site" (profiles 25-34, 26). The basalt horizon on top of the Shabeley Laag Submember is formed by stacked basalt flows. The thickness of the single flows is increasing northwards from 2-4 m to more than 30 m in the northwestern most outcrops. At least four individual basalt flows have been observed. Locally, two reddish paleosol intervals are intercalated within the basalt flows.

Cross-section IV (N 9°45.427560 E 40°32.467140) encompasses the complete succession from the top of the Godiray Member to the top of the upper basalt horizon. It also includes the lower basalt flow and is therefore assigned as holostratotype. Cross-section W28 (N 9°45.427620 E 40°32.693040) describes the deposits of the Upper Shabeley Laag member from top of the lower basalt flow to the upper basalt flow and is presented as parastratotype. The parastratotype for the lower Shabeley Laag Member is described by cross-section V (N 9°45.775140 E 40°32.861400).

4.6 Dhagax Member

The Dhagax Member (Fig. 5 – VI) comprises the volcano-sedimentary succession between the top of the uppermost basalt horizon capping the Shabeley Laag Member and the top of the reddish ignimbrite. Dhagax is the Somali and Afar word for "stone" and also the local name for the steep cliff which is built along the western boundary of the research area. The currently recorded thickness of the unit is 17 m. Outcrops are mainly found west of the ephemeral Bedumu river bed.

The lower part of the member comprises 6 m of greenish, grey to reddish mudstones. No sedimentary structures were found because the dangerous outcrop situation prevented detailed studies. A 0.3 m thick whitish limestone layer is intercalated at the top of the mudstone succession. The fine-grained deposits are laterally cut by bluish-grey, medium-coarse-grained, weakly indurated tuffitic sands that exhibit trough cross-bedding. The sandy deposits are exposed as lenticular sand-body cutting into the fine-grained lacustrine mudstones and within exposures along the eastern bank of the ephemeral Bedumu River. The bluish-grey deposits overly brownish silty deposits and are overlain by 9 m thick, very fine-grained, bluish-grey pumice tuffs that consists predominately of volcanic glass shards, feldspar and quartz. In the upper part, the fine-grained pumice tuff exhibit a rusty brown color due to calcite-cementation. The top of the Dhagax Member is build up by a 2 m thick ignimbrite that contains cm-sized fiamme structures and reworked clasts floating in a fine-grained reddish matrix.

The deposits of the Dhagax Member are currently only described by cross-section VI (N 9°46.151520 E 40°31.557180) which is therefore assigned as holostratotype (fig. 5).

4.7 Caashacado Member

The sedimentary-volcanic succession below the top of the uppermost pyroclastic layer is attributed to the Caashacado Member. The name originates from the plateau west of the Bedumu River where these deposits have been studied first. The Caasahcado Member is either overlying the reddish ignimbrite on top of the Dhagax Member or rests directly on the upper basalt horizon capping the Shabeley Laag Member as observed in the northwestern part of the research area. The thickness of the Caashacado Member is strongly variable and reaches a maximum of 25 m. The so far known exposures of this unit are restricted to the area west of the ephemeral river bed of the Bedumu.

The lowermost 5 meters of cross-section 32 (Fig.5) comprise fine- to medium-grained, <1m thick sand layers intercalated with brownish silty sands. Two carbonate layers are exposed at the base. The lowermost deposits are overlain by 5 m of light grey to brownish mudstones. The muddy deposits are followed by 2 m of fine- to medium-grained, light grey to brownish sands to tuffitic sands. Abundant bivalves are present within the middle part of the sandy sequence. This sandy sequence is overlain by 1 m thick, dark grey silt containing abundant root structures and a 1.5 m thick, fine-grained tuffitic sand exhibiting horizontal and convolute lamination. The uppermost sand layer is followed by 3.5 m thick brownish siltstones containing a horizon enriched in carbonate concretions. The basal deposits of the Caashacado Member described by cross-section VI (Fig. 5) consist of 3 m of fine- to coarse-grained sands that are overlain by 4.5 m of sandy silts to silts with a 0.3 m thick whitish limestone. The top of the member is characterized by a pyroclastic layer that is locally separated into two layers by a weathering horizon (cross-section 32, Fig. 5).

Cross-section 32 (N 9°47.071800 E 40°31.398900) is presented as holostratotype whereas the upper part of cross-section VI (N 9°46.151520 E 40°31.557180) is defined as parastratotype (Fig.5).

4.7.1 Results of $^{40}Ar/^{39}Ar$ dating

Results of $^{40}Ar/^{39}Ar$ data are summarized in Table 2. Full analytical data are given in supplementary information. All samples are briefly discussed here in stratigraphic order.

Glass of the stratigraphically oldest tuff at the base of the Lasdanan Member (sample W133/2) was dated at 5.37±0.04 Ma. The K/Ca ratio of the glass was 0.27. Note that size fraction was 500-1000µm and no thin shards were dated to avoid issues with K and Ar mobility and neutron irradiation effects (Morgan et al., 2009).

Two different grain sizes of a tuff at the base of the basal tuff complex of the Dhidinley Member (sample W78) were analyzed. The 200-500µm fraction shows heterogeneous age results and the youngest age might represent the eruption age. However, ages of the larger 500-1000µm fraction are less scattered and 4 out of 20 analyses of this fraction were identified as outliers (see supplementary information). W78 therefore yields a weighted mean age of 4.43±0.02 Ma based on the larger size fraction.

Different grain size fractions of feldspars samples from a tuff layer exposed at cross-section 42-43 halfway the Dhidinley Member (sample 09/16) were analyzed and appeared to be heterogeneous in age. The 3 youngest grains of the 500-1000 µm fraction arrive at 4.25±0.02 Ma. The oldest grains of both grain size fractions arrive at an weighted mean age of 4.40±0.01 Ma. Assuming that no argon loss has occurred and the heterogeneous age distribution is caused by some sort of (xenocrystic?) contamination, 4.25 Ma might represent the age of deposition.

Feldspar from the greyish ignimbrite on top of the Dhidinley Member (sample U11) yields reproducible results with a weighted mean age of 3.94±0.02 Ma. Two out of 20 analyses were identified as outliers.

Two grain size fractions of the weathered lapilli tuff on top of the Godiray Member (09/29) were analyzed. The youngest population in the bimodal distribution arrives at 3.97±0.03 Ma based on 5 out of 10 analyses. This age might represent the depositional age assuming no argon loss.

Feldspars of different grain sizes have been analyzed for the

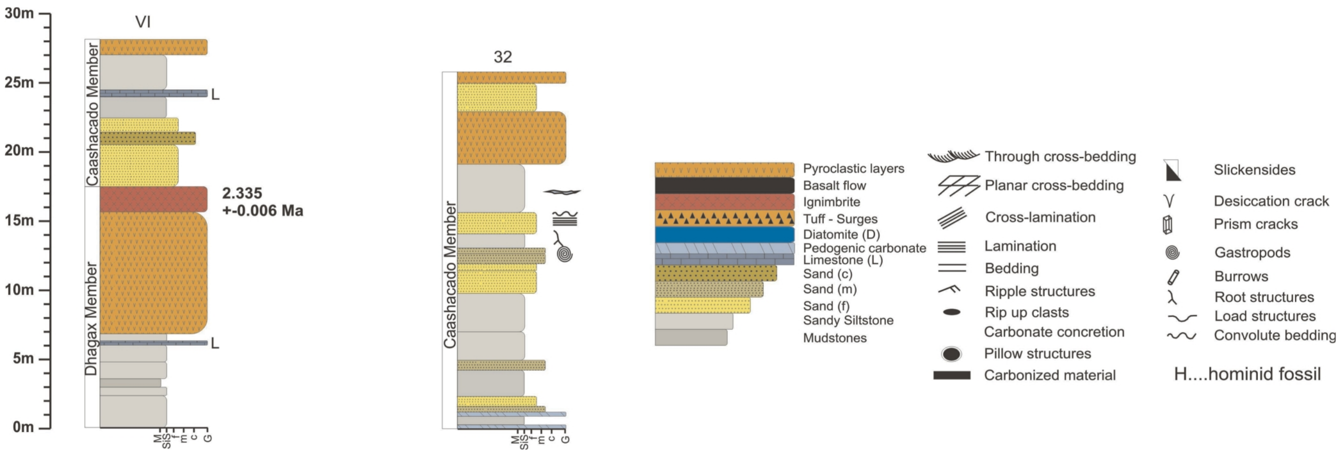


Figure 5: Profiles of the Dhagax- and Caashacado Member. Position of sections is shown on Figure 1.

Table 2: Results of $^{40}Ar/^{39}Ar$ dating

Irradiation ID	Sample	$^{40}Ar^{*}/^{39}Ar_K$	± 1 SE	± 1 SE (%)	N	N_{total}	MWSD	$^{40}Ar^{*}/^{39}Ar_K$ standard	± 1 SE	Age (Ma)	± 1 SE (analytical)	± 1 SE (external)	K/Ca	Inverse isochron intercept	Size fraction
Ignimbrite Caashacado Member															
VU82-W1	U51	0,3960	0,0010	0,26%	9	10	0,50	4,3368	0,0043	**2,35**	**0,01**	0,01	35.1 ± 2.9	309 ± 54	250-500 µm
Grey ash tuff at base upper Shabeley Laag Member															
VU82-W2	09/16A	0,6484	0,0023	0,35%	4	10	0,21	4,3210	0,0043	3,85	0,01	0,02	6.8 ± 1.0	300.8 ± 5.9	500-1000 µm
VU82-W3	09/16A	0,6605	0,0040	0,60%	2	10	0,18	4,3056	0,0043	3,94	0,02	0,02	2.7 ± 1.3	N/A	250-500 µm
	09/16A combined	0,6519	0,0029	0,45%	6	20	2,12			**3,87**	**0,02**	0,02	5.2 ± 1.2	294.5 ± 8.5	
Grey ash tuff at base upper Shabeley Laag Member															
VU82-W8	09/32	0,7761	0,0810	10,44%	2	4	2,96	4,2692	0,0043	4,66	0,49	0,49	1.0 ± 0.1	N/A	500-1000 µm
VU82-W10	09/32	0,6510	0,0175	2,69%	1	7	N/A	4,2760	0,0043	**3,91**	**0,11**	0,11	10.16 ± 0.95	N/A	400-500 µm
VU82-W11	09/32	1,1343	0,0101	0,89%	1	7	N/A	4,2766	0,0043	6,80	0,06	0,06	17.8 ± 2.5	N/A	250-400 µm
	09/32 combined	0,6662	0,0352	5,28%	3	18	4,59			4,00	0,21	0,21	1.03 ± 0.38	309.7 ± 4.0	
Weathered lapilli tuff on top of the Godiray Member															
VU82-W9	09/29	0,7228	0,0104	1,45%	2	2	1,15	4,2692	0,0043	4,34	0,06	0,06	0.115 ± 0.076	N/A	500-1000 µm
VU82-W12	09/29	0,6607	0,0052	0,79%	4	8	0,93	4,2692	0,0043	3,97	0,03	0,03	0.242 ± 0.072	306.7 ± 6.1	250-500 µm
	09/29 combined	0,6610	0,0052	0,79%	5	10	0,79			**3,97**	**0,03**	0,03	0.123 ± 0.041	306.8 ± 6.2	
Greyish ignimbrite on top of the Dhidinley Member															
VU75-J5	U11	0,8700	0,0017	0,19%	18	20	2,14	5,6750	0,0057	**3,94**	**0,01**	**0,02**	16.0 ± 1.3	311 ± 18	500-1000 µm
Tuff layer exposed at cross-section 42-43 halfway the Dhidinley Member															
VU82-W4	09/16	0,7107	0,0018	0,26%	3	15	1,01	4,3610	0,0044	**4,25**	**0,01**	0,02	11.0 ± 1.6	400 ± 91	500-1000 µm
VU82-W5	09/16	0,7404	0,0022	0,30%	4	10	1,37	4,2729	0,0043	4,45	0,01	0,02	12.7 ± 0.9	245 ± 44	250-500 µm
	09/16 combined	0,7356	0,0012	0,16%	7	25	0,91			4,40	0,01	0,01	13.8 ± 1.5	345 ± 29	
Tuff at the base of the basal tuff complex of the Dhidinley member															
VU75-J6	W78	0,9723	0,0015	0,16%	16	20	2,08	5,6337	0,0056	**4,43**	**0,01**	**0,02**	10.3 ± 1.0	304.2 ± 3.0	500-1000 µm
VU75-J7	W78	1,2564	0,0676	5,38%	10	10	1420	5,6131	0,0056	5,74	0,31	0,31	5.1 ± 1.4	927 ± 475	200-500 µm
Lapilli tuff of Lasdanan member															
VU82-W6	W133/2	0,8950	0,0072	0,80%	9	9	1,10	4,2692	0,0043	**5,37**	**0,04**	0,04	0.270 ± 0.006	298.6 ± 7.7	500-1000 µm

in bold: accepted age

the grey ash tuff exposed at the base of the sandy facies within the upper Shabeley Laag Submember (sample 09/16A). The age distributions are heterogeneous ranging from 3.16 – 5.45 Ma for the 500-1000µm fraction and from 3.62 – 6.74 Ma for the 250-500µm fraction. The median cluster of 6 analyses yields 3.87± 0.02 Ma. Based on these data it is difficult to constrain the depositional age, other than most likely younger than 3.87 Ma assuming that the older grains represent xenocrystic (or other?) contamination.

Three grains size fractions of a second sample from the grey tuff in the upper Shabeley Laag Submember were analyzed (sample 09/32). This sample was taken 3 km apart from 09/16A. All size fractions show a heterogeneous age distribution ranging from 3.9 – 136 Ma (see supplementary information). The youngest 3 data yield a weighted mean age 4.00±0.21 Ma, but MSWD is still high (table 1) and therefore observed scatter is caused by geological complexity of the sample. Based on these data it is difficult to constrain the depositional age, but is probably younger than 3.9 Ma consistent with the data of sample 09/16A.

Feldspars from the red ignimbrite at the base of the Dhagax Member (sample U51) yields reproducible results with a weighted mean age of 2.35±0.01 Ma. One out of 10 analyses was identified as an outlier.

5. Discussion

5.1 Age range of the Galili Formation

A composite stratigraphic chart has been generated to visualize the lithostratigraphy and age range of the Galili Formation (Fig. 6). The composite section is based on the holo- and parastratotype sections of the individual members. This chart also shows the stratigraphic position of the most important fossil sites, as well as the $^{39}Ar/^{40}Ar$-ages.

5.1.1 Lasdanan Member

Due to the complex outcrop situation, three composite stratigraphic columns of the Lasdanan Member are given. The basalt horizons are numbered 1 – 5. The northernmost deposits including the Satkhawini fossil site are shown in column I. Stratigraphic column II shows the idealized section of the sediments exposed in the central part whereas section III summarizes the deposits of the southernmost outcrops including the Lasdanan and Moquorbashi fossil sites. The lower age boundary of the Lasdanan Member is given by the radioisotope age of the tuff layer exposed at cross-section 38 (Fig. 2), which is immediately situated above the basalt horizon 2. The lapilli tuff has been dated to 5.37±0.04 Ma. This age has to be considered as minimum lower age boundary as 20 m of basalt and sediments underlying the dated tuff layer are present. The upper age boundary of the Lasdanan Member is provided by radioisotope results from a tuff layer at the base of the Dhidinley Member. This tuff layer is exposed 2-3 m above the uppermost basalt of the Lasdanan Member and has been dated to 4.43±0.01 Ma. Therefore, the age of the Lasdanan Member can be constrained to >5.37 - >4.43 Ma.

5.2 Dhidinley Member

Sanidines separated from a tuff located at the base of the basal tuff complex yielded an $^{40}Ar/^{39}Ar$ age of 4.43±0.01 Ma (Fig. 3, section 16-18). This age is considered as lower age boundary of the Dhidinley Member. The up-

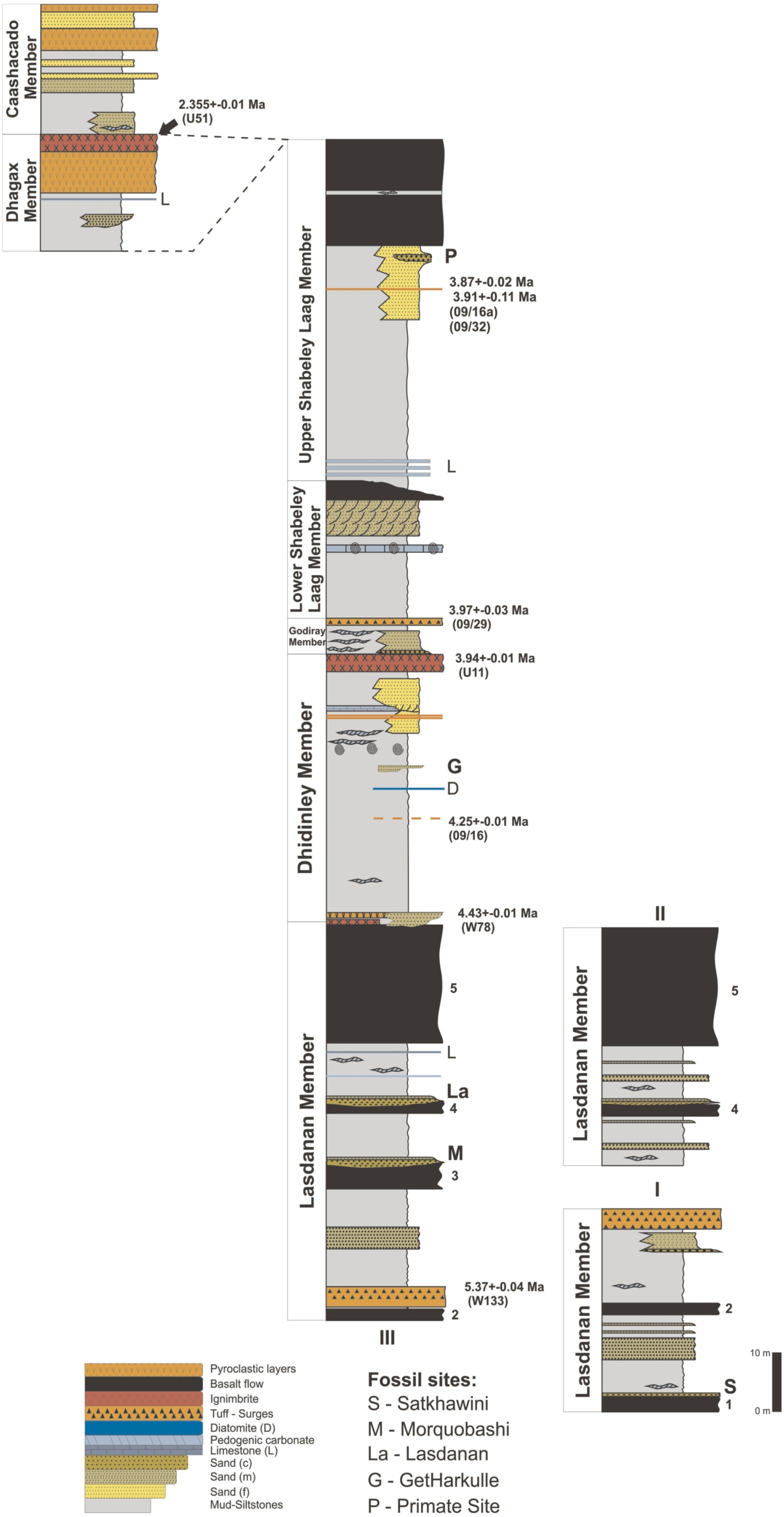


Figure 6: Composite stratigraphic chart of the Galili Formation based on the individual measured sections shown in figures 2-5. Position of radioisotope ages and most important fossil sites are included.

per age boundary is given by the grey ignimbrite on top of the Dhidinley Member that has been dated to 3.94±0.02 Ma. The tuff layer exposed at cross-section 42-43 (Fig. 3) yielded an age of 4.25±0.02 Ma. The stratigraphic position of this tuff layer to the GetHarkulle fossil site cannot be determined for sure. Therefore, the age of the fossils recovered from the Dhidinely Member including the fossil site GetHarkulle can be therefore constrained to <4.43 to >3.94 Ma.

5.2.1 Godiray Member

The lower age boundary of the Godiray Member is given by the $^{40}Ar/^{39}Ar$ age obtained from the grey ignimbrite on top of the Dhidinley Member (3.94±0.02 Ma). Several attempts have been made to separate feldspars from the weathered lapilli tuff on top of the Godiray Member. One sample gave a result of 3.97±0.03 Ma making it therefore indistinguishable from the grey ignimbrite. Based on this result, no upper age boundary can be constrained for the Godiray Member.

5.2.2 Shabeley Laag Member

The lower age boundary of the Shabeley Laag Member is time-equivalent with the age of the lapilli tuff on top of the Godiray Member (3.97±0.03 Ma). Therefore, no reliable radioisotope age is available for the lower Shabeley Laag Submember. The tuff layer exposed at the base of the sandy facies within the upper Shabeley Laag Submember has been sampled on two locations. The radioisotope results are 3.87±0.02 and 3.91±0.11 Ma. The error range of the second $^{40}Ar/^{39}Ar$ results would make the Shabeley Laag Member partly older as the Dhidinley Member and is therefore excluded. Biostratigraphic data indicates an upper age boundary between 3.6 to 3.36 Ma for the upper Shabeley Laag Member (Kullmer et al., 2008).

Based on the available data, the Shabeley Laag Member has been deposited between 3.97±0.03 Ma and <3.87±0.02 Ma. The hominid fossils recovered from the “primate site” therefore exhibit a minimum age of 3.87±0.02.

5.2.3 Dhagax and Caashacado Member

The deposits of both members overly the basalt flows on top of the Shabeley Laag Member and are therefore younger than 3.87±0.02. $^{40}Ar/^{39}Ar$ results from the reddish ignimbrite on top of the Dhagax Member provide an age of 2.355±0.01 Ma. The radioisotope data implies that a remarkable gap in deposition exists between the top of the Shabeley Laag basalt flows and the base of these overlying deposits. The strong weathering of the basalt flows together with the intercalated paleosols, as well as the highly unconformable contact between the upper basalt horizon and the Dhagax Member also indicate prolonged pauses in deposition and therefore supports the idea of a hiatus. The deposits of the Caashacado Member rest both on the Shabeley Laag and Dhagax Member. So far, no radioisotope data is available for the Caashacado Member.

Based on the available data, the Dahagx Member is older than 2.355±0.01 Ma, whereas the Caashacado Member is younger than 2.355±0.01 Ma and points to an earliest Pleistocene age of deposition.

5.3 Correlation with other fossiliferous formations of the Afar depression

The Miocene to Plio-Pleistocene fossiliferous deposits of six other paleoanthropological research areas have been investigated so far in the SW Afar Rift (for compilation see WoldeGabriel et al., 2013). Fig. 7 shows the stratigraphic range of deposits exposed at Woranso-Mille, Hadar, Ledi-Geraru, Dikikia, Gona, Middle Awash and Galili.

The deposits described at the Central Awash Complex have been organized in the >300 m thick Sagantole and informal “W” Formation (Renne et al., 1999; WoldeGabriel et al., 2013). From base to top, the Sagantole Formation consists of the fluvio-lacustrine Kuseralee (5.6 - 5.2 Ma), basaltic Gawto (5.2 - >4.98 Ma), fluvial-lacustrine-fluvial Haradaso (4.98 - 4.4 Ma), fluvial Aramis (4.4 - <4.3 Ma), tuffitic Beidareem (<4.3 - 4.2 Ma), fluvial Adgantole (<4.1 -3.89 Ma) and fluvio-lacustrine Belodhelie members (3.97-3.85 Ma; Renne et al., 1999; WoldeGabriel et al., 2013).

Based on the available data, the Lasdanan Member would be time-equivalent with the upper part of the Kuseralee Member, the complete Gawto and Haradaso Members as well as the lowermost part of the Aramis Member. The Aramis, Beidareem and the lower part of the Adgantole Members have been deposited during the same time as the Dhidinley Member. The Godiray Member has been deposited within the interval described by the Adgantole Member whereas the Belodhelie Member and the overlying informal “W” formation (3.75 - >3.39 Ma; Renne et al., 1999) is represented at Galili by the Shabeley Laag Member.

The Bouri Formation described by DeHeinzelin et al. (1999), exposed at the Bouri Horst, represents a Pleistocene succession of a combined thickness of more than 80 m. It has been subdivided into the Hataye (2.5 - 1.0 Ma), Dakanihylo (1 - 0.26 Ma) and Herto (0.26 - 0.16 Ma) Members (de Heinzelin et al., 1999; Asfaw et al., 2002; Clark et al., 2003; WoldeGabriel et al., 2008). The Dhagax and Caashacado members would represent the time-equivalent deposits to the lower part of the Hataye Member at Bouri.

The Dikika research area is located on the southern side of the Awash River, opposite of Hadar. The exposed fossiliferous strata have been assigned to the Hadar (>3.8 Ma - 2.9 Ma) and Busidima (2.7 - <0.16 Ma) Formations (Wynn et al., 2008). The Hadar Formation is further subdivided into the Basal Member below the Sidi Hakoma tuff (3.42±0.03 Ma, Wynn et al., 2008; 3.446±0.041, Renne et al., 2011), the Sidi Hakoma Member (between the Sidi Hakoma tuff and Triple Tuffs; TT-4 dated at 3.256±0.018 Ma), the Denen Dora Member (between the Triple Tuffs and Kada Hadar Tuff, dated at 3.20±0.01 Ma) and the Kada Hadar Member (above Kada Hadar Tuff, $^{39}Ar/^{40}Ar$ data from Wynn et al., 2008; WoldeGabriel et al., 2013 and references herein). The Shabeley Laag Member at Galili may partly encompasses the interval of the Basal Member, whereas the Dhagax and Caashacado Members have been deposited in the same time range as the lower parts of the Busidima Formation.

The Gona research area is located southwest of Hadar. It includes the frontal fault blocks of the western rift margin and the adjacent rift floor west and north of the Awash River. The deposits at Gona comprise upper Miocene to Plio-Pleistocene volcanic and sedimentary rocks that have been subdivided into the Adu-Asa (>6.4-5.2 Ma), Sagantole (>4.6-3.9 Ma), Hadar (3.8-2.9 Ma) and Busidima (2.7-<0.16 Ma) Formations (Quade et al., 2008).

The Lasdanan and Dhidinley Members at Galili comprise the time-equivalent deposits to the upper Adu-Asa Formation and the Sagantole Formation. The latter has been further subdivided into the As Duma, Segala Noumou, and As Aeala Members (Quade et al., 2008). The Lasdanan Member constitutes the counterpart of the As Duma Member and lower Segala Noumou Member whereas the Dhidinley Member encompasses the time-equivalent deposits of the upper Segala Noumou Member and partly the As Aeala Member. The complete Godiray and the lowermost Shabeley Laag Member would be time-equivalent with the upper part of the As Aeala Member.

The Hadar Formation exposed at Gona is partly contemporaneous to the Shabeley Laag Member at Galili, whereas the Dhagax and Caashacado Members have been deposited during the time interval of the Busidima Formation at Gona.

The Hadar research area encompasses the type section of the Hadar Formation. The Hadar Formation consists of the Basal, Sidi Hakoma, Denen Dora and Kada Hadar Members in ascending stratigraphic order. The individual members are defined by tephra layers (Taieb et al., 1976; Walter, 1981; Tiercelin, 1986). $^{39}Ar/^{40}Ar$ ages of the Sidi Hakoma, TT-4 and Kada Hadar Tuffs indicate that deposition of Hadar Formation started before 3.446±0.041and continued after 2.92 Ma (Walter, 1994; WoldeGabriel et al., 2013). So far no sedimentary or volcanic rocks of the GF could be assigned to this time interval.

The Woranso-Mille research area is characterized by densely faulted and deeply dissected fossiliferous sediments, lava flows and interbedded tephra (Deino et al., 2010; WoldeGabriel et al., 2013; Haile-Selassie et al., 2015). The 36 m thick succession has been deposited between 3.596 – 3.330 Ma based on a combination of radiometric and paleomagnetic data. Only the upper parts of the Shabeley Laag Member seem to have been deposited during the time-interval of the Woranso – Mille succession.

The Hadar Formation exposed at Gona is partly contemporaneous to the Shabeley Laag Member at Galili, whereas the

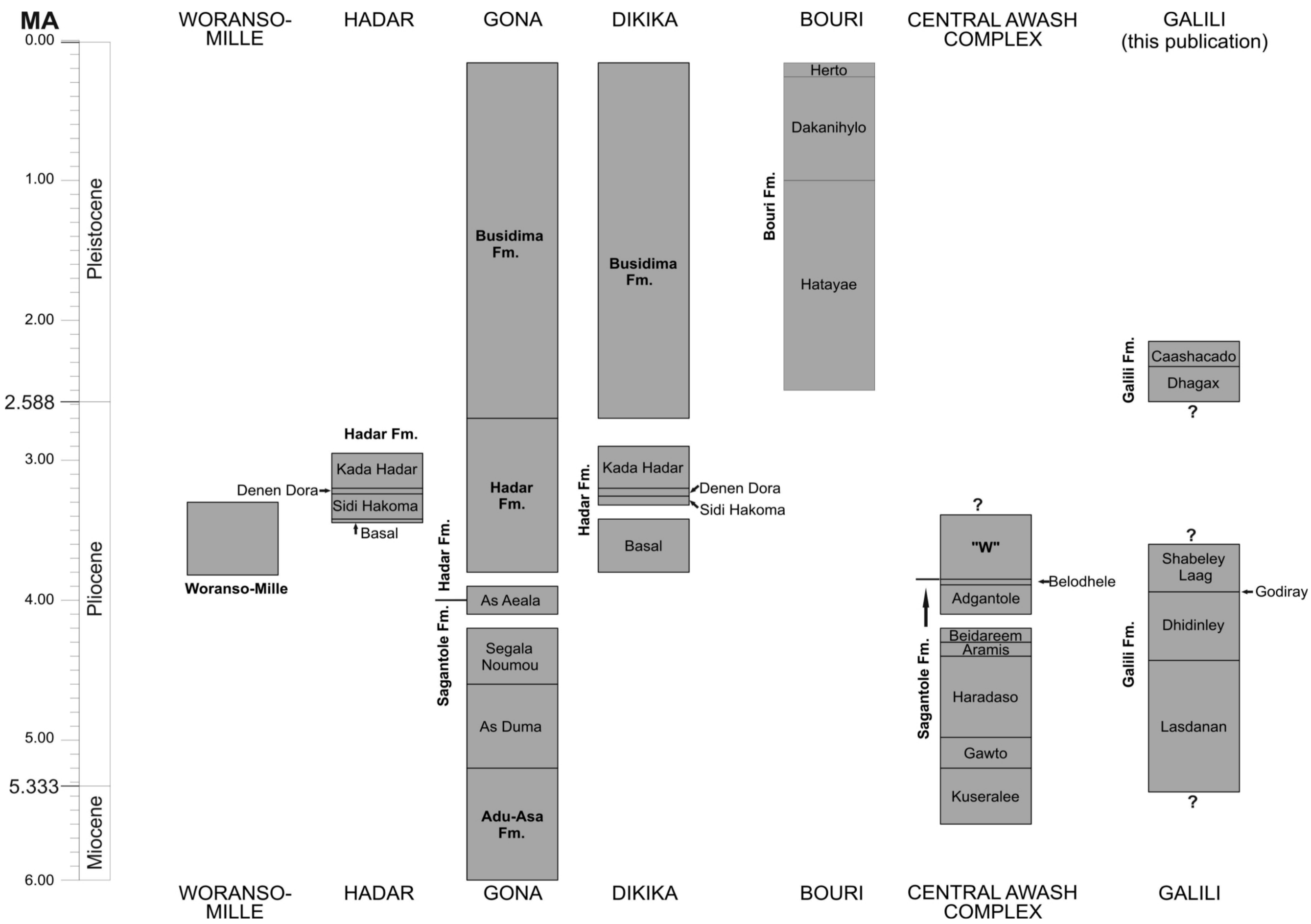


Figure 7: Stratigraphic range of the Galili Formation and correlation with other fossil sites in the Afar Depression. See references listen in text for formation and member boundaries. Miocene/Pliocene/Pleistocene boundaries from Gradstein et al. (2012).

Dhagax and Caashacado Members have been deposited during the time interval of the Busidima Formation at Gona.

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5.4 Development of the Galili Formation

5.4.1 >5.37- <4.43 Ma Lasdanan Member

The lowermost radioisotope age indicates that basin development most probably started in the Late Miocene. The triple junction has already developed and the overall depositional setting of this time range is governed by the development of thin sedimentary basins which interfingered with the thick basalt flows of Dahla Series. Deposition of the Lasdanan Member is dominated by thick basalt flows with intervening fluvial sandstones, shallow lacustrine to floodplain mudstones and locally thick acidic volcanic layers. The sedimentary successions pinch out laterally resulting in stratigraphic contact of encasing basalt flows. This outcrop situation indicates a landscape dominated by basalt ridges where deposition took mainly place in low areas between ridges and is stopped by eruption of basalt flows. The topographic situation resulted in lateral stratigraphic contacts of the encasing basalt flows and make lateral correlations of individual sedimentary packages almost impossible. Similar sedimentary settings are reported for the Adu-Asa Formation at Gona (Kleinsasser et al., 2008). The eruption of basalt flows and afterwards deep erosion by rivers and periods of prolonged weathering could explain the long time span represented by the Lasdanan Member (≥5.37-<4.43 Ma). Coarse-grained, fluvial sands to sandstones of the Lasdanan Member constitute the Satkhawini, Moquorbashi and Lasdanan fossil sites. Hominid teeth have been recovered from the latter two.

5.4.2 4.43 – 4.25 Ma basal Dhidinley Member

The Dhidinley Member records a change in style and intensity of volcanic activity. Eruption of thick basalt flows stopped after deposition of the uppermost basalts of the Lasdanan Member and changed to a more acidic volcanism resulting in deposition of tuff and ignimbrite layers. Sedimentation of the basal Dhidinley Member took place in an environment still influenced by the topography created by the eruption of the latest Lasdanan basalt flows. Low areas are indicated by occurrences of fluvial sands to sandstones eroding the underlying basalt flows and thick floodplain deposits. Elevated areas are characterized by strongly weathered basalt flows covered by thin muddy intervals. The basal tuff complex (4.43 Ma) is mainly preserved in areas with no fluvial sandy deposits and is therefore interpreted to indicate high areas. The basal fluvial deposits yielded a rich fossil assemblage, especially large mammals.

5.4.3 4.25 - 3.94 Ma Dhidinley Member

This lower interval of this time-span is characterized by the development of a widespread, shallow lake indicated by deposition of 15 m of multi-coloured mudstones. The outcrop situation shows that the deepest part of the lake basin where the thickest mudstone successions accumulated was situated in the central parts of the research area. The associated lake margin areas are mainly present in the southern exposures and comprise brownish to grey, silty mudstones characterized by root structures and calcrete concretions. Limestone and diatomite layers indicate periods of maximum lake levels with only minor siliciclastic input. Volcanic activity during this time decreases and only thin tuff layers were deposited. Furthermore, the widespread distribution of the lacustrine and lake margin deposits shows that the segmentation into individual small depo-centres of the basin was mainly overcome. A small fluvial system developed in the southern parts of the research area. The sandy channels to muddy floodplain deposits constitute the “GetHarkulle” fossil site that yields a rich fossil assemblage including a well preserved hominid femur. Deposition of the fluvial sands seems to be accompanied by a general shallowing of the lake as indicated by deposition of coarser siltstones and higher frequency of sand layers and calcrete concretions. The lacustrine setting is followed by a sandy fluvial deposition. Greenish-grey to brownish, coarse-grained fluvial sands to sandstones eroding the underlying mudstones constitute the lower part of this interval. The widespread occurrence of these fluvial deposits strengthens the assumption of basin-wide change in depositional style. The greenish-brownish fluvial sands are overlain a couplet consisting of a thin, whitish basal tuff layer and bluish-grey tuffs. The latter are completely composed of glass shards. The change in depositional style could be caused by changes in the tectonic setting shortly before the volcanic events causing the eruption of the tuff layers. The existing fluvial system reworked the tuffs into channelized, cross-bedded tuffites and planar bedded crevasse to floodplain deposits until eruption of the grey ignimbrite at 3.94 Ma. This up to 4 m thick ignimbrite layer marks the top of the Dhidinley Member.

5.4.4 <3.94 Ma Godiray Member

The depositional record of the Godiray Member indicates that fluvial deposition continued after the catastrophic eruption of the ignimbrite topping the Dhidinley Member. The presence of rivers eroding down onto the ignimbrite layer is evidenced by greenish-grey, cross-bedded sands. Development of widespread floodplain areas is indicated by grey, reddish to brownish mudstones exposed adjacent to the sandy deposits. Prolonged pauses in deposition are considered to have caused formation of thick calcrete concretion horizons to layers. The distribution of fluvial channel and floodplain deposits is also shown by the preservation of the whitish lapilli tuff on top of the Godiray Member. This volcanic layer is mainly found on top of muddy floodplain deposits and is missing where fluvial channel deposits are present.

5.4.5 <3.94 - 3.87 Shabeley Laag Member

A change from fluvial to lacustrine deposition is indicated by the basal deposits of the lower Shabeley Laag Submember. The multi-coloured mudstones are interpreted to have formed in a shallow lake setting. The widespread occurrence of the mudstones indicates that the lake covered most of the research area. Based on the outcrop situation, the deepest part of the basin was probably located in the central parts of the research area. Gastropod limestones and sand layers characterize the lake margin areas. The latter contained abundant well preserved mammal fossils. The lacustrine mudstones are overlain by fluvio-deltaic, bluish-grey sands to sandstones. Brownish mudstones to siltstones and calcrete horizons constitute the floodplain deposits adjacent to the fluvial deposits. Large mammal fossils have been recovered both from fluvial and floodplain deposits. A calcrete layer within the latter yielded a very well preserved monkey skull. A return to lacustrine deposition is indicated by interbedded diatomite layers on top of the bluish-grey fluvial sands. The top of the lower Shabeley Laag Submember is marked by a lateral discontinuous basalt flow. Pillow structures point to deposition on aqueous conditions which is in good agreement to the interpreted lacustrine environment. The change from acidic to basaltic volcanism could be related to the eruption of the Afar Stratoid Series between 4 and 3 Ma (mostly <3.5 Ma, Kidane et al., 2003). The thickest occurrences of the lower basalt horizon are found above and close to exposures of the bluish-grey fluvial sands. This indicates that the lower basalt flow probably follow a topography created by deposition of the fluvial sands. Lacustrine conditions continued for some time after the eruption of the lower basalt flow until deposition of fluvial sandy deposits before 3.87 Ma.

5.4.6 >3.87 – 2.335 Ma Shabeley Laag Member and Dhagax Member

The upper part of the Shabeley Laag Member is dominated by fluvial sandy deposits. Abundant primate teeth including hominid teeth have been recovered from a lag deposit at the base of a fluvial channel in the southernmost parts of the research area ("primate-site").

The top of the Shabeley Laag Member is characterized by stacked basalt flows with intervening paleosol horizons. The distribution of the outcrops indicates that the majority of the research area has been covered by these flows. Based on the radioisotope dating of the underlying tuff layer, the eruption of the basalt flows took place during the main eruption phase of the "Afar Stratoid Series" (<3.5 Ma, Kidane et al., 2003). The paleosol horizons further indicate prolonged pauses between eruptions of individual flows. The outcrop situation of the overlying deposits of the Dhagax and Caashacado Members implies that several areas covered by the stacked basalt flows acted as highs where no deposition took place until 2.335 Ma. Sometime after the eruption of the stacked basalt flows, a shallow lake formed in the westernmost parts of the research area. Its muddy deposits constitute the lower part of the Dhagax Member. The fine-grained lacustrine sediments are followed by sandy fluvial deposition and finally the thick pumice tuff.

5.4.7 <2.355 Ma Caashacado Member

The reddish ignimbrite on top of the Dhagax Member has been dated to 2.335 Ma and was therefore deposited after the eruption phase of the oldest basalts assigned to the Afar Stratoid Series (Audin et al., 2004). This time span precedes the development of the nowadays active magmatic segments and axial volcanic ranges (Ebinger and Casey, 2001).

The distribution of the uppermost Caashacado Member is interpreted to be governed by topographic features created both by the stacked basalt flows on top of the Shabeley Laag Member and the Dhagax Member. Deposits of the Caashacado Member are unconformably overlying the Shabeley Laag basalt flows in the NW corner of the research area. The Dhagax Member is missing there indicating that this part formed a topographic high until ≤2.335 Ma. The thickest strata assigned to the Caashacado Member are found in topographic lows floored by the reddish ignimbrite topping the Dhagax Member. The basal deposits of the Caashacado Member comprise fluvial sands that are overlain by brownish-grey, shallow lacustrine mudstones. Lake-margin areas are indicated by sandy mollusc packstones and rooted mudstones. Thin fluvial and floodplain deposits are present in the upper part of the member. The outcrop situation and the exposed deposits indicate that deposition at this time was most probably constrained to shallow topographic lows located along the western boundary of the research area. The uppermost recognized deposits of the Galili Formation consist of two pyroclastic layers separated by a weathering horizon. The top layer forms the floor of the western plateau and constitutes therefore the upper boundary of the Galili Formation.

8. Conclusions

1) The newly defined Galili Formation describes 230 m thick Late Miocene to earliest Pleistocene fossiliferous deposits exposed in the transition zone between the Northern Main Ethiopian Rift and the Southern Afar Rift. In contrast to most of the other fossil sites to the west, the outcrops of the Galili Formation are located about 35 km towards the east of the

Awash River. Only the fossiliferous deposits of the Chorora Formation are located more eastward, close to the Somali escarpment.

2) The Galili Formation consists in ascending stratigraphic order of the Lasdanan, Dhidinley, Godiray, Shabeley Laag, Dhagax and Caashacado Members that are defined by volcanic horizons.

The Lasdanan Member consists of five thick basalt flows with intercalated fluvial to shallow lacustrine deposits and tuff-ignimbrite successions that pinch out laterally. The lowermost basalt flow has been dated by a tuff that revealed an $^{40}Ar/^{39}Ar$ age of 5.37 Ma, which constitutes the minimum lower age boundary of the Galili Formation.

The overlying Dhidinley Member record a pause in eruption of basalt flows. Basalt tuffitic to sandy-muddy deposits are followed by thick lacustrine mudstones that are erosive overlain by fluvio-deltaic sandy-tuffitic depositsand a thick grey ignimbrite. The basal tuffs have been dated to 4.43 Ma whereas the top ignimbrite yielded an age of 3.94 Ma. The deposits of the Godiray Member comprises fluvial sandy deposits with adjacent floodplain mudstones and pedogenic carbonate layers. The top is characterized by a widespread, strongly altered lapilli tuff that yields an $^{40}Ar/^{39}Ar$ age of 3.97 Ma.

The Shabeley Laag Member is subdivided into a lower and upper submember. The lower submember starts with shallow lacustrine mudstones that are overlain by bluish-grey fluvial sands and a pillow basalt flow. The basal section of the upper Shabeley Laag Member consists of lacustrine mudstones followed by fluvial-deltaic sandy deposits. The top of the Shabeley Laag Member comprises thick, stacked basalt flows that are separated by reddish paleosol horizons. A tuff layer exposed in the middle of the upper Submember has been dated to 3.87 Ma. The two basalt horizons of the Shabeley Laag Member correlate to the "Afar Stratoid Series" eruption. The thick upper basalt horizon of the Shabeley Laag Member is either overlain by the Dhagax or Caashacado Members.

The lower part of the Dhagax Member consists of lacustrine mudstones that are erosive cut by fluvial sandy deposits. Thick bluish-grey pumice tuffs and a reddish ignimbrite layer constitute the upper part of the Dhagax Member. The reddish ignimbrite has been dated to 2.335 Ma.

The uppermost Caashacado Member is exposed both on top of the Dhagax or the Shabeley Laag Member. The muddy and sandy deposits reflect deposition in shallow lacustrine and fluvial settings. The unconformity and the gap in the $^{40}Ar/^{39}Ar$ ages indicate a prolonged pause in deposition after eruption of the Shabeley Laag basalt flows.

3) The deposits of the Lasdanan, Dhidinley and Godiray Members are time-equivalent to the Sagantole Formation exposed at the Central Awash Complex (CAC) and Gona. The Shabeley Laag Member has been deposited during the same time-interval of the “W” Formation (CAC), the basal Hadar Formation at Dikika and Gona and of the fossiliferous deposits exposed at Woranso-Mille. The Busidima Formation at Bouri, Dikika and Gona are partly time-equivalent with the Dhagax and Caashacado Members at Galili.

4) Several fossil sites have been found within the Lasdanan, Dhidinley and Shabeley Laag members. The Moquorbashi and Lasdanan fossils site in the Lasdanan Member produced several hominid teeth that can be dated to <5.37 to >4.43 Ma. The age of fossils found in the “GetHarkulle” fossil site of the Dhidinely Member can be constrained to <4.43 to 3.94 Ma. Abundant primate teeth and several hominid teeth have been found in the sandy deposits of the “primate-site” in the Upper Shabeley Laag Submember. The currently available radioisotope data allow constraining a lower age boundary for these fossils of 3.87±0.02.

Additional work including detailed sedimentological studies, stable isotope and paleomagnetic analyses are underway to clarify the influence of tectonic and climate on deposition.

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