Breakage Patterns of Long Bone Articular Ends, Hadar, Ethiopia:

Implications for Assessing Cause of Death of A.L. 288-1 ('Lucy')

Matthew Hill[1], John Kappelman[2], Lawrence Todd[2], Fantahun Zelelew[3]

[1] Iowa State University, [2] University of Texas, Austin, [3] ARCCH

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Abstract: Recent publication of a hypothesis that breakage patterns of several of the limb bones of the Pliocene fossil 'Lucy' (Australopithecus afarensis) indicates death induced by a vertical deceleration event caused by a fall from height (Kappelman et al. 2016). This has generated a number of comments about the distinctiveness of articular end/adjacent shaft damage ascribed to compressive impact. Results of documentation that targeted AL288-1 long bone end fragmentation along with a variety of species from 141 other Hadar localities (N = 431 specimens with emphasis on humeri and femora) demonstrates that the compressive fracture of Lucy's humeri and distal femur are clearly distinct from the baseline breakage patterns of other Hadar fossils. While not providing direct support for the specific cause of death of AL288-1, these data highlight the unusual breakage patterns on this specimen's limb bones and strengthen the observation that the breakage patterns on Lucy's bones represent forces other than the normal formational dynamics of carnivore damage, weathering, depositional loading, and fossilization cracking that alter many of the other specimens. Common fractures of articular surfaces include cracking and horizontal displacement with limited numbers of vertically displaced pieces. Compression and displacement of broken fragments along the long axis of the long bone as described by Kappelman et al. for AL.288-1 are an extremely rare feature of the Hadar Pliocene fauna and point to a distinct difference between the fracture dynamics acting on Lucy's bones and those reflected in the more diverse regional assemblage.

BREAKAGE SAMPLE

HADAR A.L. LOCALITY	ORDER: ARTIODACTYLA	CARNIVORA	PERISSODACTYLA	PRIMATES	RODENTIA	NO IDENTIFICATION	TOTAL SPECIMENS CODED
2	2	0	0	7	0	0	9
5	1	0	0	0	0	0	1
26	2	0	0	0	0	0	2
42	2	0	0	0	0	0	2
55	1	0	0	2	0	0	3
70	2	0	1	0	0	0	3
75	0	0	1	0	0	0	1
86	1	0	0	0	0	0	1
94	1	0	0	0	0	0	1
99	2	0	0	0	0	0	2
100	3	0	0	0	0	0	3
107	0	0	1	0	0	0	1
109	3	1	0	0	0	0	4
113	0	1	0	0	0	0	1
116	0	0	0	2	0	0	2
121	0	1	0	0	0	0	1
122	1	4	1	0	0	0	6
124	0	1	0	0	0	0	1
126	2	0	1	4	0	0	7
127	1	0	0	0	0	0	1
128	0	0	0	1	0	0	1
129	0	0	0	2	0	0	2
132	4	0	0	0	0	0	4
133	1	0	0	2	0	0	3
135	0	1	0	0	0	0	1
137	0	0	0	3	0	0	3
138	1	0	0	0	0	0	1
145	1	0	0	1	0	0	2
147	6	0	2	0	0	0	8
154	0	0	1	1	0	0	2
155	0	0	8	0	0	0	8
156	10	0	0	0	0	0	10
157	0	0	0	1	0	0	1
158	0	0	0	1	0	0	1
161	2	0	1	1	0	0	4
163	0	0	0	1	0	0	1
165	1	0	0	0	0	0	1
166	0	1	0	0	0	0	1
177	2	1	0	0	0	0	3
182	3	0	1	0	0	0	4
183	3	0	1	0	0	0	4
185	1	0	0	2	0	0	3
187	0	0	0	2	0	0	2
196	0	0	0	2	0	0	2
198	0	1	0	0	0	0	1
201	0	0	0	1	0	0	1
204	0	0	0	1	0	0	1
207	0	0	0	1	0	0	1
213	0	0	0	1	0	0	1
222	0	0	0	2	0	0	2
223	0	0	0	1	0	0	1
224	0	1	0	0	0	0	1
225	0	1	0	0	0	0	1
227	2	0	1	0	0	0	3
234	6	0	0	0	0	0	6
236	3	0	0	0	0	0	3
237	0	0	0	1	0	0	1
244	0	0	0	1	0	0	1
246	1	0	0	0	0	0	1
251	3	7	1	0	0	0	11
255	3	0	0	0	0	0	3
257	1	0	0	0	0	0	1
262	3	0	0	0	0	0	3
273	0	1	0	0	0	0	1
285	0	0	0	2	0	0	2
286	0	0	0	1	0	0	1
288	6	1	4	80	6	0	97
294	0	0	0	1	0	0	1
295	0	0	1	1	0	0	2
300	0	0	0	1	0	0	1
304	0	0	0	1	0	0	1
305	0	0	1	0	0	0	1
308	1	0	0	0	0	0	1
309	0	0	0	1	0	0	1
315	2	0	2	0	0	0	4
320	14	0	0	0	0	0	14
321	0	1	0	0	0	0	1
322	0	0	0	2	0	0	2
325	1	0	1	0	0	0	2
326	0	0	1	0	0	0	1
327	1	0	0	0	0	0	1
329	1	0	0	0	0	0	1
330	0	0	0	1	0	0	1
332	0	0	0	1	0	0	1
333	0	0	0	11	0	0	11
333e	0	0	0	1	0	0	1
333w	0	0	0	3	0	0	3
333x	0	0	0	2	0	0	2
338	2	0	2	2	0	0	6
339	0	0	1	0	0	0	1
353	0	0	2	0	0	0	2
363	0	0	0	2	0	0	2
365	0	0	1	0	0	0	1
370	0	0	0	1	0	0	1
392	0	0	0	1	0	0	1
394	1	0	0	0	0	0	1
396	2	0	0	0	0	0	2
398	1	0	0	0	0	0	1
399	1	0	0	0	0	0	1
400	1	0	0	1	0	0	2
402	0	0	0	1	0	0	1
403	4	2	2	0	0	0	8
406	2	0	0	0	0	0	2
411	0	0	1	1	0	0	2
430	0	0	0	2	0	0	2
431	0	0	0	5	0	0	5
445	0	0	0	1	0	0	1
467	0	4	0	0	0	0	4
499	0	1	0	0	0	0	1
528	0	0	0	1	0	0	1
539	0	0	1	0	0	0	1
540	0	0	2	0	0	0	2
545	1	0	0	1	0	0	2
571	0	1	0	0	0	0	1
602	1	0	0	0	0	0	1
693	0	0	0	3	0	0	3
700	0	0	0	2	0	0	2
782	0	1	0	0	0	0	1
793	0	1	0	0	0	0	1
928	0	0	0	1	0	0	1
931	0	0	0	1	0	0	1
933	0	1	0	0	0	0	1
1068	1	0	0	0	0	0	1
1126	1	0	0	0	0	0	1
1182	0	0	1	0	0	0	1
1197	2	0	0	0	0	0	2
1233	0	0	1	0	0	0	1
1308	1	0	0	0	0	0	1
1373	1	0	1	0	0	0	2
1580	1	0	0	0	0	0	1
1596	1	0	0	0	0	0	1
1631	1	0	0	0	0	0	1
1640	2	0	0	0	0	0	2
1649	1	0	0	0	0	0	1
1678	1	0	0	0	0	0	1
1697	1	0	0	0	0	0	1
1699	1	0	0	0	0	0	1
1742	1	0	0	0	0	0	1
1775	2	0	0	0	0	0	2
1822	1	0	0	0	0	0	1
1898	1	0	0	0	0	0	1
2239	0	1	0	0	0	0	1
NO LOC.	0	0	0	0	0	21	21
TOTAL	**143**	**36**	**46**	**179**	**6**	**21**	**431**

COMMON FOSSILIZATION BREAKAGE AT HADAR?

It was recently hypothesized that A.L. 288-1 ('Lucy') preserves a subset of perimortem fractures consistent with injuries in accident victims who suffer a vertical deceleration event (VDE) (Kappelman et al., 2016). Certain fractures, e.g., a four-part fracture of the right proximal humerus, and a dislocative compressive distal epiphyseal fracture of the left femur, suggest a high velocity impact following a fall from considerable height. The severity of these fractures led Kappelman et al. (2016) to hypothesize that other skeletal fractures are also consistent with a VDE. The initial description of A.L. 288-1 (Johanson et al., 1982) detailed many surface "cracks" in other elements that were attributed to fossilization processes. Although other aspects of the project (Ruff et al. 2016) now lend support to the suggestion that Lucy spent a good deal of time in the trees with the concomitant likelihood of falls also being supported, reactions to the VDE hypothesis have been varied. On the one hand, the Smithsonian's Rick Potts is quoted as saying "the study's evidence makes a convincing case for how Lucy died"[1] and Harvard's David Pilbeam has said that the researchers have "come up with what strikes me as the most plausible explanation for the breakage – mainly a fall from considerable height."[2] On the other hand, discoverer Donald Johanson (ASU) is reported to have stated "In my opinion…the breakage and plastic deformation seen on Lucy's bones, as well as many of the other hominin fossils at Hadar is the result of geologic forces acting on the bones during the fossilization process"[3] (or alternatively, in the same interview "perhaps Lucy was trampled by a stampede of large animals"[3]) and from UC Berkeley's Tim White, who after stating that the paper is "a classic example of paleontological storytelling being used as clickbait for a commercial journal eager for media coverage," goes on to suggest that "fossilization-related breakage much like Lucy's – including extensive shoulder-joint damage – appears on bones of a variety of nonclimbing animals, including gazelles, hippos and rhinos"[4] (Figure 1).

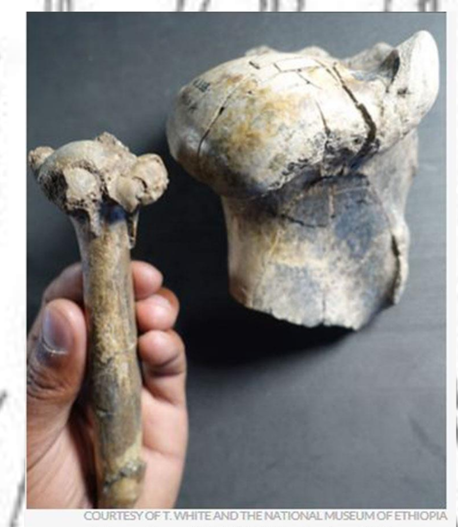


Figure 1. A.L.288-1m shown next to equid humerus A.L.338-13a said to show similar breakage. (See Fig. 9 here for our coding.)

In light of this diverse set of comments, and with particular reference to Johanson and White's assertion that the focal breaks in the VDE hypothesis (e.g., proximal humerus and distal femur) were not out of the ordinary in the context of other Hadar fossils, in October, 2016 our team conducted research in the National Museum in Addis Ababa re-examining Lucy, other Hadar hominins, and other specimens from a range of Hadar localities (Figure 2).

In addition to standard attributes such as weathering, breakage morphology, presence/absence of carnivore modification or other forms of postmortem damage that we are currently using in our taphonomic documentation of the fauna from the *Homo erectus* site at Trinil, Java (Hill et al. 2015), we also developed a series of articular end specific codes (Figure 3).

In the past, most studies of bone breakage have focused on long bone shafts, and there has been little comparative study of articular end specific damage. Given the questions about whether the articular damage to A.L. 288 is distinctive, or a common occurrence in Hadar specimens, our recent work emphasized damage to ends of the bones in our sample of 431 Hadar fossils from 142 collection localities and several with no locality designation (see breakage sample list at left).

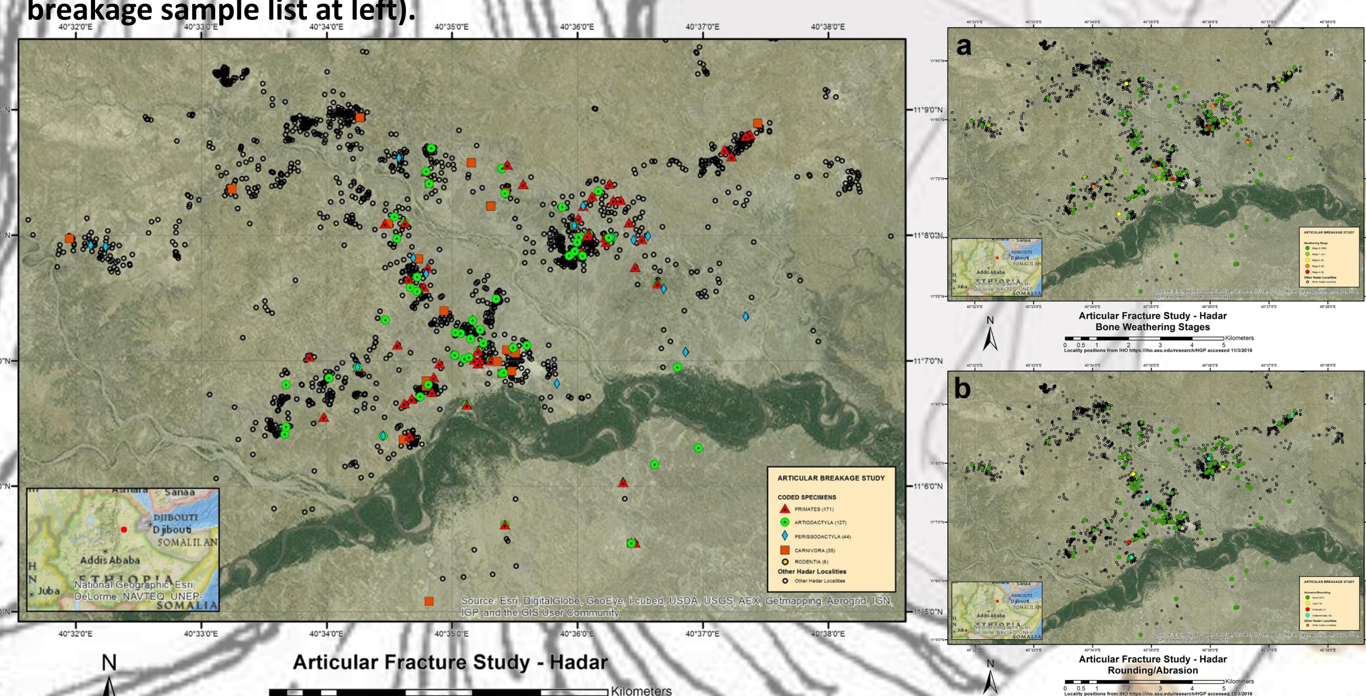


Figure 2. Comparative documentation of Hadar breakage examined all accessible major limb bones (focus on humeri and femora) from collections accessible in the Ethiopian National Museum (breakage list to left). In addition to articular end specific breakage coding, data on other attributes such as weathering and abrasion were documented.

To date, a key criticism of the Kappelman et al. research has been that the compressive breaks described as being perimortem and indicative of a VDE are suspect because there is no comparison to other specimens and that such comparison would show compressive fractures to be common at Hadar and in other assemblages. We have collected data to address these concerns that focus on two key questions:

- **How does other taphonomic information from the locality contribute to the evaluation of A.L.288-1 breakage?**
- **Are the types of compressive breaks to several A.L.288 specimens, particularly to both proximal humeri (A.L.288-1m and A.L.288-1), left distal femur (A.L.288-1ap), and right proximal tibia (A.L.288-1aq) common in the Hadar collection or elsewhere?**

Notes:

None of these comments have appeared in peer reviewed publications, just as comments to media coverage:

[1] http://www.smithsonianmag.com/science-nature/did-anthropologists-just-solve-millions-year-old-mystery-Lucy-death-180960276/

[2] http://news.nationalgeographic.com/2016/08/lucy-tree-fall-human-ancestor/

[3] http://www.csmonitor.com/Science/2016/0829/Has-the-mystery-of-Lucy-s-death-been-solved-Maybe.-Maybe-not?cmpid=push013s

[4] https://www.sciencenews.org/article/fossil-autopsy-claims-lucy-fell-tree

ASSEMBLAGE CHARACTERISTICS AT A.L.288

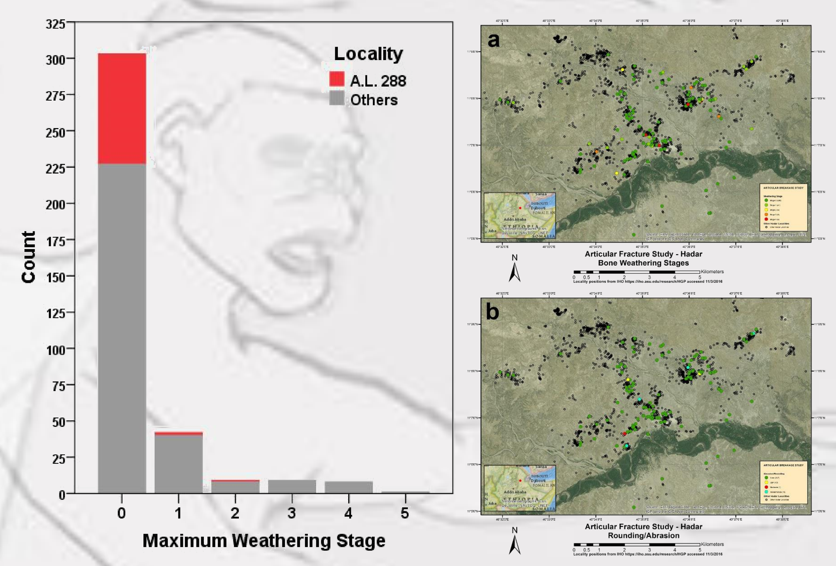


Figure 3. Surface weathering of A.L.288 and other specimens in our breakage sample is minimal with the majority falling into Stage 0.

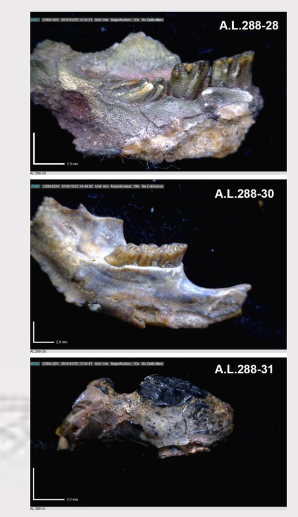


Figure 4. Other materials recovered from A.L.288 include small, fragile rodent bones.

Figure 5. The majority of all bones are in near perfect surface condition as represented by distal end of A.L.288-1m; only three of the specimens from the locality show even slight surface modification such as the shallow surface cracking exemplified by A.L.288-1s.

Lucy's remains were discovered as surface finds but were shown to have eroded out of a medium-grained sandstone near the base of the Kada Hadar Member; subsequent processing and screening of this unit produced numerous skeletal elements that demonstrated Lucy's exact stratigraphic provenience and also produced crocodile and turtle eggs and crab claws (Johanson & Taieb 1976). The discovery unit, KH-1s, is 0.5 m thick at the Lucy site but varies considerably in thickness across the landscape. Surface condition on most the material recovered from A.L.288 is excellent, with most of the collection, both Lucy and the other species, exhibiting no surface weathering. The generally unweathered states of most of the bones from A.L. 288 (both Lucy's and others, Table 1) in our breakage sample (Figures 3, 5) argue for rapid burial, with the potential for spatial association of perimortem fractured pieces to be high. The generally unweathered condition of the majority of specimens in the rest of our breakage sample may be reflective of selective collection bias of the better preserved materials (see Thompson et al. 2015 for discussion of how collection protocols can be reflected in assemblage properties). Both the published accounts, and the range in body-sizes represented in the Ethiopian National Museum collections (Figure 4) suggest the attempt at full collection at A.L.288.

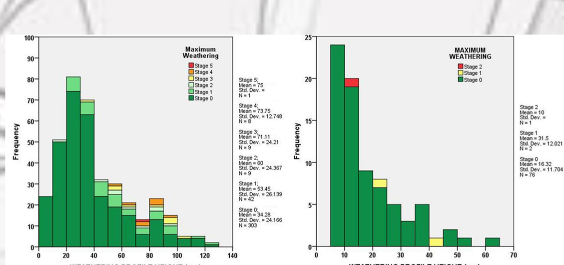


Figure 6. Larger bones from all Hadar specimens included in our sample tend to be more weathered than smaller, which may be a function of rate of burial.

Table 1. Summary of specimens included in Hadar breakage study.

LOCALITY		ORDER: NO IDENTIFICATION	ARTIODACTYLA	CARNIVORA	PERISSODACTYLA	PRIMATES	RODENTIA	Total
OTHER	N	21	137	35	42	99	0	334
	%	6.3%	41.0%	10.5%	12.6%	29.6%	0.0%	100.0%
A.L.288	N	0	6	1	4	80	6	97
	%	0.0%	6.2%	1.0%	4.1%	82.5%	6.2%	100.0%
Total	**N**	**21**	**143**	**36**	**46**	**179**	**6**	**431**
	%	**4.9%**	**33.2%**	**8.4%**	**10.7%**	**41.5%**	**1.4%**	**100.0%**

CODING ARTICULAR BREAKAGE

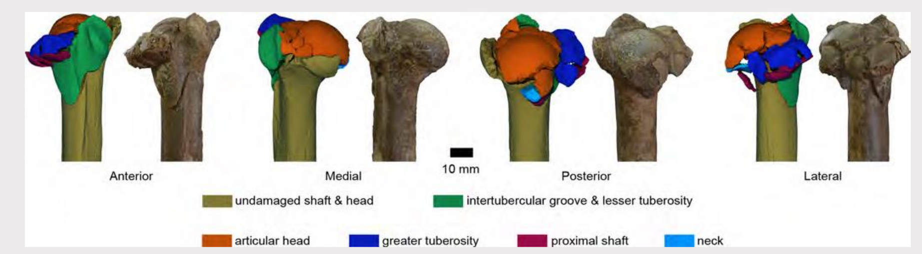


Figure 7. Illustration of numerous tiny fragments of A.L.288-1m proximal humerus segmented from CT scans compared with photos demonstrate the compressive nature of this proximal humerus break (Kappelman et al. 2016).

Figure 8. Compressive shear displacement of A.L.288-1m proximal shaft.

Documentation and interpretation of fracture patterns to long bones are one of the staples of taphonomic, zooarchaeological, and forensic studies. However, most systems for recording have emphasized shafts rather than articular ends. To compare the A.L.288 compressive breaks described by Kappelman et al. (2016), we developed at coding protocol that recorded type and anatomical direction of articular end fragments (Figure 9) as well as a more general set of articular surface condition class codes (Figure 10). The goal of this approach was simple – to assess the frequency of compressive articular displacement breaks described on A.L. 288 specimens (Figures 7, 8, 9) in relation to a more comprehensive Hadar sample.

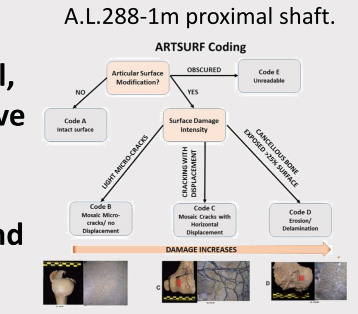


Figure 10. Protocol for coding articular surface condition.

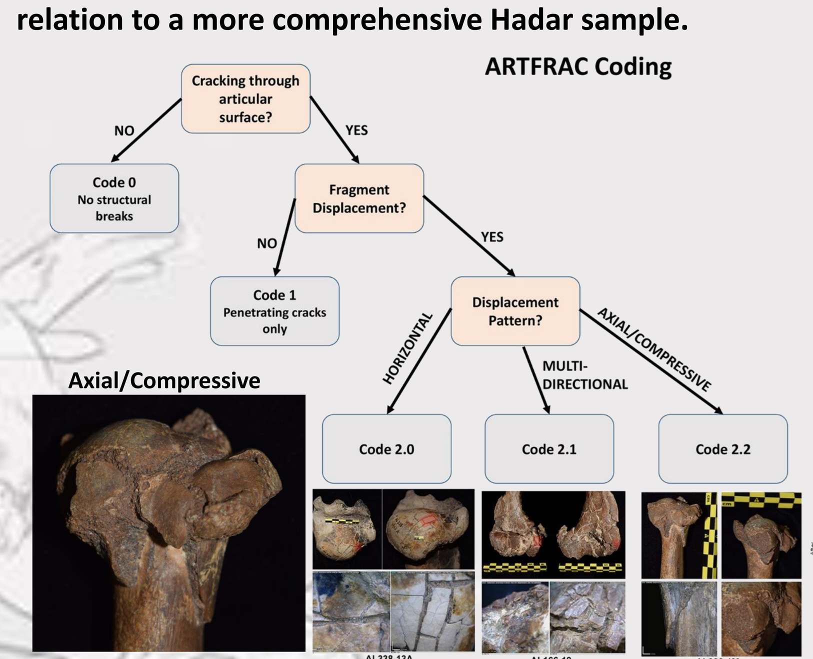


Figure 9. Coding protocol used in Hadar breakage study emphasizes the identification of compressive, axially oriented displacement of articular surfaces and adjacent shaft fragments. Note that *contra* White's comment[4] re. Fig. 1 here, AL338-13A differs from AL288-1M.

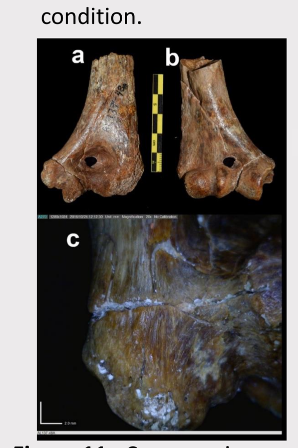
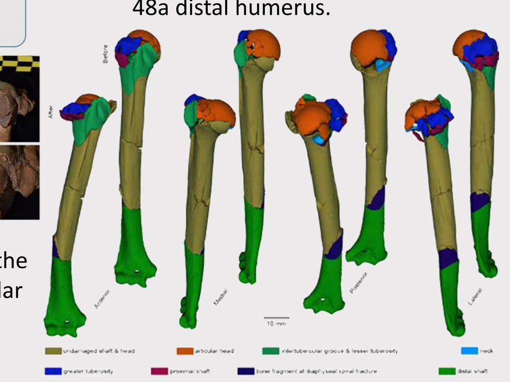


Figure 11. Compressive break (code 2.2) of A.L.137-48a distal humerus.



Working with curatorial staff at the National Museum in Addis Ababa we assembled upper limb bones (humeri and femora) for basic taphonomic and specific articular breakage (Figure 9) coding. All coding was conducted with a two-person team with a third team member available to help reach a consensus on difficult to assess specimens. Although other attributes such as weathering, abrasion/rounding, and carnivore modification were recorded on all 431 specimens, articular breakage could be coded on only 376 bones (Table 2). Within this sample, the rarity of compressive fractures is clear – only 1.3% (N=5) fell into our 2.2 breakage category (Figure 9) and four of these were specimens described by Kappelman et al. (2016) from A.L. 288. The single other example (Figure 11) was specimen A.L.137-48a, which exhibits slight compressive displacement.

Table 2. Summary of articular breakage coded specimens (Figure 9) from A.L.288 and other Hadar localities demonstrates the rarity of compressive damage.

LOCALITY	Articular Breakage Code: 0	1	2	2.1	2.2	9	Total
A.L.288	21	4	2	0	**4**	1	32
Others	199	67	38	3	**1**	36	344
TOTALS	**220**	**71**	**40**	**3**	**5**	**37**	376
PERCENT	**58.5**	**18.9**	**10.6**	**0.8**	**1.3**	**9.8**	100.0

BROADER COMPARISONS

Compressive breaks are demonstrably uncommon in the Hadar collections, and none of us can recall similar breaks in other assemblages we've worked with; in fact, this is why the unique fracture patterns in some of Lucy's limb elements attracted our attention in the first place. However, we've never specifically done assemblage-level studies based on a compressive fracture search image. Therefore, we have begun reexamination of other assemblages using the same compressive fracture identification coding system. Examples from coding a sample of bison bones from a Late Holocene Buffalo Jump (Glenrock, Wyoming) and the reexamination of our taphonomic documentation of the Pleistocene Trinil site (Java), confirms that A.L. 288 compressive breaks are rare. Physical examination of a sample of limb bones from Glenrock (Figures 12, 13, Table 3), yielded no compressive fractures. Although we have not re-visited the Trinil collections in Leiden and Berlin (Hill et al. 2015) using the articular fracture coding (Figure 9), scans of photos of limb bones (Figure 14) have not indicated any likely candidates for compressive fracture designation.

Figure 12. Although breaks to long bone shafts are common in a faunal assemblages such as those from the Late Holocene Glenrock Buffalo Jump shown here, are common and indicative of causes of breakage such a carnivore damage and marrow processing impacts, no compressive breaks (code 2.2) were observed in a February 2017 documentation (Table 3).

Table 3. Summary of articular fractures of Glenrock Buffalo Jump specimens.

CODE	ARTICULAR BREAK: PROXIMAL	DISTAL
0	115	137
1	6	3
2.0	8	1
Total	129	141

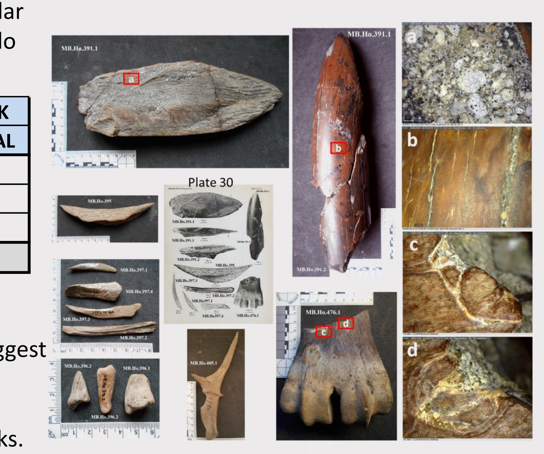


Figure 14. Morphologies of broken bones from Trinil suggest a diverse set of breakage dynamics, but none that produced compressive breaks.

Figure 13. Horizontal displacement of articular fragments (code 2.0) observed on Glenrock Buffalo Jump bones was associated with percussive impact fractures to shafts. Impacts as part of marrow processing can sometimes produce enough force to cause horizontal displacement of adjacent articular surfaces.

Figure 15. Series of bovid distal humeri from Trinil showing likely perimortem breaks likely related to rotational forces associated with entrainment in lahar.

CONCLUSIONS

This breakage-type specific study documents that assertions that compressive fractures are common across species and at multiple localities at Hadar is not supported. These are not oft-encountered breakage morphologies. Evaluating specific alternative formational scenarios such as breakage due to trampling, which could occur during a "stampede by a herd of large animals" could include both analysis of cortical surface markings (e.g., Thompson 2015) – none of which have been observed on A.L. 288 – or evaluation of spatial relationships of fragments (Figure 16) – none of which were recorded at A.L. 288.

Of the range of potential breakage dynamics suggested by Kappelman et al. (2016) as potential sources of the long-axis oriented compressive fractures at A.L.288-1 (e.g., seizures, fluvial transport, blunt force trauma, large animal induced fractures), none provide the degree of interpretive consistency and parsimony as the interpretation of fractures resulting from a vertical deceleration event from considerable height. Such events are rare in life histories of most species, and therefore not commonly encountered in paleontological or zooarchaeological research. Damage to Lucy's bones cannot be dismissed by unsupported "seen it many times before" data-free authoritative assertions but should instead be tested.

Figure 16. Example of long bone shaft fragments likely caused by trampling (early Holocene bison site, 25SX115, USA).

Acknowledgements:

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