A CRITICAL EVALUATION OF OUR UNDERSTANDING OF BONE TRANSPORT AND DEPOSITION IN FLUVIAL CHANNELS

by

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ABSTRACT

Forensic scientists, archaeologists, and paleontologists are interested in understanding fluvial bone transport respectively to find human remains, determine if human behavioral information persists in skeletal assemblages, or to estimate the temporal and spatial resolution of fossil assemblages. This dissertation reviews what we think we understand about fluvial bone transport, then tests the hypotheses that: 1. Elongate and concave bones adopt preferred orientations relative to flow, 2. There is a relationship between bone shape and relative transportability, and 3. There is a relationship between bone density and relative transportability. Generally two research techniques prevail, 1. Flume observations, and 2. Fluvial seeding trials. Flume data are often poorly reported, have small sample sizes, and the conditions within the flume are usually incompletely reported. Fluvial seeding trial results are characterized by a series of well documented anecdotes, largely due to specimen loss causing small sample sizes. The results from these techniques are contradictory so research to clarify what conclusions are valid is needed. Three techniques were utilized to address these problems, river surveys, river seeding trials, and river seeding trials using bone casts. No correlation between elongate bone orientation (N=157) and flow direction was observed, though concave bones (N=89) oriented ~70% concave down, while flat bones lay flat against the bed. Similarly, there was no association between bone shape and transportability. Denser bones were less transportable than less dense bones however there was substantial overlap in transportability between dense and less dense bone casts. These results suggest our understanding of bone transport is simplistic and incomplete. This is probably because most research has utilized flumes which provide unrealistically uniform conditions, so flume results are a poor analog for the heterogeneous natural environment. Moreover, bones are constantly changing density which is a variable previous authors have more or less assumed was constant. This simplifying assumption is violated so frequently that this assumption has led the scientific community to assume bone transport behaviors that are not frequently observed in natural systems. Ultimately the analytical tools based on this incomplete understanding of bone transport should be discontinued or validated to avoid spurious conclusions when interpreting skeletal assemblages.

CHAPTER ONE

INTRODUCTION

The field of taphonomy straddles the intersection between forensic anthropology, archaeology and paleoanthropology, and paleontology. Each of these disciplines concerns itself with interpreting skeletal assemblages, which usually entails inferring the history of the remains and testing those inferences. The major difference between these fields is the time scale over which the remains were generated. In forensics, remains were generated in a matter of days to a few decades, while archaeology involves decades to hundreds of thousands of years. Paleontology can span time ranges from a few decades to hundreds of millions of years. However, because all three fields utilize the same analytical methods to interpret skeletal assemblages, they often draw upon identicle literature on the same subjects. This creates a dispersed modern empirical or observational taphonomic literature that spans the publications of all three disciplines, often with investigators utilizing different techniques and interpreting results with different analytical philosophies. The result is a disparate literature in great need of synthesis.

The second chapter of this dissertation attempts to access and synthesize the literature concerning all of fluvial taphonomy, including aqueous decay, transport of bodies, body parts, and isolated bones in fluvial systems. This chapter is intended for a forensic audience because the conclusions generated from a synopsis can be professionally implemented immediately in the forensic science community. The synthesis is equally useful for the archaeology and paleontology communities, though

much of the text is irrelevant to these fields because it revolves around locating human remains in modern fluvial systems.

With a coherent synthesis and synopsis of our understanding of fluvial transport of bones it becomes necessary to clarify conclusions within the existing literature that are contradictory, and validate the analytical methods presently used in professional practice. Practically, this is simply tying up loose ends within the literature. Two conclusions were frequently found in the literature, 1. That bones adopt preferred orientations relative to flow direction, and 2. That bone density and shape are controlling variables (or not!) in determining relative bone transportability.

Chapter three investigates the conclusion that bones adopt preferred orientations in natural fluvial systems. The question was approached by predicting preferred orientations of bones based on the existing literature then testing the prediction by observing the orientations of bones found in natural river systems. This hypothesis testing method maximizes the inferential value of preexisting research, while using modern observations to test recent historical hypotheses. The result is an analytically robust hypothesis test with the philosophical rigor of a manipulative experiment.

Chapter four attempts to determine what the relationship is, if any, between bone shape and transport potential, and bone density and transport potential. To isolate the effects of bone shape or bone density, bone casts were made and used. This allowed both the shape and density to be controlled independently. By comparing the relative transport of bone casts with the same density and different shapes, the effect of shape can be largely isolated (though size is still a confounding variable). Similarly, by comparing the

relative transport of bone casts with different densities, but the same shapes, the effect of density can be isolated. This study design is exploratory in nature because previous research has yielded conflicting conclusions concerning the effects of bone shape and bone density on transport. Consequently, empirical trials were used to create large datasets that could show any relationships if they exist. Because no clear patterns were observed in the data gathered, the data were used to test null hypotheses.

Ultimately the results presented here indicate that the prevailing views and assumptions in the literature concerning how bones are transported and deposited in rivers are insufficient to predict the observed behavior of bones in modern fluvial systems. This raises the question of why the body of literature yields an incorrect result. It is possible that the results presented here are a false negative, however this study is the largest ever attempted and the only research to directly test the the assumptions in the literature. An alternative explanation for the negative results is presented in Chapter five which provides a brief synopsis of the results from chapters three and four, and explains what could have caused the difference between the predictions and the observations. These explanations are largely inferences with the logical strength of hypotheses, so they constitute an excellent starting place for future research.

The practical significance of this work centers on directly testing the assumptions underpinning existing fluvial taphonomic analytical models. Throughout chapters three and four the assumptions forming the basis of existing fluvial taphonomic analytical tools are tested and fail. The failure of these assumptions calls in to question the validity of using these analytical tools to interpret fossil and archaeological assemblages. This lends

further support to the opinion that taphonomic methods should be validated prior to use across widespread disciplines.

CHAPTER TWO

FLUVIAL TAPHONOMY

Contribution of Authors and Co-Authors

Manuscript in Chapter 2:

Author: Thomas Vincent Evans

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FLUVIAL TAPHONOMY

Thomas Evans

It is the task of the natural scientist to search for laws which will enable him to deduce predictions. This task may be divided into two parts. On the one hand, he must try to discover such laws as will enable him to deduce single predictions ('causal' or 'deterministic' laws or 'precision statements'). On the other hand, he must try to advance hypotheses about frequencies, that is, laws asserting probabilities, in order to deduce frequency predictions.

—Karl Popper, 1959, *The Logic of Scientific Discovery*.

Introduction

Human remains routinely enter fluvial systems through natural (i.e., erosion of cemeteries and archaeological sites), accidental (i.e., drowning), suicidal, and criminal (i.e., body disposal or intentional drowning) events. Regardless of the mechanisms of entry into a river, accidental or intentional, it is beneficial for human material to be recovered and subjected to a forensic or anthropological analysis. If the remains are the product of criminal activity, discovery of additional remains may be beneficial for the prosecution by increasing the potential for identification, cause, and manner of death determination (Komar and Potter 2007) and/or aiding in the location of a crime scene. Unfortunately, searching for any materials (i.e., evidence, remains, etc.) in rivers is difficult, slow, and complicated (see also Becker 2000; Dutelle 2007; McUne and

Gagnon 2007; Tackett and Whitfield 1987; Teather 1994), especially due to the significant physical hazards for diving personnel (Burke and O'Rear 1998; Dutelle 2007; Falkenthal 1999; McUne and Gagnon 2007; Tackett and Whitfield 1987; Teather 1994). A greater understanding of fluvial transport and deposition of remains increases the recovery potential of evidence and remains by narrowing search areas. In addition, the forensic anthropologist can use diagnostic tools to aid in identifying potential taphonomic histories of the remains which they are asked to analyze. Such tools include an understanding of fluvial taphonomic processes and the associated taphonomic modifications due to these processes.

The purpose of this chapter is to inform the reader of our present understanding of fluvial taphonomic processes and to describe the resulting taphonomic modifications (i.e., the results of the processes). What follows covers decay in rivers, full body transport, articulated body part transport, isolated bone transport, and the analytical techniques that can be used to interpret skeletal remains recovered from a fluvial context. Each section includes a description of the taphonomic modifications that can aid investigators in diagnosing a fluvial history for remains, when this information is available.

Since there is a paucity of literature covering human fluvial taphonomy, literature from other fields (e.g., zoology, paleontology, etc.) has been incorporated; however, the reviewed literature has been restricted to observational and experimental research. Some review articles concerning fluvial taphonomic processes are not included here, but the interested reader should seek these resources directly (Haglund and Sorg 2002; Osterkamp 2011; Rodriguez 1997). In addition, no information about sediment transport

theory is presented regarding isolated bone transport; a review of this literature is beyond the scope of this chapter, and the interested reader should access any of the many textbooks (Thorne *et al.* 1987) and reviews (Middleton and Southard 1984; Parker 2006) on the subject.

Previous Research

Historically, research concerning the transport of remains in rivers has been performed in the fields of paleontology and archaeology, and both fields face similar analytical problems to the forensic scientist: the reconstruction of the past from fragmentary or partial evidence. Since the evidence interpreted by paleontology and archaeology is nearly entirely skeletal, most research has focused on the transport and deposition of isolated bones, with few exceptions. Similarly, most literature reviews focus on isolated bones, for example, in paleontology (Behrensmeyer 1990, 1991; Rogers and Kidwell 2007; Shipman 1981), archaeology (Boaz 1982; Gifford 1981; Lyman 1994), and most recently in forensics (Evans 2006; Haglund and Sorg 2002; Nawrocki *et al.* 1997).

Given the interest in fluvial taphonomy in three disciplines (paleontology, archeology, and forensics), what is the state of our understanding of fluvial processes and taphonomic signatures? Surprisingly, we know very little, since most research has used small sample sizes, poor or no controls, unknown or unreported sample histories, and poorly reported experimental conditions, resulting in most data and interpretations yielding preliminary or tentative results. Presently, it is not possible to combine all

studies into a coherent corpus of understanding; there are conflicting observations and conclusions, which raise doubts and concerns related to the applicability of many of the conclusions presently in the literature. There is also a considerable amount of speculation in the literature about how fluvial processes take place, most of which have no basis in published observations or experimentation. Presented here is a comprehensive and straightforward analysis of the published literature to determine what we understand and what is still opaque.

Decay in Fluvial Systems

The decay of tissues in rivers proceeds differently than decay in lakes and ponds, since the decay products are swept downstream, the biota is different in flowing water, currents physically buffet tissues (Piorkowski 1995), bodies fall apart as they impact the bed during transport (Kline *et al*. 1997; Piorkowski 1995), and the effects of temperature and seasonality manifest differently in rivers. Consequently, this review will not include the decay of bodies in lakes, ponds, wells, tubs, or any other standing body of water.

Decay of tissues in rivers is integral to the taphonomic history of fluvially altered remains, since decay produces the different entities that are transported and deposited in rivers. Intact bodies move and are altered differently than articulated units and isolated bones. As such, it is important to consider what units are produced during decay and how these units will be altered differently as they move in different ways downstream. Unfortunately, the disarticulation sequence of human bodies in rivers is still poorly understood, which complicates our understanding of which articulated units are

transported and the approximate order in which isolated bones become available for transport.

Little information is presently available on how tissue breakdown occurs in fluvial environments or the rate at which it occurs (but see Chaloner *et al.* 2002; Piorkowski 1995), as well as how the processes might change depending on the season. What can be stated with confidence is that decay is slower in fluvial systems than on land (Hobischak 1997a, 1997b; Hobischak and Anderson 2002; MacDonell and Anderson 1997), most likely due to lower temperatures (Doberentz and Madea 2010; Heaton *et al.* 2010; Madea 2002; Petric *et al.* 2004; Reh 1969; Reh *et al.* 1977) and lack of terrestrial vertebrates and invertebrate scavengers. Terrestrial invertebrates will colonize body parts that are exposed above the water surface, thus hastening decay (Barrios and Wolff 2011; Haglund 1993; Hobischak 1997a, 1997b; Hobischak and Anderson 2002; Kline *et al.* 1997; MacDonell and Anderson 1997; Mann *et al.* 1990:109; Piorkowski 1995), while partial submersion in water can keep tissues wet enough for terrestrial invertebrate colonization in environments where desiccation would occur otherwise (Goff and Odom 1987:47-48). In the absence of insect consumption soft tissue above water can become mummified, even while the rest of the body is submerged. The amount of flesh above and below water changes as bodies sink and float throughout decay (Hobischak 1997a, 1997b; Hobischak and Anderson 2002; MacDonell and Anderson 1997).

Like terrestrial decay, the warmer the water, the faster the decay (Minshall *et al.* 1991). Once in water, a body is rapidly colonized by invertebrates (Brusven and Scoggan 1969; Duband *et al.* 2011; Kline *et al.* 1997; MacDonell and Anderson 1997; Piorkowski

1995; Vanin and Zancaner 2011), which facilitate tissue breakdown, including crustaceans (Duband *et al.* 2011; Mottonen and Nuutila 1977:1097-1098; Petric *et al.* 2004; Vanin and Zancaner 2011). Invertebrates can be found all over a submerged body (Chaloner *et al.* 2002; Duband *et al.* 2011; Minakawa 1997; Piorkowski 1995), although they are most often located near body orifices and locations of trauma (Brusven and Scoggan 1969; Chaloner *et al.* 2002; Haglund 1993; Heaton *et al.* 2010; Kline *et al.* 1997; Minakawa 1997; Piorkowski 1995; Schuldt and Hershey 1995; Vanin and Zancaner 2011) or on the sheltered underside of bodies in fast flows (Kline *et al.* 1997; Piorkowski 1995). Aquatic invertebrates can be used as a postmortem interval (PMI) indicator (Barrios and Wolff 2011; Wallace *et al.* 2007, 2008), although in some places and habitats there is no consistent succession of invertebrates on decaying bodies (Keiper *et al.* 1997; Hobischak 1997a, 1997b; Piorkowski 1995). Unfortunately, the invertebrates present in a river change depending on the season (Hobischak 1997a, 1997b; Hobischak and Anderson 2002) as well as the microhabitat (riffle vs. pool) (Brusven and Scoggan 1969; Chaloner *et al.* 2002; Hobischak 1997a, 1997b; Hobischak and Anderson 2002; Keiper *et al.* 1997; MacDonell and Anderson 1997), which complicates the use of invertebrates as a PMI indicator. Mold or algae are often intimately involved in aqueous decomposition (Casamatta and Verb 2000; Chaloner *et al.* 2002; Haefner *et al.* 2004; Hobischak and Anderson 2002; Keiper *et al.* 1997; Kline *et al.* 1997; Minshall *et al.* 1991; Piorkowski 1995), with aquatic organisms growing faster in warmer water, thus facilitating faster decay (Minshall *et al.* 1991). Microbial life can also control decay in

fluvial systems (Hobischak and Anderson 2002; Kline *et al.* 1997; Piorkowski 1995), although this mechanism of decay has rarely been reported.

Bodies from rivers tend to have a consistent sequence of decay prior to disarticulation (Doberentz and Madea 2010; Heaton *et al.* 2010; Hobischak 1997a, 1997b; Hobischak and Anderson 1999, 2002; MacDonell and Anderson 1997; Madea 2002; Madea and Doberentz 2010; Perry 2005; Petric *et al.* 2004; Reh 1967, 1969; Reh *et al.* 1977; Seet 2005), beginning with the development of "washer woman's skin", skin discoloration (e.g., marbling, black discoloration, etc.), distension and bloating, skin peeling, hair loss, loss of nails, and loss of skin. Finally, progressive skeletonization and disarticulation occurs, proceeding generally from distal to proximal joints (Haglund 1993), although there is variability in the observed disarticulation sequence.

Presently there are three main fluviatile PMI indicators: invertebrate succession, algal succession, and the sequence of body decay. If local invertebrate and algal information is unavailable, then using the decomposition research of Heaton *et al.* (2010), Hobischak (1997a, 1997b), Hobischak and Anderson (1999, 2002), Madea (2002), Madea and Doberentz (2010), Reh (1967, 1969), Reh *et al.* (1977), and Seet (2005) to estimate PMI is presently the best practice. There are a number of reviews and articles regarding the use of aquatic insects (Barrios and Wolff 2011; Haskell *et al.* 1989; Hawley *et al.* 1989; Hobischak and Anderson 2002; Keiper *et al.* 1997; Keiper and Casamatta 2001; Merritt and Wallace 2001) and algae (Casamatta and Verb 2000; Haefner *et al.* 2002, 2004; Keiper and Casamatta 2001) to determine PMI.

Full Body Transport

Little has been published concerning the transport of full bodies in fluvial environments; consequently, our understanding is extremely limited. Nearly all data on the subject come from anecdotes (Darwin 1839:141), case reports (D'Alonzo *et al.* 2012; Mann *et al.* 1990:109), or disasters (Berryman *et al.* 1988:844; Moore *et al.* 2008; Varricchio *et al.* 2005). Human bodies have a density near that of water (Donoghue and Minnigerode 1977). Consequently, bodies can be expected to float and sink repeatedly depending on a number of variables including state of decay and density of water (salt and sediment concentrations) (Heaton *et al.* 2010). Warmer water leads to faster bloating, so remains will float earlier during the PMI, consequently moving downstream sooner. The bulk density of the body determines floatation, which includes any clothing or objects attached to a body. Body floatation is common and increases the rate of transport considerably, since the body is moving slightly slower than the fluid medium. Often, transport is episodic (Strobel *et al.* 2009), though typically faster and more common during periods of higher water (Bickart 1984:527-528; D'Alonzo *et al.* 2012; Glock *et al.* 1980; Guatame-Garcia *et al.* 2008; *contra* Strobel *et al.* 2009). Intermittent transport is caused by a body being caught on the upstream side of woody debris, rocks, or other channel obstructions (Cederholm and Peterson 1985; Cederholm *et al.* 1989; Cederholm *et al.* 1999:9-10; Heaton *et al.* 2010; Hobischak and Anderson 1999; Minakawa 1997; Minakawa and Gara 2005; Piorkowski 1995; Rodriguez 1997:461; Strobel *et al.* 2009; Teather 1994:6-8, 10, 29-30). In addition, pools or eddies behind obstructions (woody debris or rocks) can also trap bodies and stop downstream transport

(Brooks and Brooks 1984, 1997; Cederholm *et al.* 1989; Minakawa 1997; Minakawa and Gara 2005; Piorkowski 1995; Strobel *et al.* 2009). Sediment bars of any kind also can be loci of body deposition (Butler 1987:133; Glock *et al.* 1980; Haglund *et al.* 1990); however, channel obstructions and eddies/pools retain the majority of bodies (Cederholm *et al.* 1989; Cederholm and Peterson 1985; Minakawa 1997; Minakawa and Gara 2005; Strobel *et al.* 2009). Therefore, more episodic transport and lower net transport are expected in rivers with more obstructions, and faster and more continuous transport is expected in rivers with no or fewer obstructions. Bodies can be transported hundreds of miles in days or months in large river systems (Bassett and Manhein 2002; Brady 2012; D'Alonzo *et al.* 2012; Pampin and López-Abajo 2001); therefore, the longer a body is missing, the farther downstream it may have traveled. This is not always the case, as bodies have been found upstream of their river entry location (Bassett and Manhein 2002; Brewer 2005; Heaton *et al.* 2010). In larger rivers, bodies tend to stay on the same side of the river that they entered (Bassett and Manhein 2002; Brewer 2005; Dilen 1984).

It should be noted that none of the previous research concerning fluvial transport of full bodies includes a taphonomic description of the human bodies recovered. Consequently, any taphonomic interpretations of the history of a body recovered from a river should be governed by context of recovery as well as indicators of decay taking place under water.

Articulated Unit Transport

Similar to full body transport, articulated unit transport has received little attention in the experimental or observational literature, and what has been published has

entirely utilized faunal (nonhuman) remains. This is a function of the difficulty in obtaining human remains for destructive experimentation as well as difficulty in obtaining permits to run experiments in public waterways using human remains. It is useful to note that the disarticulation sequence of human body parts in rivers is nearly unknown and consequently so are the articulated parts typically transported in fluvial systems resulting from this disarticulation. In addition, the amount of soft tissue which was present on articulated parts during fluvial transport and prior to the recovery of skeletonized remains is also unknown, so no modeling or hypothesis formation can take place without further observations and experiments into fluvial decay processes.

Like full bodies, articulated elements move most often and furthest during higher flow events (Bickart 1984; Gifford 1977:166, 187; Gifford and Behrensmeyer 1977:250). It is unclear if articulated units have a greater transport potential, since articulation, in comparative studies with isolated bones, yielded both faster (Coard 1999; Coard and Dennell 1995; Trapani 1996, 1998) and slower (Coard and Dennell 1995) transport. More authors have observed an increased dispersal potential, so *in toto*, it appears that articulation generally increases transportability with some exceptions. As more skeletal elements are articulated, preferred orientations of bones become more cryptic, with bone orientations no longer reflecting flow direction (Coard 1999; Coard and Dennell 1995). Like isolated bones, articulated units often adopt long axis orientations that are either parallel or perpendicular to the flow direction (Coard and Dennell 1995). Temporary burial (complete or partial) slows net transport considerably (Trapani 1996, 1998). The shape of articulated elements contributes to transport potential (Trapani 1996, 1998), but

the manner in which shape alters transport is not well understood. Dry articulated units tend to move faster than saturated parts (Coard 1999), particularly when they float. Floating can also occur from decay gases building up in tissues, causing the entire unit to float (pers. obs.). Floatation increases the transport potential of articulated units dramatically (Coard 1999). It also provides a transport mechanism that does not leave any observable trace on the soft or osseous tissues.

Little research has described the taphonomic modifications caused by the transport of articulated material. Consequently, taphonomic history interpretations of articulated remains found in rivers should be governed primarily by context of recovery. Since articulated remains are often partially devoid of flesh, some of the taphonomic modifications isolated bones experience from fluvial transport may also apply to articulated remains.

Isolated Bone Transport

Introduction Fluvial systems are immensely complicated, making the transport of any material in a river difficult to describe let alone fully understand. Presented here is a synopsis of what we understand about isolated bone transport, starting with bone floatation and saturation with water, the factors that alter bone transport rates, a discussion of what taphonomic modifications may be found on remains, some proposed analytical techniques for remains recovered from fluvial environments, and a brief discussion of sheet flow (a way in which bones enter fluvial systems).

Bone Floatation and Saturation Bone floatation has been observed by many investigators in laboratory and field experiments as well as during aqueous decay experiments (Table 6.1). Similarly, bone floatation has been observed in bones of all sizes (rodent up to elephant) and from many taxa (amphibians, birds, and mammals) (Table 6.1). Consequently, this mode of transportation should not be ignored, since it is common and can cause rapid downstream movement without producing evidence to suggest that the process occurred. Bone floatation occurs when the bulk density of a bone (see Chapter 4, this volume) is less than the fluid medium in which it resides. These conditions can occur after dry periods with lower flow, followed by rapid river rise, potentially entraining dry skeletal material in higher flows. In addition, fresh skeletal material may float, caused by the buildup of decay gasses inside the bone (Ayers 2010; pers. obs.).

Behrensmeyer (1973:31-32) measured mammal bone bulk densities, which ranged from 0.64 to 2.30 g/cm^3 (Appendix 2, pp. 174-175). Gutierrez and Kaufmann (2007) report bulk densities for juvenile guanaco (*Lama guanicoe*) bones ranged from 0.63 to 2.12 g/cm^3 (2007:156, Table 1) and 0.55 to 2.42 g/cm^3 (2007:157, Table 2) for adult bones. Kaufmann *et al.* (2011:341, Figures 3 and 4) depict the range of densities for wet and dry guanaco bones, and demonstrate that both wet and dry bones can have densities below 1.0 g/cm^3. Yang *et al*. (2011: Figures 1 and 2 and Table 1) report the dry density of Dybowski's frog (*Rana dybowskii*) femora as between ~0.55 to just slightly higher than ~1.00 g/cm^3, with the density increasing slightly with age. These observations of initial bone densities suggest that many bones will at first float in water.

Similarly, Young (1989:12, 49) reported densities of subfossil (partially mineralized) bone ranging from 1.40 to 3.06 g/cm^3 and modern bones ranging from 1.00 to 2.10 g/cm^3. His observations suggest that skeletal material on river beds can have densities close to 1.00 g/cm^3 even when (partially) saturated with water, making bones easy to transport or float.

When placed in water, bones begin to hydrate, increasing their bulk density. The rate at which bones hydrate is variable, with some bones becoming saturated in a matter of hours, while others can take months (Table 6.2). Since bone density is continually changing during hydration, it is difficult to determine the transport properties of bones that have recently entered a river and are yet to undergo full saturation. During hydration bones will move faster and more readily than when saturated, since they have a lower density and require less force to initiate and maintain transport. The analyst should be aware that bones that have been in river systems for days, weeks, and even months, still may not be saturated and may be capable of partial or complete floatation, facilitating their faster and more frequent transport.

Bone floatation is undetectable, since floatation itself produces no permanent taphonomic modifications on osseous remains, so it is best to consider floatation as a possibility when interpreting any skeletal assemblage recovered from a fluvial environment.

Factors That Alter Bone Transport Rates During fluvial transport bones move faster than other clastic material (Pavlish *et al.* 1998, 2002; Schick 1984, 1986, 1987), and which bones have a higher transport potential depends on a number of factors,

including: taxon, size (Blob 1997; Pante and Blumenschine 2009, 2010; Pavlish *et al.* 2002), mass (Knell 2009; Kontrovitz and Slack 1991; Morden 1991a, 1991b), density (dry or wet) (Boaz and Behrensmeyer 1976; Coard 1999), shape (Blob 1997; Morden 1991a, 1991b), projected surface area (Coard 1999; Kontrovitz and Slack 1991), orientation (Blob 1997; Elder 1985), age of organism (Kaufmann *et al.* 2011), weathering stage, and freshness (presence of grease) (Morden 1991a, 1991b). Since many studies have disagreed on which is most important, it is unclear which, if any, factor is most important in skeletal element transport. Given the conflicting conclusions between many authors, it is prudent simply to note that all the above factors alter the transport of skeletal elements; however, a brief discussion of some of these factors follows.

Larger bones (length, volume, area, or diameter) tend to move slower than smaller bones (Brady 2005; Brady and Rogers 2005, 2007; *contra* Boaz and Behrensmeyer 1976), with the converse also being true; smaller bones under some conditions move farther, faster, and more readily than larger bones (Aslan and Behrensmeyer 1996; Duckworth 1904; Evans 2007; Long and Langer 1995:88; Nawrocki and Pless 1993; *contra* Andrews and Whybrow 2005). As expected, some larger bones are left behind when transport occurs to other elements (Long and Langer 1995:88; Spennemann 1992; Weigelt 1989 [1927]:36). It should be noted that there is a good deal of variation in transport potentials, so smaller bones can move less than larger bones, and vice versa (Aslan and Behrensmeyer 1996; Hanson 1980; pers. obs.). Similarly, light bones move farther, more readily, and more rapidly (Duckworth 1904; Evans 2007; Long and Langer 1995:88; Nawrocki and Pless 1993; *contra* Andrews and Whybrow 2005) than larger and

heavier bones (Aslan and Behrensmeyer 1996). Denser bones tend to move slower than less dense bones as suggested by faster bone movement when bones are dry and slower movement when wet (Coard 1999; Evans 2010; Kaufmann *et al.* 2011; Morden 1991a). Similarly, fresh (unweathered) bones tend to move faster in a flow than degreased or weathered bones (Morden 1991a), which may be a function of bone density changes caused by degreasing.

Both shape and orientation alter bone transport, and both variables function in concert, so they are treated together here. Shape governs the transport characteristics of some bones (innominates, scapulae, vertebrae, etc), and bone transport properties change when they break (Boaz and Behrensmeyer 1976) or are abraded. During transport or exposure to a current, skeletal material often adopts a stable orientation which yields less net transport (Frison and Todd 1986:61-69). Flat bones tend to lay flat on the river bed and not move (Boaz and Behrensmeyer 1976; Elder 1985; Evans 2007; Gifford 1977:165, 187-198; Gifford and Behrensmeyer 1977:261-263), while skeletal elements with processes or other portions that extend upward from the river bed and higher into the flow tend to have higher transport potentials (Coard and Dennell 1995). Concavo-convex elements orient convex-up most frequently (Dodson 1973; Elder 1985; Evans 2007; Gifford 1977; Gifford and Behrensmeyer 1977; Knell 2009; Trapani 1996; Voorhies 1969), and move slowly, if at all. Elongate bones tend to orient parallel or perpendicular to flow with parallel orientation most common when water depths greatly exceed the height of a bone (Boaz and Behrensmeyer 1976; Coard and Dennell 1995; Dodson 1973; Elder 1985; Morden 1991a; Pavlish *et al.* 2002; Voorhies 1969) and perpendicular

orientation predominates with shallower flow (Voorhies 1969) or when bones orient parallel to the lee side of bedforms (Pavlish *et al.* 2002; Trapani 1996, 1998; Voorhies 1969). When long bones orient parallel to flow, the heaviest end tends to be downstream (Boaz and Behrensmeyer 1976; Voorhies 1969). Similarly, open diaphysis tubes (cylinders) orient parallel to flow and are filled or covered by sediment rapidly and do not move (Evans 2007; Morden 1991a).

It appears that interactions with the bed ultimately govern bone transport, since stabilization of bones in/on the bed prevents their movement temporarily or permanently (Frison and Todd 1986:61-69). Bedforms alter all aspects of bone transport, including the rate (velocity), orientation, and mode of movement (Trapani 1996, 1998). Bedform migration over bones temporarily stops their movement (Pavlish *et al.* 2002; Trapani 1996, 1998; Voorhies 1969), although the magnitude of this effect depends on bone length. If long bones are parallel to flow and are covered by a bedform with a shorter wavelength than the length of the bone, then those bones are never fully exposed before the next bedform migrates over them, keeping the bone permanently buried (Trapani 1996, 1998). Besides burial, scour around a bone can stabilize its location or orientation, thus reducing bone transportability (Frison and Todd 1986:61-69; Hanson 1980). Similarly, bones can trap other skeletal material by pinning them down (Pavlish *et al.* 2002) or creating eddies in which other bones are deposited (Brady 2005; Pavlish *et al.* 2002), thus stabilizing bone locations. Generally, bones move toward areas in a flow with lower flow velocities including moving upstream into the troughs of bedforms (Trapani 1996, 1998; pers. obs.).

Fluvially Derived Taphonomic Modifications **Abrasion** can take many forms on a bone surface including bone smoothing, rounding, polish (sometimes shiny), scratches, gouges, frosting, pitting, denting, chipping, grooves, and notches. Rarely are long grooves and scratches produced (Shipman and Rose 1983:77-80, 1988). In addition to these individual marks, the bone surface will generally become thinner, eventually leading to small openings (**windows**) that enlarge with further abrasion (Fernández-Jalvo and Andrews 2003; Korth 1978, 1979; Nawrocki *et al.* 1997). Similarly, lacunae and vascular canals (any natural opening) will gradually enlarge (Bromage 1984; Nawrocki *et al.* 1997; Thompson *et al.* 2011:791, Figure 3.4). Articular surfaces rapidly thin to expose underlying cancellous bone (Fernández-Jalvo and Andrews 2003; Korth 1978, 1979; Llona and Andrews 1999), and in juvenile vertebrates the epiphyses will detach if not fused (Fernández-Jalvo and Andrews 2003). Edges can be fractured or chipped as well (Andrews 1990).

River seeding experiments indicate that the abrasion state of skeletal material does not correlate with transport distance (Aslan and Behrensmeyer 1996:414; Van Orden and Behrensmeyer 2010). For example, lighter bones can be moved faster and further with little abrasion, while larger bones could move less and be "sandblasted" in place (Thompson *et al.* 2011; Van Orden and Behrensmeyer 2010). Bones have moved hundreds of meters or kilometers downstream without showing signs of abrasion (Behrensmeyer *et al.* 1989:116; Hanson 1980; pers. obs.), while abrasion in the form of scratches, scrapes, pitting, and gouging has been observed on bones with as little as 1 km of fluvial transport (Herrmann *et al.* 2004). Consequently, no correlation exists between

transport distance and abrasion state, so abrasion should not be used as a transport distance estimation tool or as a PMI indicator. There is no clear picture of how much abrasion is caused by transport and with what sediment types (but see Thompson *et al.* 2011), although it seems that larger clasts (or higher energy) are needed to cause extensive rounding on a bone (Evans 2007). Since many bones with a known transport history show no or minimal abrasion, the presence of abrasion on bones suggests an episode of prior fluvial transport, but the opposite cannot be taken as indicative of a lack of fluvial transport.

Acid etching of bone surfaces usually occurs over nearly the entire bone surface and presents as a delocalized surface roughening (Duckworth 1904). Small pits form, expand outward, and finally connect, making irregular and rough galleries in the bone surface. Often, acid etching is accompanied by bone discoloration, probably caused by the same acids that are etching the bone. Determining when acid etching will occur is primarily a function of the ions present in the solution surrounding a bone and their concentration. For freshwater with few ions in solution any acid in solution should start to degrade bone. Christensen and Myers (2011) observed bovine bone degradation under different pH levels and found that a pH of 7 did very little damage to the bone, while low pH levels (4 and 1) were associated with significant bone degradation. Similar results were observed for cooked salmon bones degraded in different pH solutions by Collins (2010). Harnett *et al.* (2011) observed the progressive dissolution of bone in HCl and H_2SO_4 and graphed mass loss over time. They noted that bone surfaces became porotic and pitted prior to complete dissolution. None of these studies are directly analogous to

fluvial systems, however, since bones were allowed to react in a standing body of water, keeping the reaction products in solution with the bone and thus establishing a dynamic equilibrium over time. Fluvial systems have continuous water flow, and reaction products cannot build up around a bone, so more acid etching is expected in even mildly acidic rivers than was observed in the work of Christensen and Myers (2011), Collins (2010), or Harnett *et al.* (2011). Figures 6.1 and 6.2B display bones recovered from an acidic river displaying mild to advanced acid etching.

Discoloration of bones can occur from a variety of agents, most of which are poorly understood or unknown (see Chapters 11 and 12, this volume). The most common color change is to a light or medium brown (see Figure 6.2), which appears to be caused by partial or complete burial in a river bed or through submersion in discolored water (Nawrocki *et al.* 1997; pers. obs.). A light green staining often accompanies the growth of algae on bone surfaces (Nawrocki *et al.* 1997; pers. obs.), a modification that can be found on bones in nearly all rivers and which can occur in less than a year (pers. obs.). Black staining has been observed often in conjunction with adipocere formation which is usually found in small cavities in the bone (Figure 6.3). Yellow staining appears to be the consequence of fat leaching out of the bone, discoloring its surface. Figure 6.2 displays bones recovered from two rivers, all with discoloration.

Invertebrate consumption of bone and **larval casings** are frequent fluvial taphonomic indicators. Larval boring appears as smooth-walled troughs, approximately U-shaped in cross section, and often meandering. At times, feeding traces can be confused with acid etching. Generally, feeding traces are much smoother, deeper,

regular, and sinuous than the irregular pitting of acid etching (see Chapter 9, Figure 9.12, this volume). It should be noted that both acid etching and invertebrate feeding traces can be found on the same bone. Figure 6.4 displays bones recovered from an Alaska river with evident invertebrate casings.

Sediment impaction within cracks, hollow spaces, and foramina is common in bones recovered from sandy or coarse bed rivers (Figure 6.5). The size, composition, and variety of clasts will be a function of the river from which the remains came; however, impacted sediment on or in a bone is a good indicator of some aqueous history, freshwater or marine (see Chapter 7, this volume). If sand or gravel grains are wedged in cracks or holes in bones, it can suggest a fluvial origin, since there are few processes operating in a standing body of water (lake or pond) that can wedge sediment in to openings (Nawrocki *et al.* 1997). Figure 6.5 shows sand impaction in bone cracks and foramina. It is possible that shrinking and swelling of bones through wetting and drying is the mechanism causing clastic material to be wedged tightly in cracks and holes.

Bone cracking and warping from drying can occur when skeletal material is removed from (moving or still) water. While the focus of this review is modifications to bones from fluvial taphonomic processes, it should be noted that taphonomic modifications also occur on bones when removed from fluvial systems. The most obvious change is the drying of bones either during transport or in the laboratory. Drying often causes bones to contract, which causes extensional stresses along the exterior cortical bone surfaces, particularly on long bone (humeri, radii, ulnae, femora, tibiae, or fibulae) diaphyses. The result is often an elongate and deep crack (or cracks) extending

from the exterior cortical bone into the medullary cavity often over nearly the entire length of a diaphysis (Figure 6.6). During drying of thousands of bones for experimentation, the author has observed hundreds of long bones crack, often violently and with a sharp, loud, startling popping sound. (See also Prassack (2011) for a discussion of bone cracking during drying.) In addition to deep cracking, drying can alter the shape of skeletal material. When bones are wet, they are flexible to varying degrees. As a bone dries it loses this flexibility and will retain the shape it was in during drying. Consequently, it is possible to bend or flex a bone while wet and dry it in a new, altered shape. This flexing is readily observable in scapulae, which can flex considerably while wet (Figure 6.7). When observing skeletal material recovered from fluvial systems, it is important to remember that any large cracking and some bending may be a function of fluvial residence and removal, rather than some other taphonomic processes.

Analytical Techniques Six methods have been proposed to identify skeletal assemblages that have experienced fluvial transport: Voorhies Groups (Voorhies 1969), equivalent particle diameters (Behrensmeyer 1973, 1975), relative transport potentials (Hanson 1980), transport index (Frison and Todd 1986; Trapani 1996, 1998), mobility numbers (Pavlish *et al.* 2002), and observing bones in preferred orientations (Lyman 1994; Toots 1965; Voorhies 1969). Unfortunately, none of these techniques have been tested or validated, and as such none are suitable for use in forensic case work. In addition, there are data for each method that suggest that they are not universally applicable. Consequently, this author is unaware of any analytical technique that presently can be used to identify fluvially transported skeletal remains reliably, although

research is presently underway to remedy this situation. Presented below is a brief overview of each method to orient the reader on this topic.

Voorhies (1969:69, Table 12) divided bones into slow-, medium-, and fast-moving groups, based upon flume experiments with coyote and sheep skeletons. Behrensmeyer (1973, 1975) continued the grouping of bones based on transport behavior, and coined the term "**Voorhies Groups**", meaning grouping bones based on their relative transport rates. Since the term has never been precisely defined, some authors have generated between two and five different transport groups, depending on their method of study (settling column, flume, etc.) and the behavior of the bones that they studied. This method assumes bones have consistent relative transport rates, and subsequent research has demonstrated that bones display many different rates of transport relative to each other (Aslan and Behrensmeyer 1996; Boaz and Behrensmeyer 1976; Dodson 1973; Kaufman *et al.* 2011; Korth 1978; Morden 1991a; Trapani 1996, 1998) which falsifies the underlying assumption required for the method to work.

Behrensmeyer (1973, 1975) developed an equation that roughly equates bone transport potential with the transport potential of a spherical quartz grain with the same settling velocity. The hypothesis is that by comparing the grain size on or in which bones are deposited, a transported bone assemblage can be identified. If the quartz equivalent diameters of the bones are roughly equivalent to the grain size diameters of the surrounding sediment, then the bones were likely transported and deposited with the sediment; however, if the predicted grain size and the sediment size are different, then some other transport and deposition history is likely for the skeletal material. Since being

proposed, some research has suggested that this oversimplified model is incorrect (Gifford 1977; Gifford and Behrensmeyer 1977; Trapani 1996), and experiments are underway by the author to validate this method directly.

Hanson (1980:164-170) developed an equation for a dimensionless number proportional to the relative transport rate of skeletal material in a fluvial system. Since fluvial systems are complex with far too many variables to model simply, he made a few simplifying assumptions in the development of his equation. As a result, it is unclear how applicable the final equation is to the transport of bones in rivers. He then tested his equation by using it to calculate the relative transport potential of bones, and compared the observed transport properties of bones in a flume to those predicted by his equation. A scatter plot (1980:171, Figure 9.5) shows a rough trend suggesting a general correlation between transport potential and his dimensionless variable, but there is significant overlap of transport behaviors across the entire figure, suggesting that the method does not work reliably enough to use in casework.

Frison and Todd (1986) proposed the Fluvial Transport Index, a dimensionless number that describes the relative dispersal potential of skeletal remains. It is a descriptive tool that can be applied to an assemblage with known transport distances downstream. This method requires further validation, and its reliance upon known transport distances makes its application to forensic situations limited, given that this information is usually unknown.

Pavlish *et al.* (2002) proposed "Mobility Numbers", which are dimensionless numbers that may be proportional to the relative transport potentials of different bones

(similar to Hanson 1980). In a small-scale assessment of the method, Pavlish *et al.* (2002:235, Figure 2) plotted the Relative Distance Traveled versus Mobility Number and found a general correlation between transport distance and mobility number, although there was a wide spread in the data. The spread in the data suggests that the tool does not have sufficient resolution to be useful in a forensic context.

It has been suggested that skeletal assemblages that have experienced fluvial transport or reorientation can be identified by measuring and plotting the orientations of bones in the assemblage. This method assumes that bones consistently adopt a known and recognizable preferred orientation relative to a flow, and that full disarticulation did not occur until after final deposition (i.e., that the elements did not reach their final location as part of an articulated unit with a different combined shape and density). Field data demonstrate that the orientation of skeletal material is largely a function of bed orientation (pers. obs. and unpublished data) in addition to flow direction. Consequently, bone orientations are not a reliable indicator of interaction between bones and a fluid flow.

Sheet Flow There are many ways in which bones can enter a river, including the action of **sheet flow** over land surfaces during rainfall events. Sheet flow is the movement of shallow sheets of water over land surfaces until the fluid and their transported objects reach gullies or other channels in which they can be entrained in channelized flow.

Generally, bones on mild slopes do not move quickly (Andrews and Whybrow 2005; Frostick and Reid 1983), although bones in small depressions parallel to slope

move faster than bones on featureless surfaces (Frostick and Reid 1983). Spherical- and rod-shaped bones move downslope faster than blade- or disc-shaped bones (Frostick and Reid 1983; Pokines *et al.* 2011). Similarly, larger, denser bones move downslope slower than smaller, lighter bones (Andrews 1990:17; Baker 2004), and saturated bones move less than dry bones which may float on water or water and sediment mixtures (Woodruff and Varricchio 2011). When surface flow entrains sediment and bones, there is a higher likelihood of bone breakage (Woodruff and Varricchio 2008, 2011). It has been suggested that a higher land surface slope and higher water discharge will move material downstream faster (Frostick and Reid 1983). While this seems logically sound, there is no published data to support this inference.

Recommendations for Human Remains Recovery

When searching for remains in rivers, it is recommended to look on the upstream sides of obstructions (woody debris, bridge piers, rocks, etc.) (Nawrocki and Baker 2001; Young 1989; Evans 2010; Hanson 1980; Schick 1984, 1986), in eddies behind obstructions (Schick 1984, 1986), on bars (of any kind: lateral, point, median, etc.; Behrensmeyer 1982; Nawrocki *et al.* 1997), and to focus the search on the same side of the river as the body/parts entered (if known). All locations with drops in flow velocity (competence) should be searched, including banks, the upstream and lateral edges of deeper pools, and the edges of large bedforms (Aslan and Behrensmeyer 1987, 1996; Evans 2010; Schick 1984, 1986). Deep pools in channels not associated with debris are less likely to capture remains. Woody debris is particularly effective at catching and

retaining remains (Evans 2007), so all woody debris should be searched thoroughly. One should also search for bodies both up and downstream in rivers with significant shipping traffic or tidal influence. If a body entered a waterway it may be useful to contact jurisdictions downstream to determine if they have found any remains. Conversely, if remains are found, it may be useful to contact upstream jurisdictions to determine if they have missing persons. In addition, cadaver dogs can be used to facilitate searches, particularly of fleshed out remains (Osterkamp 2011).

When searching for skeletal material in fluvial systems, the reader should be aware that it is most common to find larger bones and miss many smaller skeletal elements (Aslan and Behrensmeyer 1996; Evans 2010). Small bones can be caught in any location with a space large enough to hold them (between rocks, vegetation, or woody debris), so if searching for small bones, one should look in the spaces between material in and on the bed. It is noteworthy that skeletal material can be found in rivers, if a search is implemented, often with a potential of high recovery rates (Aslan and Behrensmeyer 1996; Schick 1984, 1986; pers. obs.). Increasing the search effort may not yield large gains in bone recovery, since smaller material may have been transported away, or buried, causing them to be increasingly difficult to locate and recover.

Conclusions

Presently, our understanding of fluvial taphonomic processes is in its infancy; thus, describing suites of taphonomic characters (**taphofacies**) expected from different river types is premature. Every river which the author has surveyed (n = 13) has yielded

a different suite of taphonomic modifications on the remains found in the channel. Consequently, no one taphofacies model will suffice for "fluvial systems". What we understand about decay in river systems is largely anecdotal, and most of the research that has been performed has been on a small scale, so the variability in decay processes across different river environments is poorly understood. Similarly, transport of both full bodies and articulated parts in fluvial systems suffers from a lack of systematic, large-scale research, since most of what we know comes from isolated observations.

Comparatively, there is far more research concerning the transport and deposition of isolated (nonhuman) skeletal elements in fluvial systems. Unfortunately, the topic is far more complicated than studying the transport of standard geologic clasts (rocks, sand, etc.), since bones change shape, density, and articulation during decay and transport, and the size, sex, age, and body mass of the living organism also may affect bone transport dynamics. Shape changes occur through breakage and abrasion, while density alterations take place due to loss of grease, decay (build up and loss of decay gases), water uptake, breakage, and abrasion. Aside from their clast properties continually changing, bones are periodically buried (partially or completely) and become fixed (armored or imbricated) in river beds. All these factors yield inconsistent or episodic transport which is difficult to predict or even describe. As a result, the taphonomic modifications to bones and skeletal assemblages are difficult to interpret, since the process of fluvial transport is so complicated and convoluted. While highly transportable bones (small, light, less dense bones) are rapidly moved and winnowed, these are the same bones that are most easily destroyed by other taphonomic processes or buried. Consequently, correctly interpreting

the taphonomic modifications to bones and skeletal assemblages in fluviatile systems is difficult at best in theory and often cryptic in practice. Often, the analyst must consider many taphonomic processes operating sequentially and/or concurrently in potentially many different microenvironments that change over time. Since fluvial processes are so variable, there is a massive variability in taphonomic modifications found on remains which have experienced fluvial environments.

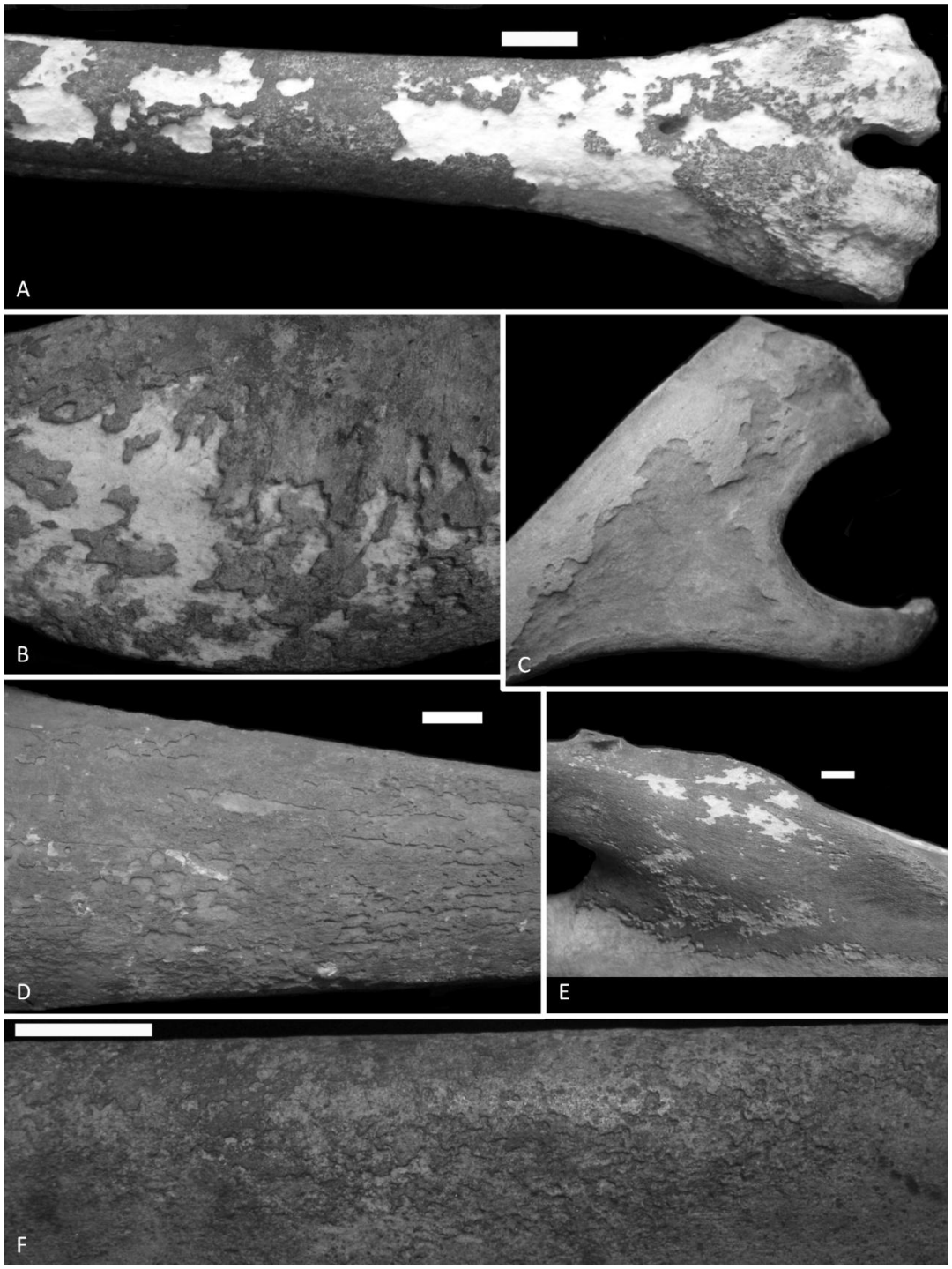

Figure 6.1 Acid etched bones from Levelock Creek, Alaska. The creek is acidic because of acids leaching out of the surrounding tundra. (a) Caribou metatarsal showing deep cortical bone erosion. (b) Caribou dentary with deep discontinuous cortical bone erosion. (c) Caribou antler depicting shallow continuous cortical bone removal. (d) Shallow discontinuous erosion pits on a rib. (e) Surficial incipient erosion pits on a cortical bone surface. (f) Extensively developed disconnected pitting on a diaphysis.

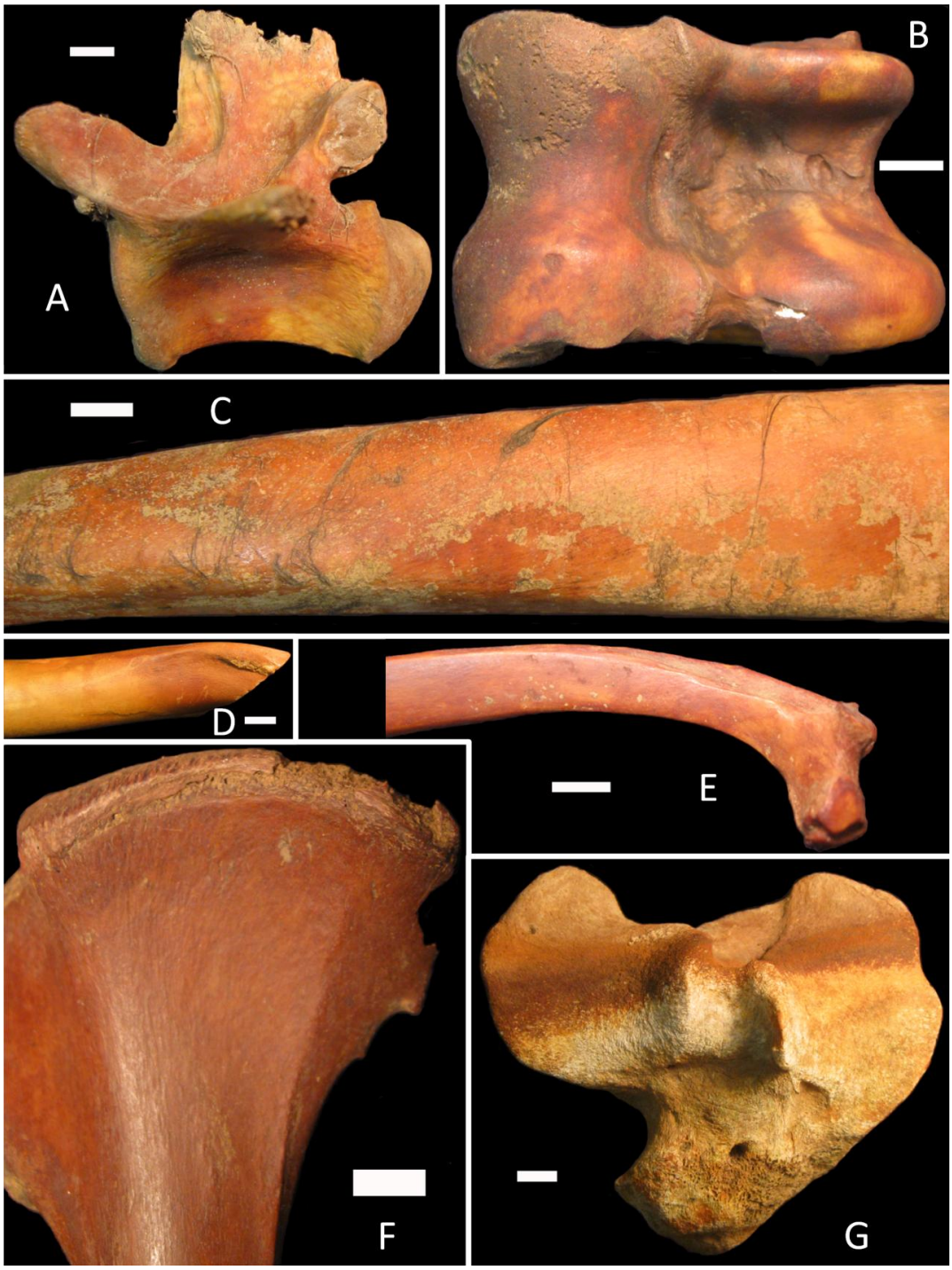

Figure 6.2 (a) Alligator bone that discolored during a one year residence in a river. (b) Astragalus showing discoloration and incipient acid dissolution. (c) A rib shaft with discoloration and aquatic vegetation adhering to the bone surface. (d) Sawn diaphysis with discoloration. (e) Rib with deep reddish discoloration. (f) Ilium with uniform brownish discoloration. (g) Proximal tibia showing bands of discoloration, likely caused by partial burial in a river.

Figure 6.3 Location of adipocere formation. Adipocere, when preset, is often found in confined spaces (foramina, medullary cavity, articular fossae, etc.). (a) Adipocere formation in an acetabular fossa. (b) Adipocere formation in spaces between bones as well as in a nutrient foramina.

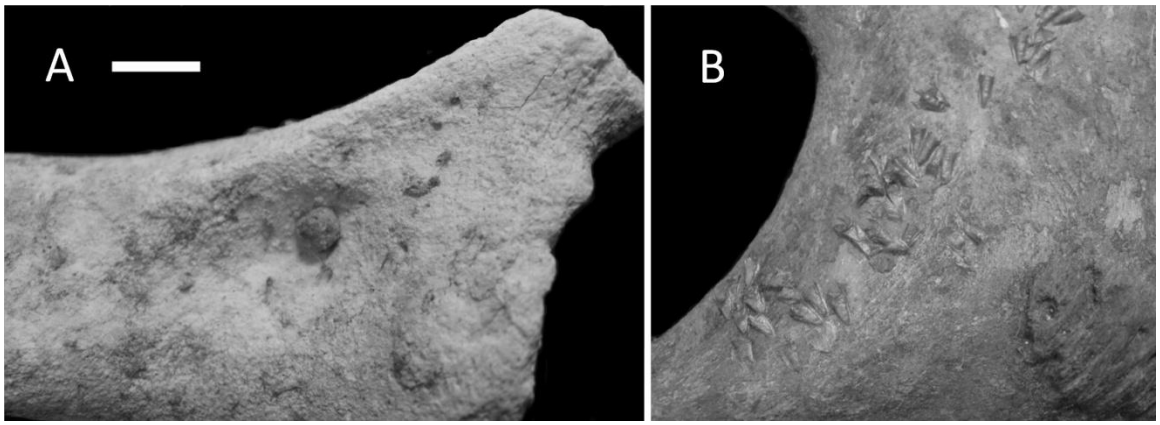

Figure 6.4 Invertebrate casings can be of many shapes and sizes: (a) is a calcified shell in a bone depression, and (b) is a series of thin larval casings.

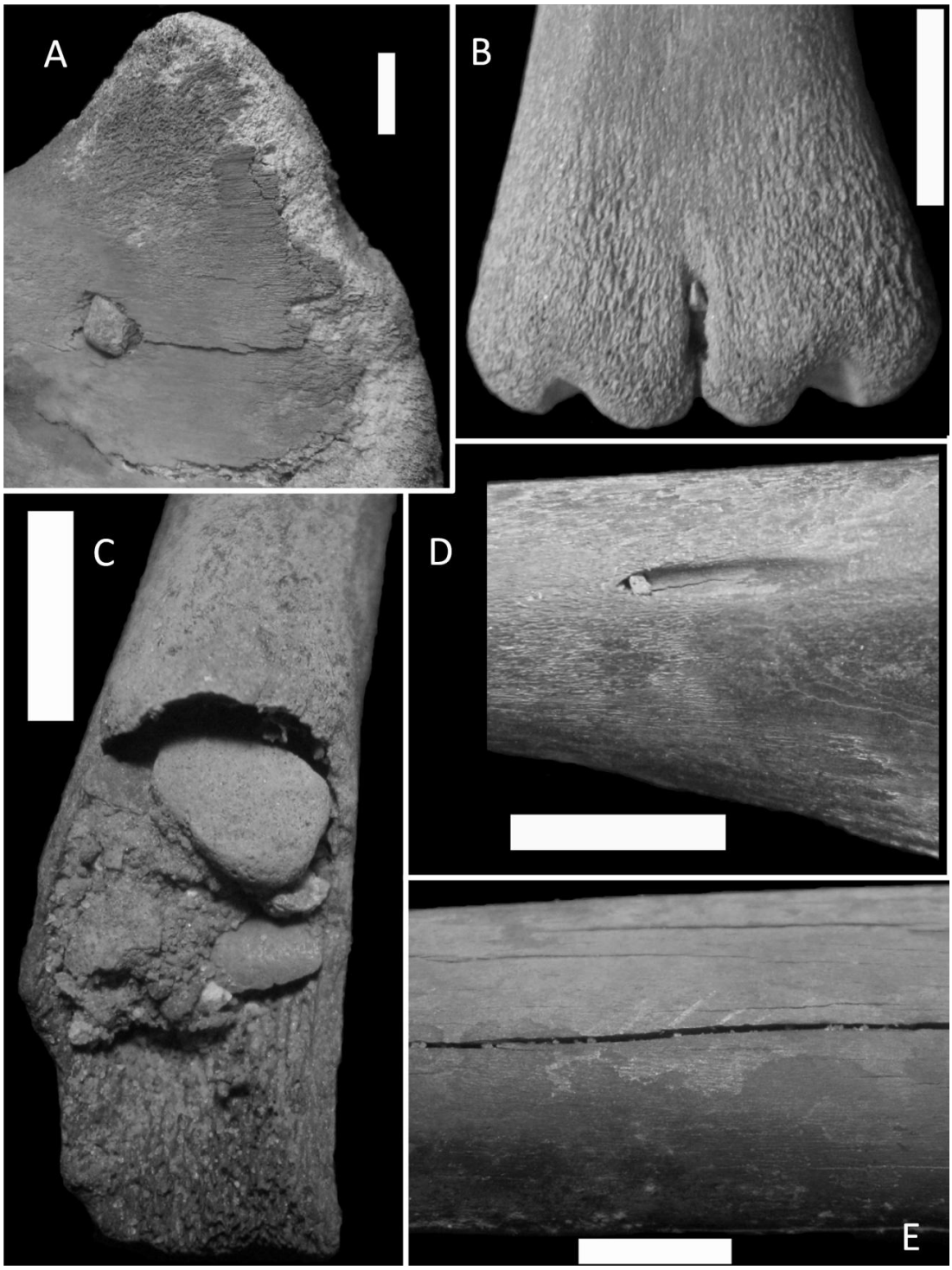

Figure 6.5 Sediment impaction in holes and cracks. Sediment is often found in small cracks or holes in bone. (a) Grain of gravel pressed into an ilium while it was wet and pliable. (b) Sand grain wedged in the slot between two fused metatarsals. (c) Sand and gravel in a diaphysis. (d) Sand grain wedged into a nutrient foramina. (e) Sand grains firmly fixed in a crack in cortical bone.

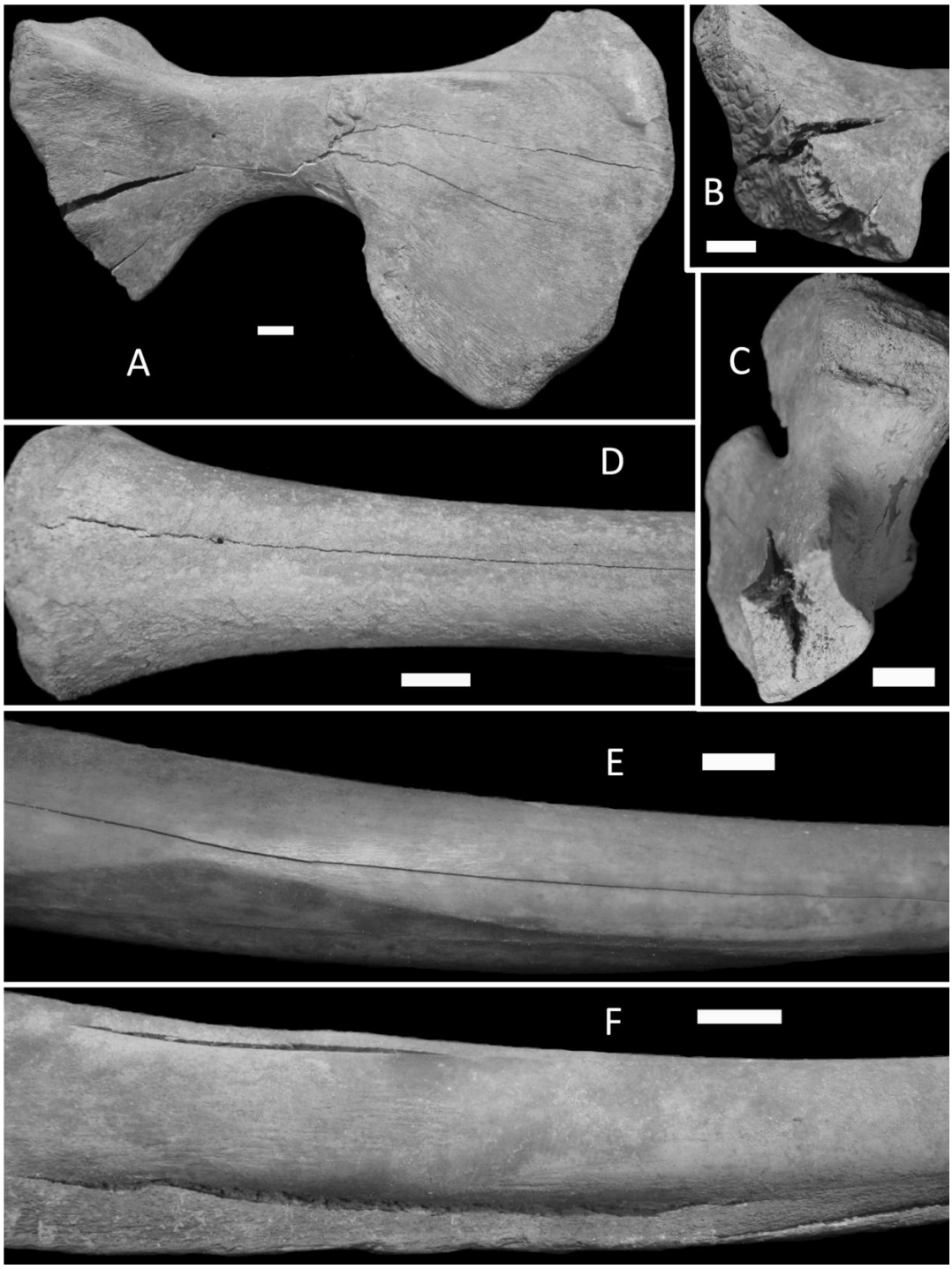

Figure 6.6 Drying cracks. All cracks formed as bones dried. (a) Juvenile ilium illustrating both small and large drying cracks. (b) Close up of the deepest crack in the ilium from (a). (c) Sawed end of a rib demonstrating the degree of cracking and warping of cortical bone during drying. (d) Crack in the anterior surface of a metacarpal shaft. (e) Elongate drying crack in a tibia that extends the length of the bone, and penetrates the medullary cavity. (f) Two cracks deforming the surface of a rib causing the bone to deflect outward.

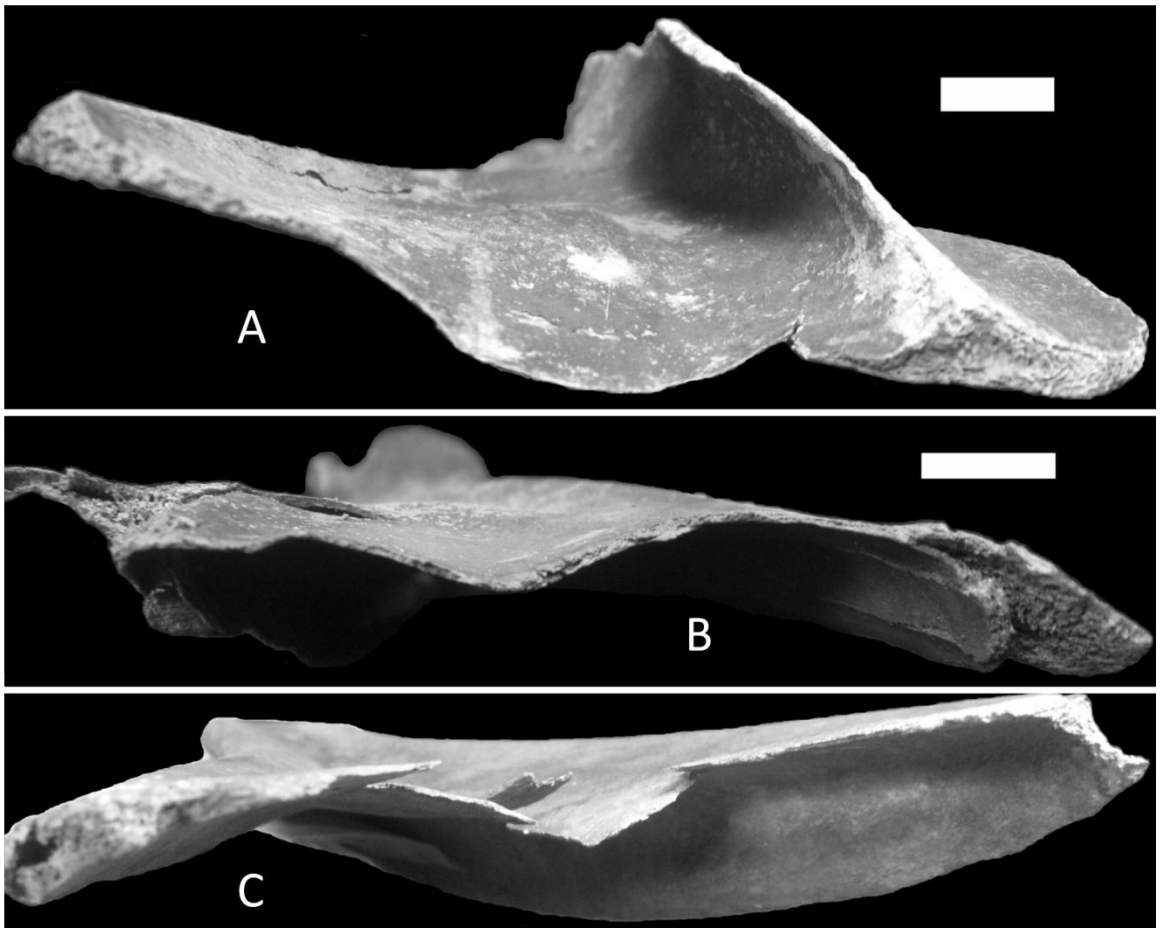

Figure 6.7 Scapulae deformation. (a) Medially warped superior scapular border. (b) Laterally warped superior scapular border. (c) Warped and cracked superior scapular border illustrating that bone can deform both medially and laterally simultaneously.

Table 6.1. Studies of floating bones, including bones observed, taxa, duration, and the type of aqueous environment in which the bones were floating.

Citation and Page Number	Floating Bones	Taxa	Duration of Floatation	Observation Made In:
Alley 2007:39, 40, 42	Ribs, thoracic vertebrae, and articulated vertebrae	Pig (*Sus scrofa*)	1-2 weeks	Standing Water
Ayers 2010:37, table 3, p. 27, table 5, p. 35, appendix C, p. 82, 83, 92	Vertebra, phalanx, other bones	Pig (*Sus scrofa*)	1-2 days	Standing Water
Behrensmeyer 1973:31	Foot bones and vertebrae	Not reported	Hours	Standing Water
Behrensmyer 1975:485	Foot bones and vertebrae	Not reported	Hours	Standing Water
Boaz and Behrensmeyer 1976:57, figure 2	Cranium	Human (*Homo sapiens*)	Not reported	Flume
Coard 1999:1371	Thoracic and lumbar vertebrae, ribs, and sacrum	Mouflon sheep (*Ovis musimon*), Pig-tailed macaque (*Macaca nemestrina*), Alsatian dog (*Canis familiaris*)	7-30 meters	Flume
Coard and Dennell 1995:447	Cranium	Pig-tailed macaque (*Macaca nemestrina*)	Not reported	Flume
Dodson 1973:18	Nearly every bone in the body	Mouse (*Mus*) and Frog (*Rana*)	Few days (mouse), month (frog)	Standing Water
Evans 2010b:28	Not reported	Not reported	Month and a half	River, standing water
Frison and Todd 1986:67	Smaller elements'	Indian elephas (*Elaphas maximus*)	Minutes	River
Gnidovec 1978:18, 20, table 3, p. 19, figure 8, p. 21	Not reported	Mammals, birds, and herps	3 hours	Standing Water
Gutierrez and Kaufmann 2007:155, figure 2, p. 158	Lateral tubersotiy, head, distal epiphysis of humerus, femur, caudal vertebrae, sacral vertebrae, and others	Guanaco (*Lama guanicoe)*	Several hours	Standing Water
Kaufmann *et al.* 2011	Many, see Tables 1-3	Guanaco (*Lama guanicoe)*	Minutes	Flume
Morden 1991:77	Cervical vertebra, thoracic vertebra, ribs, calcaneus, and metacarpal	Human (*Homo sapiens*)	5 days	Standing Water
Trapani 1996:116, 148	Cranium, most bird bones	Pigeon (*Columbia livia*)	Not reported	Flume
Trapani 1998:481, and table 1, p. 480	Cranium	Pigeon (*Columbia livia*)	Not reported	Flume
Voorhies 1969:67, text and footnote	Sacrum and sternum	Sheep, coyote (species not reported)	Not reported	Flume
Personal Observations	Nearly every bone in the body	Mammals, birds, frogs, salamanders, snakes, lizards	Seconds to 2.5 months	Buckets, rivers, settling columns, etc.

Table 6.2. Observations of the time to saturation or time to sinking.

Citation	Time to Saturation or Sinking
Behrensmeyer 1973:31-32, figure 2	Hours, 70+ hours (time to saturation)
Behrensmyer 1975:485, figure 2, p. 486	Hours, 70+ hours (time to saturation)
Coard and Dennell 1995:442	5 to 7 days (time to saturation)
Dodson 1973:18	Few days to a month (time to sinking)
Gnidovec 1978:18, 20, table 3, p. 19, figure 8, p. 21	8 to 83 hours (time to sinking)
Gutierrez and Kaufmann 2007:155, figure 2, p. 158	Hours (time to saturation)
Trapani 1996:82-83, table 6.1, p. 84	2-13 days (time to saturation)
Young 1989:12,49	Bones released gas for over half an hour
Personal Observation	2.5 months (time to sinking)

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CHAPTER THREE

A CRITICAL EVALUATION OF BONE ORIENTATION INTERPRETATION OF REMAINS RECOVERED FROM POTENTIAL FLUVIAL CONTEXTS

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A CRITICAL EVALUATION OF BONE ORIENTATION INTERPRETATION OF REMAINS RECOVERED FROM POTENTIAL FLUVIAL CONTEXTS

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Abstract

Skeletal element orientations are often used to infer fluvial transport or winnowing in the taphonomic history of remains utilizing a method that assumes there is a correlation between flow direction and bone orientation. Analysts assume a correlation between bone orientation and flow direction because preferred bone orientations have been observed during flume trials. However because flumes are an unnaturally homogenous environment, flume results may not be an accurate analog for bone transport in natural fluvial systems. The hypothesis that there is a correlation between flow direction and bone orientation was tested by observing the orientation of remains found in natural rivers, and bones of various shapes that had been seeded in river systems. No consistent orientation of elongate bones that moved in natural rivers was observed. However, concave bones, on average, oriented concave down ~70% of the time, similar to flume based predictions. Orientation results for elongate bones directly conflict with flume observations of elongate bone orientation. The discrepancy can likely be explained by the variation in substrates, bed materials, obstructions, channel cross section

geometry, the bed material transport effects, increased turbulence, and a higher prevalence of three-dimensional flow patterns that are all inherent in natural fluvial channels. Some of the discrepancy might also be related to changes in bone density that occur during residence in natural channels. Flumes provide a remarkably uniform environment in which to perform observations, which is largely why they are such an effective tool. However, natural river systems are heterogeneous with constantly changing conditions. Similarly, flume trials utilizing bone have frequently been run over short time spans in which bone density does not change radically. Naturally bone density continually changes during long periods of transport, causing bones to float, be neutrally buoyant, or behave more like woody debris. Consequently, bones do not adopt the predicted orientations in natural fluvial systems because the analog used to develop the predictions is sufficiently different from natural conditions.

Keywords: BONE ORIENTATION, FLUVIAL TRANSPORT, PREFERED ORIENTATION, TAPHONOMY

1.1 Introduction

Analysts interpreting assemblages of skeletal material; like archaeologists, paleoanthropologists, and paleontologists, are confronted by a dizzying array of potential histories the remains could have experienced. Each potential history (e.g., scavenging, disarticulation, dismemberment, etc.) removes information from the remains, and some processes add information (e.g., weathering, cut-marks, bone charring from cooking fires, etc.). Analysts use taphonomic modifications to bone surfaces, and orientations of remains to test hypotheses of which taphonomic processes operated on a suite of remains.

Knowing which processes operated on an assemblage can indicate what information has been removed (e.g., human involvement with remains post mortem) and what information can be reliably gleaned from those remains. The transport and deposition of bones in fluvial systems is one of many taphonomic processes and is of interest to the archaeological and paleoanthropological communities because water movement could alter bone orientations, and create false associations with artifacts, thus removing information concerning human behavior, or creating assemblages that could be erroneously interpreted as human caused. Similarly, the transport of skeletal remains can alter the temporal and spatial resolution of fossil assemblages, so paleontologists often attempt to determine if remains have experienced fluvial flow as a means of estimating the temporal and spatial resolution of the fossil assemblages they are interpreting.

Toots (1965b) and Voorhies (1969) suggested that fluvially transported or winnowed (and reoriented) skeletal assemblages can be identified, in part, by measuring and plotting the orientations of bones in the assemblage. Many subsequent authors have utilized this technique to interpret archaeological (Kreutzer, 1988; Todd and Frison, 1986), paleoanthropological (Boaz, 1994; Dominguez-Rodrigo et al. 2012; Maguire et al. 1980; Potts 1988; Shipman et al. 1981), and paleontological assemblages (Alberdi et al. 2001; Fiorillo, 1987, 1988b; Hill and Walker, 1972; Hunt, 1978; Lawton, 1977; Saunders, 1977; Voorhies, 1969:11). Generally, if assemblage constituents display preferred orientations consistent with the assumed action of a fluid flow, then the observed orientations are considered one line of evidence suggesting fluvial winnowing or deposition (Eberth et al. 2007). Utilizing this reasoning requires knowing three things:

(1) how to collect orientation data in the field, (2) a way to display the information in an informative and meaningful way in presentations (talks and publications), and (3) a reliable means for interpreting the orientation data, which requires knowledge of the preferred orientations (including polarities) of bones when exposed to a current. In other words, for this interpretation method to work, a correlation must exist between fluvial transport (or reorientation) and the orientation bones adopt, and the analyst must also possess the skills necessary to collect and present the information in a meaningful way.

To address each component of this technique, the field methods for collecting orientation data are reviewed in Appendix A, and suggestions for presenting orientation data are presented in Appendix B. However, the focus here is a test of the hypothesis that there is a significant correlation between bulk current direction and bone orientation, which was accomplished by observing bones in natural fluvial systems.

1.2 Background: Predicted Skeletal Element Preferred Orientations in a Flow

Research concerning bone preferred orientations in flows has historically been performed in laboratory flumes and consisted of investigators *qualitatively* reporting bone orientations relative to a uniform constant current direction. Most studies of this kind have reported that some bones adopt preferred orientations when exposed to a uniform unidirectional current; these studies, the taxa, bones utilized, and the observed preferred orientations are tabulated in Table 1. Relatively consistent bone orientation trends are observable in Table 1 for bones with similar morphologies (elongate, convex, etc.), though there is variability in the orientations adopted (Table 1, personal observation). For

example, Trapani (1996:111, 1998:480) reports Rock Dove (*Columbia livia*) bones oriented parallel to bedform edges causing burial in nearly every orientation relative to flow, demonstrating that, while trends exist in idealized conditions, exceptions to the trends are possible and likely when irregular bed surfaces are present. A synopsis of the general orientation trends observed in Table 1 is depicted in Table 2. Generally five preferred orientations are observed, including: 1. Elongate bones parallel to the current, 2. Elongate bones perpendicular to the current, 3. Elongate bones with the largest end downstream (a polarity), 4. Concave bones oriented concave down, and 5. Flat bones laying flat on the bed.

It should be noted that while the orientations presented in Tables 1 and 2 have been observed in flumes, there is no *a priori* reason why these same orientations should be found displayed by bones in natural river systems because while flow direction may control orientation of bones in flumes, other variables may control bone orientations in heterogeneous natural systems. Flumes present consistent conditions, like constant discharges, depths, slopes, and bed composition, which is unrealistic. Natural fluvial systems are normally heterogeneous with changing discharge, bed compositions, channel cross sections, etc. So it is expected that observations made in flumes will only partially reflect natural heterogeneous processes. Consequently, the conclusions drawn from flume observations of bones have the logical strength of untested hypotheses. Thus the question becomes, how close to reality are flume observations of bone transport to natural bone transport in rivers?

The few published studies that have involved seeding bones in rivers have recovered insufficient samples to determine if bones do adopt the preferred orientations predicted by flume trails, largely because of lost skeletal material (Table 3). Furthermore, of the recovered bones, only a subset had the required shapes for orientation analyses (e.g., vertebrae do not provide elongate bone orientation information). In other words, many bones used in bone transport studies have had irregular shapes or shapes that do not fit into one of the three shape categories identified in Table 2 (e.g., many mammalian ankle bones). For example, most mammalian vertebrae are not flat, elongate, or concave up or down. This means that while many bones have been used in river seeding studies, many of those bones were not and could not be used to form interpretations about bone orientations because they are irregularly shaped. Thus, the bone orientation data that has been reported from rivers is fragmentary and amounts to a series of well documented qualitative anecdotes of bone orientations in fluvial systems (Frison and Todd, 1986:53-55; Gifford and Behrensmeyer, 1977:262; Hanson, 1980:173; Schick, 1984, 1986). Lack of data is to be expected because performing river seeding trials with animal remains is logistically complicated. As such, there has been little research performed seeding bones in rivers leading to a general lack of understanding of bone transport complexity in natural environments.

A validation study was implemented to determine if bones in natural fluvial systems adopt the orientations predicted from flume observations (Table 2). If bone orientations in natural fluvial flows do not correlate with the flow direction, then the hypothesis that there is a significant correlation between fluvial interaction with bones

and bone orientation is incomplete. Alternatively, if a correlation exists between bone orientations in natural fluvial systems and bulk current direction, then the hypothesis that bones adopt predictable orientations in a natural flow would be supported.

1.3 Methods

1.3.1 Methods Overview:

To test the possible correlation between bone orientation and flow direction, two methods were used, river surveys and river seeding trials. The materials and methods used in river surveys will be discussed first, followed by river seeding trials. In addition, the field locations used for each study are described followed by a discussion of data analysis techniques.

1.3.2 River Surveys:

River surveys involved walking, wading, or swimming upstream in a river and looking for skeletal material within the river channel. The river channel was defined as the area between the high points of the banks on either side of the flowing body of water determined while walking upstream. The channel was determined geomorphologically because flow data was not available for nearly all the rivers surveyed. When all bones were located, the element, taxon, bone orientation, water orientation, burial, bed description, and presence of any woody debris were recorded, and the bone collected. Bone orientations (azimuth only) were measured using a Brunton compass for elongate elements (Rogers 1994) and orientation descriptions were collected for all bones (see Appendix A for detailed methods). Measuring azimuths of bones under water is the same

as measuring bones subaerially, subject to the same measurement error. By standing directly over the bone and looking straight down, light refraction was minimized. The compass was lined up with the bone directly above it, leveled, and an azimuth read off the compass face. Water orientations were measured using a compass and a small flow indicator placed in the water that deflected parallel to current (e.g., a piece of string or aquatic vegetation) using the same method. The bed descriptions included grain size(s), shape, sphericity, angularity, roundness, textural and compositional maturity, composition, and notes on the presence of obstructions or woody debris. Table 4 lists the names, locations, and approximate lengths of the waterways surveyed, as well as the dates of visitation. During river surveys, additional skeletal material was encountered on the floodplains, and these bones were collected and used for river seeding trials. Only orientation results for elongate, concave, and flat bones are reported here because the other observations are not germane for the hypothesis investigated here.

1.3.3 River Seeding Trials:

Bones for river seeding trials were acquired in two ways; collecting bones with unknown histories during river surveys, and cleaning skeletal material with dermestid beetles. Dermestid cleaning was chosen because other forms of cleaning damage bone structure (Fernandez-Jalvo and Monfort, 2008; Steadman, et al., 2006) and contribute to grease and fat loss, all of which alter the physical properties of bones (Huyghebaert et al. 1988; Kim et al. 2004). Because fluvial transport is governed by clast state variables (i.e., density, volume, surface area, etc.), it was decided that the most conservative cleaning protocol would be used to prevent damage and alteration to the skeletal material.

Animal remains from legal hunting practices were provided by a local meat processor and cleaned with dermestid beetles. Bones were left in colonies until the beetles lost interest in them, and then bones were washed and allowed to dry for a week before given field labels with a permanent marking pen.

Seeding trials involved placing skeletal material in a river with known locations and original orientations (see Figure 1 for examples). A datum point was established and the initial locations recorded relative to that point. The seeding trials were observed annually to track the movement and deposition of the remains over space and time (for specific dates see Table 5). When bones were relocated, the same information was recorded as in river surveys with the added data of distance downstream from the datum, and the bones were collected. Transport distances were measured from the datum by laying out a fiberglass tape measure in the thalweg and subtracting the initial downstream location of the bone from their final distance downstream. Table 5 lists the rivers in which trials took place, when trials were initiated, approximately how many bones were seeded in each trial, and dates when trials were observed.

1.3.4 Field Localities:

River surveys took place in 14 rivers of varying morphologies and flow (Table 4). Because useable data for bone orientation analyses was gathered from only four of them, only those four will be described.

The Escalante River (ER) in southern Utah, is a cobble to sand bed river that meanders through a deeply incised canyon. Flow is highly seasonal and can dry up in parts of the drainage during summer months. High flow events are typically flash floods

that scour out the channel and deposits sands and gravels as floods wane. Otherwise flow is mild and moving little sediment.

Levelock Creek (LC), Alaska is a highly sinuous meandering river with a sand to gravel bed. Flow is continuous year round, with a slow rise and fall surrounding rainfall events. This locality was unique because the local residents were disposing the remains of their kills by dropping them off a bridge into the river. This provided a point source of skeletal material as well as an abundance of bones downstream.

Big Beef Creek (BBC), Washington flows through a University of Washington research station from its headwaters to its confluence with the ocean (approximately 11 km). The river is braided with a gravel to cobble bed, and is characterized by episodic pulses of high water (usually from winter storms) followed by extended periods of lower flow, changing channel morphologies, and high rates of coarse bedload transport. In the summers the average flow is ~0.1 m^3/s (a few cfs), and in the winters discharge is around 2.8 m^3/s (100 cfs), with substantial increases ~40-55 m^3/s (~1500-2100 cfs) during large winter storm events.

The East Fork Sevier River (EFSR), Utah is an approximately 40 km long river from its headwaters to the Tropic Reservoir. The river changes morphology from straight channels with shoot and pool morphology to highly sinuous deep and wide channels. The bed is comprised of gravel and sand in the upper reaches, grading down to sand and mud closer to the reservoir. Water flows through the EFSR year round, however, high flow occurs in the late spring (snow melt) and late summer (from storms).

Seeding trials took place in only two rivers, BBC and the EFSR. Seeding trials in BBC were performed with permission of the University of Washington, and were initiated just downstream of the gauging station. The reaches in the EFSR used for seeding trials were sinuous with gravel and sand beds. Because multiple trials were performed in the same river, the river reaches used were separated by noticeable competence drops (i.e., beaver dams, or large culverts and pools) to ensure bones were not swept downstream into other trials.

1.3.5 Data Analysis:

Table 2 provided the categories for data analysis; elongate, concave, and flat bones. Previous research investigating the transport of skeletal material has classified bones as "long bones" or "concave" without describing the classification process. Here the term elongate is used to denote bones that are over twice as long as wide and the bone is more or less the same dimensions in width and depth throughout its length. For example, elongate bones would include ungulate limb elements (e.g., humerus, femur, radioulna, etc.) but would not include cervical or thoracic vertebrae that are over twice as long as wide, but are not the same dimensions throughout their length. Concave bones are those that show marked concavity, where the bone curves in relative to a continuous surface. Determining a concave bone is practically easy in the field by imaging placing the bone on a surface; if the bone would lay with space under it with a continuous curve, then it would be classified as concave. Some, not all, large mammal ribs are concave, so are many cranial vault bones. In some cases parts of innominates or scapulae would be concave as well. Flat bones are simply flat pieces of bone, which include some portions

of ribs that are not concave, parts of some scapulae, etc. It is important to note that each element was classified individually based on its shape, not its element name. As in, if an ulna fragment was found it may have been classified as concave, or elongate, or excluded from the study entirely (if irregularly shaped) depending on its shape. So the name of a bone had no influence on the shape classification.

Orientation data from all river surveys and seeding trials was combined and analyzed by identifying which bones were elongate, were found in water (not on a bank), and where a measurement of both bone and flow orientation was possible. Bones recovered in eddies were not included in the analysis because the flow direction was often impossible to measure or was constantly changing. Only bones found in water were included because remains found above water may have experienced other transport processes (e.g., trampling, rodent movement, etc.). As such, this data set represents a conservative subset of the skeletal element orientation data.

Three classes of elongate bone orientation data were collected: 1. Orientations of individual bones or bone fragments with clear larger and smaller ends (had a polarity), 2. Orientations of individual bone fragments without clear larger or smaller ends (no clear polarity), and 3. Orientations of articulated skeletal material (see Supplementary Table 3 for a description of each articulated unit) where a clear larger or smaller end to the unit was impossible to identify (also had no clear polarity). A method that could present all these data types accurately was required, so orientation data was plotted on a corona dot diagram (Wells 2000). See Appendix B, or Wells (2000), for a justification for why this data presentation tool was used and an explanation for how to create similar diagrams. To

create corona dot diagrams, a polarity convention is required. For the first class of orientation data (elongate bones or bone fragments with a clear larger end), the polarity convention used was that each plotted point would represent the largest end of the bone. When a polarity was not identifiable, for orientation data in classes 2 and 3, all orientations were scaled into the northern hemisphere by convention. As such, when samples were observed, the largest end of elongate bones and bone fragments were individually identified and plotted on the corona dot diagram as solid circles. Bone fragments without a preferred orientation were plotted with stars, all in the northern hemisphere by convention. Orientations of articulated remains were plotted as solid triangles, also all in the northern hemisphere by convention. All data was scaled with the flow direction from the north to the south.

In addition, bones with clear convex sides were identified (e.g., ribs, cranial vault fragments, Figure 2) and the number of bones resting concave up and concave down were counted, normalized, and plotted for comparison. Too few flat bones were observed to form any conclusions. However, all the flat bones observed were laying flat on the bed, an orientation that provides no useful information about taphonomic processes operating on remains.

Ultimately the hypothesis being tested is a practical one: that there is a relationship between bone orientation and flow direction that is sufficiently strong to utilize in analyzing skeletal assemblages. No statistic exists that can discriminate between a practically useful correlation and one that is not useful. Because of this practicality problem, no previous study seeding bones in rivers has reported orientation statistics

(Table 3), nor has any flume studies investigating bone transport. Analysts have interpreted for themselves if the correlation between flow direction and bone orientation is sufficiently strong enough to use analytically, which is a personal preference, one based on understanding variability in the taphonomic process (fluvial transport) and the nature of the data set under analysis. To facilitate this process, each azimuth is plotted individually to give analysts the maximum information for each data point so informed decisions can be formulated. In addition, descriptive circular statistics are reported as well as hypothesis tests to determine if the observed distribution is measurably different from a uniform distribution. The mean vector, length of mean vector, median vector, concentration, cicular variance, cicular standard deviation, and 95% confidence interval were calculated for orientations from bones with clear polarities using Oriana v.4 (produced by Kovach Computing Services). A Rayleigh test, Rao's Spacing test, Watson's U^2 test, Kuipers test, and a V Test were all calculated using Oriana v. 4. All statistics were calculated in comparison with a uniform distribution. Even with statistically significant findings, analysts must still interpret the strength of any observed correlations before use, because no statistic can indicate the magnitude of an effect necessary to be useful analytically. In other words, statistical significance is not an indication of practical significance of any orientation correlation because it is possible to have statistically significant results that are still not practically useful during analysis.

1.4 Results

During river surveys 586 isolated bones were located from all 14 surveyed rivers, along with 34 articulated units. The breakdown of how many isolated bones and articulated units were found in each river and how many bones provided useable orientation data are detailed in Table 6.

Of the 6000+ bones seeded in the EFSR (six trials) and BBC (two trials), 226 were recovered. Table 7 details how many bones were recovered from each trial each year.

Because many of the bones observed were not elongate, were found out of water, or in eddies, few of the observations could be used for elongate bone orientation analyses. Out of the combined data set of 586 river survey observations and 226 seeded bone observations, only 107 elongate bone observations met the required stipulations. In addition, 46 bone fragments and 5 articulated skeletal units also met the required criteria. Supplementary Tables 1-3 lists the details of each of these samples, including: the river a sample was recovered from, observation date, skeletal element(s), taxon of origin, and some observations collected during field work. Seeded remains were almost all mammalian, most frequently adult deer, pronghorn, elk, pig, and cow. Recovered remains had a similar composition however in Alaska most of the remains came from caribou and moose. The vast majority of the elongate bones and bone fragments were appendage elements (e.g., humeri, radioulnae, femora, tibiae, and metapodials), while the concave/convex elements were usually ribs, rib fragments, diaphysis fragments, or dentaries (see Data Analysis section for classification of bone elements).

Figure 3 is six corona dot diagrams that show the elongate bone orientations found in different rivers (EFSR and LC) with all orientations depicted relative to flow direction (north to south). Figure 3A shows bone orientations with polarities from the EFSR while Figure 3B shows bone orientations with polarities from LC. Figures 3C and 3D illustrate bone orientations without polarities from EFSR and LC respectively. Figure 3E shows the orientations of articulated remains in LC. Lastly, Figure 3F is a combined analysis with all like data plotted on one figure. Data sets from the same river are positioned in the same column to facilitate comparisons between data sets. No clear relationship is apparent between natural river flow direction and any of the three aggregate data sets (Figure 3F). The same interpretation is supported by the other five river specific data sets as well (Figure 3A-E). Consequently, a casual view of Figure 3 suggests the data are well distributed throughout a circle both in river specific analyses, and in the aggregate data sets, with no clear preferred orientation(s) present.

Circular statistics support this intuitive visual interpretation. Only bone orientations with distinct polarities were analyzed with circular statistics because circular statistics requires a 360^{o} data set, so the two data sets that were arbitrarily scaled to the northern hemisphere are automatically excluded from the analysis. In addition the articulated unit data set is too small to calculate meaningful descriptive statistics. With a sample size (N=107), the mean vector was ~282.6^{o} with a vector length of .077 (indicates low clustering of points, i.e., dispersed data), and a median vector of 283^{o}. The concentration was low at 0.155 (indicating a well distributed data set), with a variance of 0.923 and a standard deviation of 129.7^{o}. The standard error was large (>50^{o}), which

indicates that the data is dispersed throughout the circle, making the confidence intervals and standard errors (>180^{o}) unreliable. The descriptive statistics alone suggest the data set is generally uniformly distributed and indicate that a comparison with a von Mises distribution is not warranted (high standard error). Results from secondary statistics are unreliable with standard errors so large as observed here, but are reported for completeness even though their values are questionable. A Rayleigh Test, a test of the null hypothesis that the data points are uniformly distributed, yielded $\rho=0.53$ at $\alpha=0.05$, suggesting the data set is evenly distributed. A Rao's Spacing Test, a test of uniform point distribution based on the spacing between points, yielded $\rho=<0.05$ at $\alpha=0.05$, suggesting that the points themselves are not evenly spaced, even if the overall distribution is close to evenly distributed. A Watson's U^2 test, a goodness of fit comparison between the data set and a uniform distribution, yielded a $0.15>\rho>0.1$ at $\alpha=0.05$, indicating the data are not significantly different from a uniform distribution. Similarly, a Kuiper's Test, a comparison of observed data to a uniform distribution, yields $\rho>0.15$ at $\alpha=0.05$, further confirming that the data set is uniformly distributed. Finally, a V Test was performed which is a comparison of the observed data to a non-uniform data set with a mean vector, and yielded a $\rho=0.403$ at $\alpha=0.05$, indicating that the data do not have a resolvable mean vector with statistical support. All these statistics indicate the same thing; that the data are statistically indistinguishable from a uniform distribution, but the data points are not quite evenly distributed. These statistics confirm interpretations based on even a brief visual inspection of Figure 3F.

Of the concave bones observed in the two combined data sets, only 89 bones met the criterion of being found in water. Of those 63 (70.8%) were found concave down, and 26 (29.2%) concave up. Concave bones were located significantly more frequently concave down than concave up, X^2 (1, N=89) = 15.382, ρ=.00009. This statistic shows the distribution is not equal between the two orientations but does not indicate that the difference is large enough to use analytically. This is a choice each investigator must make for themselves by comparing the size of the effect observed here to any orientations observed in an excavated sample, and considering that it is presently unclear what the variation is in this ratio in other rivers. However, generally it does appear that most concave bones orient concave down (convex up). Supplementary Table 4 lists the details of each of these samples, including: the river a sample was recovered from, observation date, skeletal element, taxon, orientation, and field observations. This ratio of ~70% concave down and ~30% concave up is only one measurement of concave bone orientation out of a range of potential orientation ratios observed in other river systems. Because only one observation is available this one data point should not be used to characterize the range and variation of orientation ratios in a population of other rivers. Consequently, analytical inferences based on this one observation are shrouded with unknown error. However, broad brush stroke inferences can be made acknowledging the unknown error associated with this measurement.

Supplementary Tables 1-4 also report a subset of observations made during fieldwork. Between 30% and 40% of the bones reported here were found in direct association with woody debris (Figure 4a). Association could include being caught in or

catching woody debris, or found in a location that accumulates woody debris. This number rises to ~56% when the analysis includes all bones recovered, not just those that provide usable orientation data presented here (Evans 2013a). It should be noted that all the rivers from which data are reported here had woody debris, but were not choked with debris. So bones had ample opportunity to be deposited in locations without woody debris because most of the channel lengths were not filled with debirs. Additionally some bones were found caught by larger rocks or boulders, or deposited on gravel (Figure 4b), which altered their orientations relative to flow. Rocks altering bone orientations were less common than bones being deposited with woody debris, but still a frequent occurrence. Few bones were found in conjunction with bedforms however this is probably because there were few bedforms forming during observations. While bones were found more or less equally distributed across the geomorphic space of the observed rivers, frequently bones were found on slopes of geomorphic features, with the bones orienting parallel to those features rather than parallel to flow (Figure 4c and 4d). The clast sizes upon which bones were deposited ranged from mud and silt to cobbles in nearly every river (Figure 4). These observations show that bones were found under a wide range of bed conditions (grain sizes and obstructions) as well as located throughout the geomorphic space of natural rivers. These observations are included to demonstrate the heterogeneity of the environments in which bones are naturally deposited.

1.5 Discussion and Conclusions

Of the five preferred orientations predicted in Table 2, only two were observed in natural river systems: that of flat bones lying flat on the bed, and concave bones preferentially laying concave down. Flat bones lying flat on the bed provides no useful information regarding fluvial transport or reorientation because flat bones will orient flat on any surface, so the flat orientation is not suggestive of any one taphonomic process or paleoenvironment. The significant chi-square result reported does not indicate that concave versus convex bone orientations can be used to identify fluvially reoriented remains because it provides no insight into the variability of bone orientations found in other fluvial contexts (e.g., the consistency of the 70% figure in other rivers). Given the single sample (n=89) of concave bone orientations presented here it is impossible to determine the variability in how often concave bones orient concave up or down in different fluvial environments. In other words, to determine if there is a consistent ~70% concave down ratio of concave bones, further studies in different fluvial environments would be needed. If this orientation ratio was observed in other fluvial systems, then it could potentially be used to interpret fossil or archaeological skeletal assemblages. To do so the analyst would have to excavate a skeletal assemblage with enough concave material to calculate a ratio of concave up or down elements, then analogically apply this ~70% concave down orientation to the assemblage. Presently this analogy has the strength of an untested hypothesis, and also has an unknown error since there is no quantification of the variability of orientation ratios of concave bones in different fluvial environments. As such, using this method would entail numerous untested assumptions,

and require a large enough excavated sample, to make this method undesirable or unwieldy. Furthermore, the ratio of concave up and down bones is unknown in other environments, so it is unknown how diagnostic to environment this ratio would be given that concave bones could potentially have preferred orientations in other environments as well. Finally, because the correlation between concave shape and orientation is weak, even with a statistically significant chi-square value, the number of bones found concave up or down in an assemblage can only provide weak evidence for fluvial transport or reorientation, and only when enough samples are recovered.

The elongate bone orientations displayed in Figure 3 do not conform to any of the expected preferred orientations based on flume work (see Tables 1 and 2, and Appendix B for a detailed discussion). At the least this data set suggests that our expectations concerning the orientation of elongate bones exposed to unidirectional currents should be reassessed because none of our expectations were met. Consequently, these data suggests our model of bone transport and deposition is incomplete because it does not accurately predict the orientations of fluvially transported elongate elements.

Figure 3 shows no clear visually identifiable preferred orientations of elongate bones. As such, each analyst much determine for themselves if this relationship is strong enough to use analytically. Because no visually identifiable preferred orientation is evident, conservatively elongate bone azimuth orientations should not be utilized to analyze skeletal assemblages. In other words, the relationship between elongate bone orientation and flow direction, if there is one, is weak enough that it cannot be discerned by eye, thus making it difficult or impossible to utilize in analyzing the orientations of

elongate elements in skeletal assemblages. This observation raises questions of why previous studies (Table 1) have observed clear preferred orientations of skeletal material in fluid flows. Preexisting literature suggests the answer can be broken into two components; the consistency of the flume environment and consistency of the clast (bone).

Flumes present a remarkably uniform environment where the flow can be manipulated (discharge, velocity, depth, etc.) and the bed composition and angle can be controlled as well. These features allow precise measurement of hydrodynamic variables as well as the testing of sophisticated sediment transport models. The drawback is that the consistency of flume flow and bed conditions is antithetical to the conditions observed in the vast majority of natural fluvial systems. For example, bones found in the same river systems were frequently found on beds of different grain sizes, or on beds of mixed grain sizes (Supplementary Tables 1-4). In addition, natural channels provide a suite of morphologies not present in flumes (e.g., chutes, pools, rills, etc.), and bones are found in all of those micro environments (Supplementary Tables 1-4). While bones may behave well under idealized conditions (e.g., without bed obstructions), these conditions rarely, if ever, exist or persist in nature. Natural flows frequently have bed obstructions which act as depocenters for skeletal remains (Supplementary Tables 1-4). Such obstructions may or may not preserve in the fossil or archaeological record. Woody debris or vegetation may not preserve, and bedforms or individual clasts can be removed through subsequent erosion. In addition, during paleontological excavation, to identify bed related obstructions, microstratigraphic data is required, which is rarely collected. Consequently,

even larger clasts that act as obstructions, may not be noticed or remain during data collection. Consequently, we do not expect observations of bone transport and deposition derived from flumes to accurately reflect the macroscopic behaviors of bones in real natural heterogeneous fluvial systems. The results reported here support the interpretation that the homogenous conditions in flumes do not adequately reflect the heterogeneous conditions of natural fluvial systems.

Clast characteristics also change between flume trials and natural settings, in large part due to the residence time bones have in real fluvial systems versus short term flume trials. Real bones in rivers possess rapidly and continually changing bulk densities which radically alters their transport and deposition (thus orientation). For example, when dry bones are placed in water they hydrate. The rate at which bones hydrate varies (Table 8), however, it is clear the rate is variable between bones, possibly dependent on their history (weathered and porous bones, versus fresh greasy bones, etc.). What is important is that bones may not be fully saturated with water for days, weeks, or months (Table 8), so the transport mechanisms of those bones may change continuously during prolonged hydration. To conceptually grasp the magnitude of the change in transport mechanisms between dry and hydrated bone, consider the case of floating bones. Bone floatation has been observed by many authors (Table 9) in nearly all kinds of water (fresh, salt, stagnant, and flowing). Bones from nearly all taxa investigated have floated and nearly every element has floated during some research (Table 9). As such, when considering bone transport and deposition we should acknowledge bone density changes ranging from floatation, to neutral buoyancy, to full saturation, with the realization that at

different times during decay, the density may increase, then decrease, then increase again. Because bone density changes so much, bones may spend part of their transport floating and behaving like woody debris, or moving like a neutrally buoyant clast. These changing transport modes could lead to bone deposition in locations and orientations not predicted by flume studies. The result would be a suite of observed bone orientations in rivers that do not conform to the predictions made from flume studies, which were the results reported here.

Ultimately, the assumption that bones adopt a preferred orientation in fluvial flows was based on an analogical model (flume) that was oversimplified and more uniform than natural systems and the clasts used in flume trials were, for the most part, used for short enough times that density changes (degreasing or hydration) did not dramatically alter the observed transport and deposition (however, see Coard, 1999; Dodson, 1973; Kaufmann et al. 2011; Morden, 1991a, 1991b as notable exceptions). So while flume data suggests bones adopt preferred orientations when exposed to unidirectional currents, these observations are not replicated in empirical fluvial trials and river surveys. Because a correlation is not readily apparent between flow direction and elongate bone orientation in natural fluvial systems, conservatively, elongate skeletal element orientation should not be used to identify fluvial interactions with assemblages or support the inference of fluvial transport in the history of remains.

The conclusion that elongate bone orientation is not correlative with flow direction strongly enough to use analytically only applies to isolated bone transport in river channels. Skeletal assemblages derived from isolated bones or articulated material

on floodplains may not be subject to the same vagaries as channelized flow. However, channelized flow has more consistent flow orientations than unconfined flow, so a stronger correlation between flow and orientation directions is expected in channels than on floodplains. In addition, floodplains poses more obstructions which bones could catch on causing deposition, which is expected to create an assemblage oriented relative to the obstruction rather than the transporting flow. Finally, articulated skeletal units are expected to adopt complicated orientations in flows because of their irregular shapes, changing in shape due to movement at joints, and catching on bed obstructions. Consequently, realistic floodplain deposits can be expected to yield far more complicated bone orientations as a result of unconfined fluvial flow than the relatively simpler flows found in river channels. Ultimately the expectation is that the results presented here are also likely applicable to floodplain derived deposits, but further empirical observations are warranted to test the hypothesis.

The result that elongate bone orientations are not indicative of flow direction, is contrary to the assumptions underlying established analytical techniques (Eberth et al. 2007) for skeletal assemblages, thus calling in to question the analyses that are based on those assumptions (e.g. Dominguez-Rodrigo et al. 2012). If this fundamental assumption had been tested when first suggested by Toots (1965b) and Voorhies (1969), researchers may not have used skeletal element orientations to infer the taphonomic history of remains. Such an outcome would have been more efficient and improved the rigor of the science produced since the mid to late 1960's. Ultimately this is a cautionary tale that suggests that we, as a scientific community, should test our fundamental assumptions and

methods before they are applied, because testing our assumptions will be more efficient and result in rigorous science. Similarly, a survey of the recent skeletal orientation articles shows widespread continued use of rose diagrams (e.g. Dominguez-Rodrigo et al. 2012, figures 2-5) even though a better alternative exists (Wells 2000 Appendix B). As a community we should be concerned that the assumptions upon which our analyses are based are flawed and the method we use to present our data analysis is antiquated.

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This research program would not have been possible without the many kind and tolerant people who provided animal parts (Budget Game Processing, Steve Rogers, Jane Boles, MSU Animal Resource Center, Bob Brekke, Kevin Hall), vehicles in which to transport remains (Bob Jackson, Michael Knell, Cathy Lash, Dave Varricchio), laboratory space in which to clean remains (MSU Animal Resource Center, College of Range Sciences, Dave Varricchio), and housing and showers during the many months of fieldwork (Danny Miller, Sarah Chrisman, Laura Wood, Monica Elkinton). I received help from amazing people during fieldwork who helped collect data (Pat Terhune-Inverso, Cathy Lash, Elizabet Williams), moved specimens (Don Stafford, Cathy Lash), and provided food when our supplies were eaten by bears (No Seeum Lodge, Alaska). Numerous people helped by providing needed equipment and supplies (MSU Surplus, Dave Varricchio) or transportation when none was available (Cathy Lash, Pat Terhune-Inverso, Elizabet Williams, Dave Varricchio). Partial funding for this research was provided by the Rocky Mountain Section of SEPM, and the Redd Center. Cathy Lash

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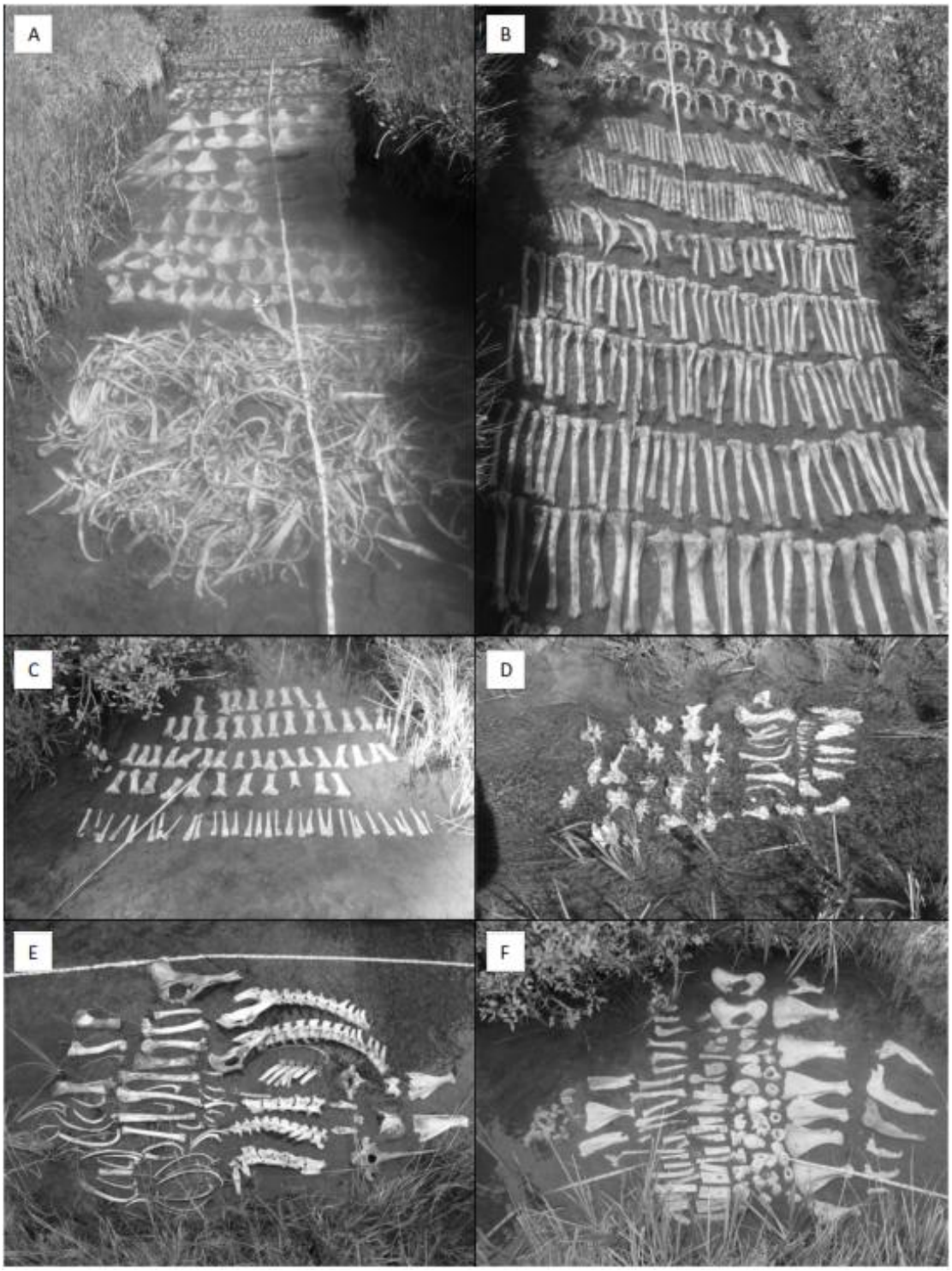

Figure 1: Example pictures of river seeding trials. A. and B. depict portions of the largest seeding trial in the East Fork Sevier River, while C., D., E., and F. all depict smaller arrays of bones that were parts of different seeding trials, also in the East Fork Sevier River.

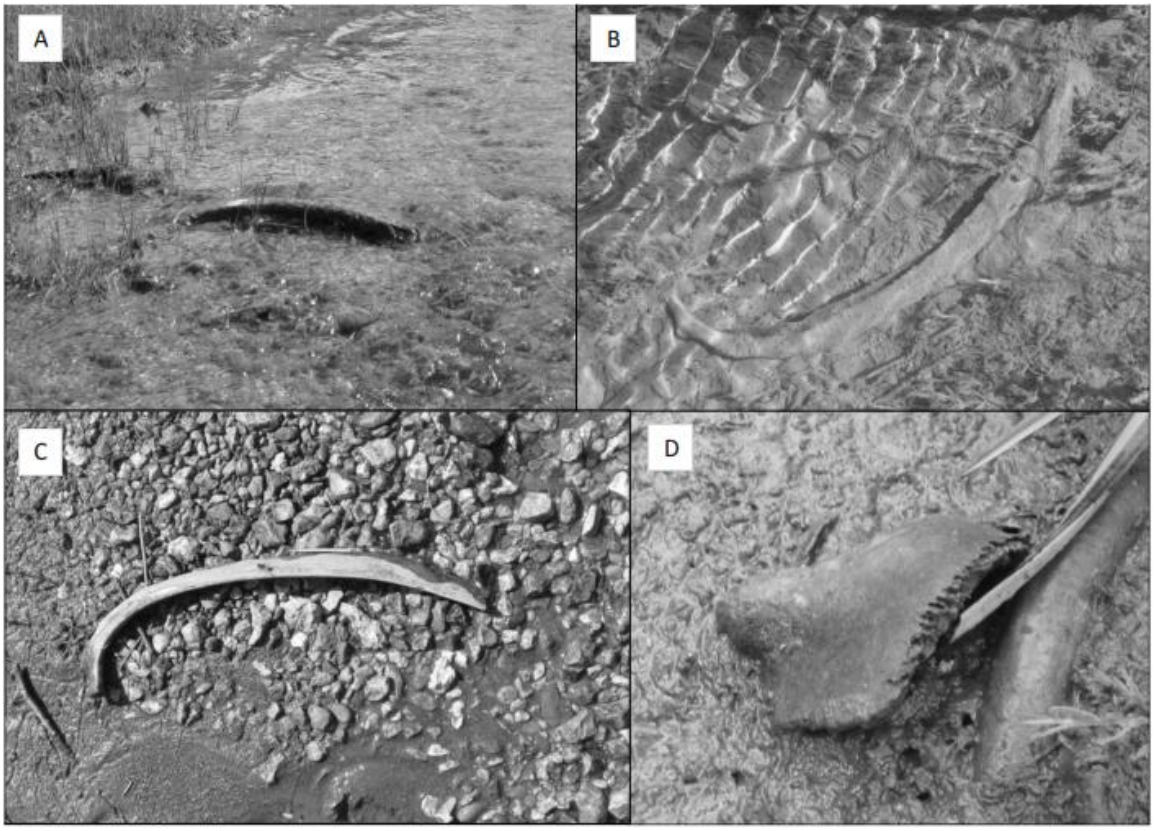

Figure 2: A. and B. are examples of concave bones (ribs) observed in fluvial systems, and C. and D. are pictures of a rib and a cranium fragment showing what concave down bones look like on a bed above water (these bones were not used in data analyses, but are depicted to show the ease of identifying concave up and down remains).

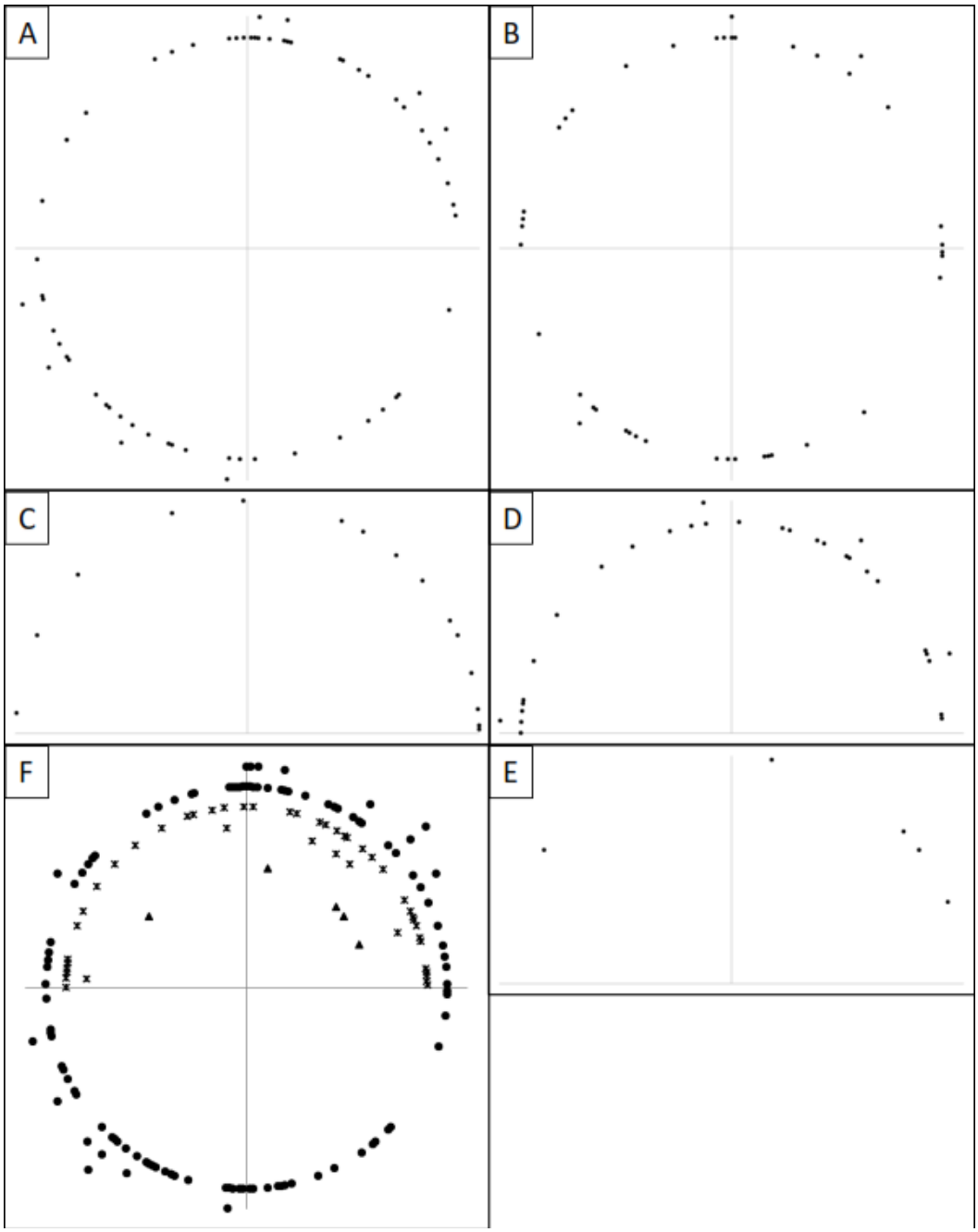

Figure 3: Bone, bone fragment, and articulated unit orientations relative to flow direction. All measurements are scaled with flow moving from north to south (top to bottom). A. Polar bone orientations observed in EFSR, B. Polar bone orientations observed in LC, C. Bone orientations without polarities from EFSR, D. Bone orientations without polarities from LC, E. Orientations of articulated remains in LC, F. All bone orientations depicted on the same figure utilizing aggregated data with: circles = individual complete bone orientations, stars = orientations of bone fragments without clear polarities all depicted in the northern hemisphere by convention, triangles = articulated unit orientations, again depicted in the northern hemisphere by convention.

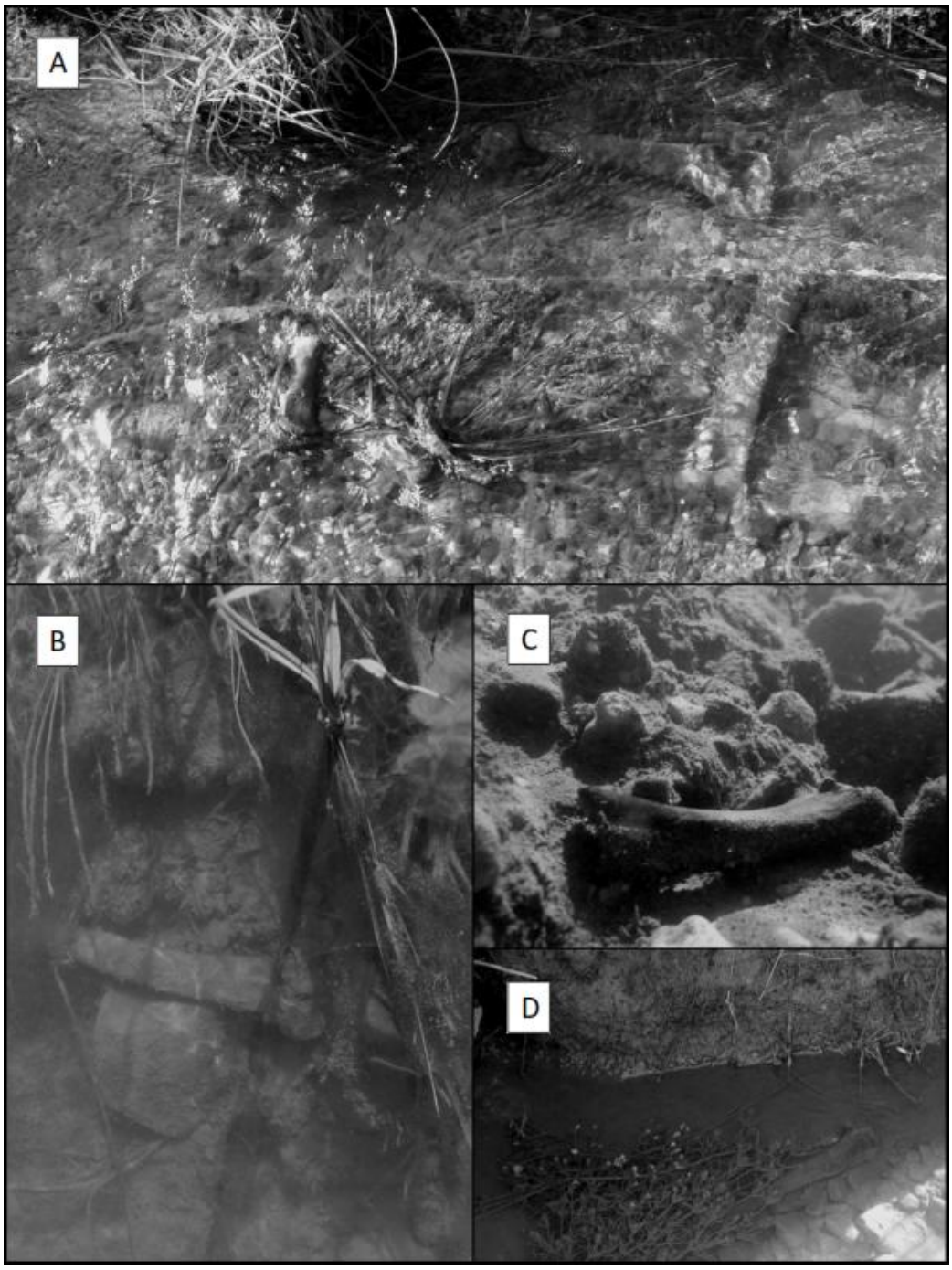

Figure 4: Examples of natural heterogeneity found rivers. A. Bones caught upstream of woody debris and vegetation, B. A bone caught upstream of a large rock, altering bone orientation, C. An elongate bone parallel to a bedform edge, not parallel to flow, D. An elongate bone parallel to the bank slope and not flow direction.

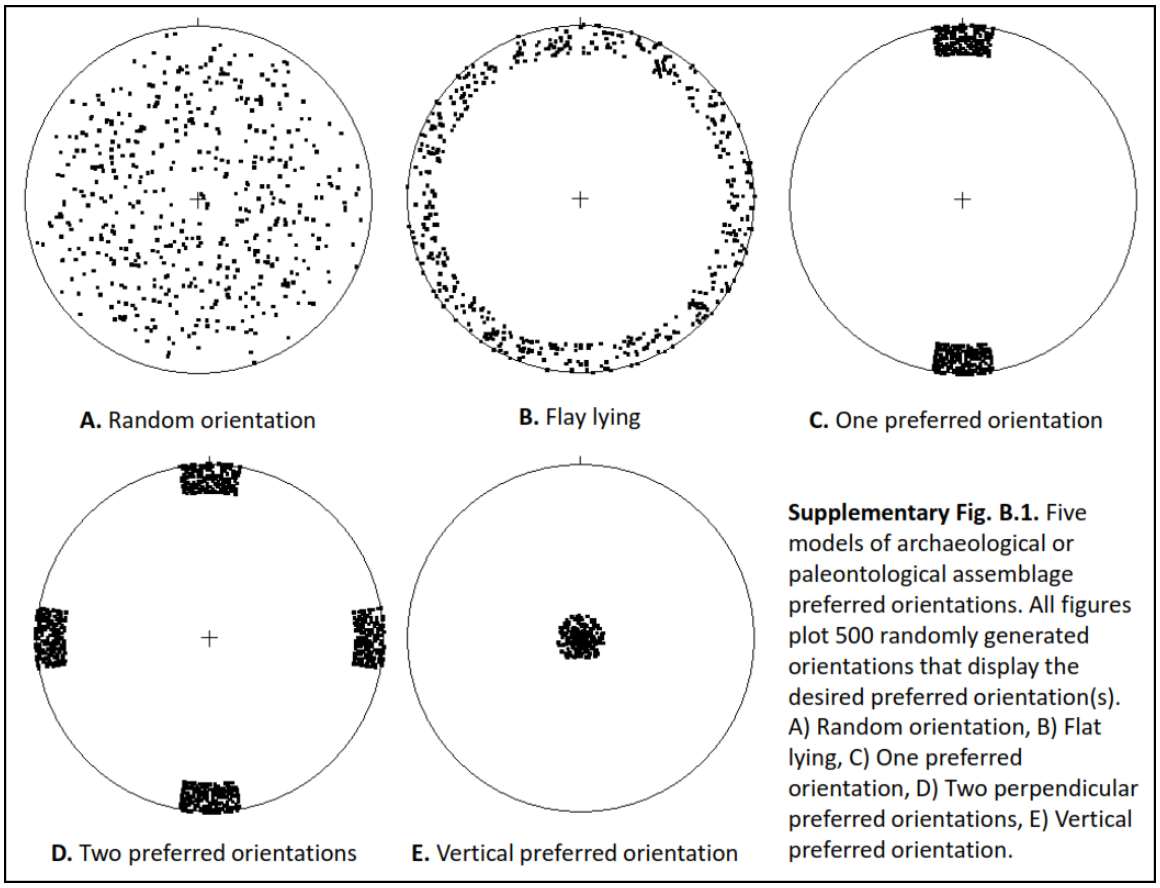

Figure A.1: Five models of archaeological or paleontological assemblage preferred orientations. All figures plot 500 randomly generated orientations that display the desired preferred orientation(s). A. Random orientation, B. Flat lying, C. One preferred orientation, D. Two perpendicular preferred orientations, E. Vertical preferred orientation.

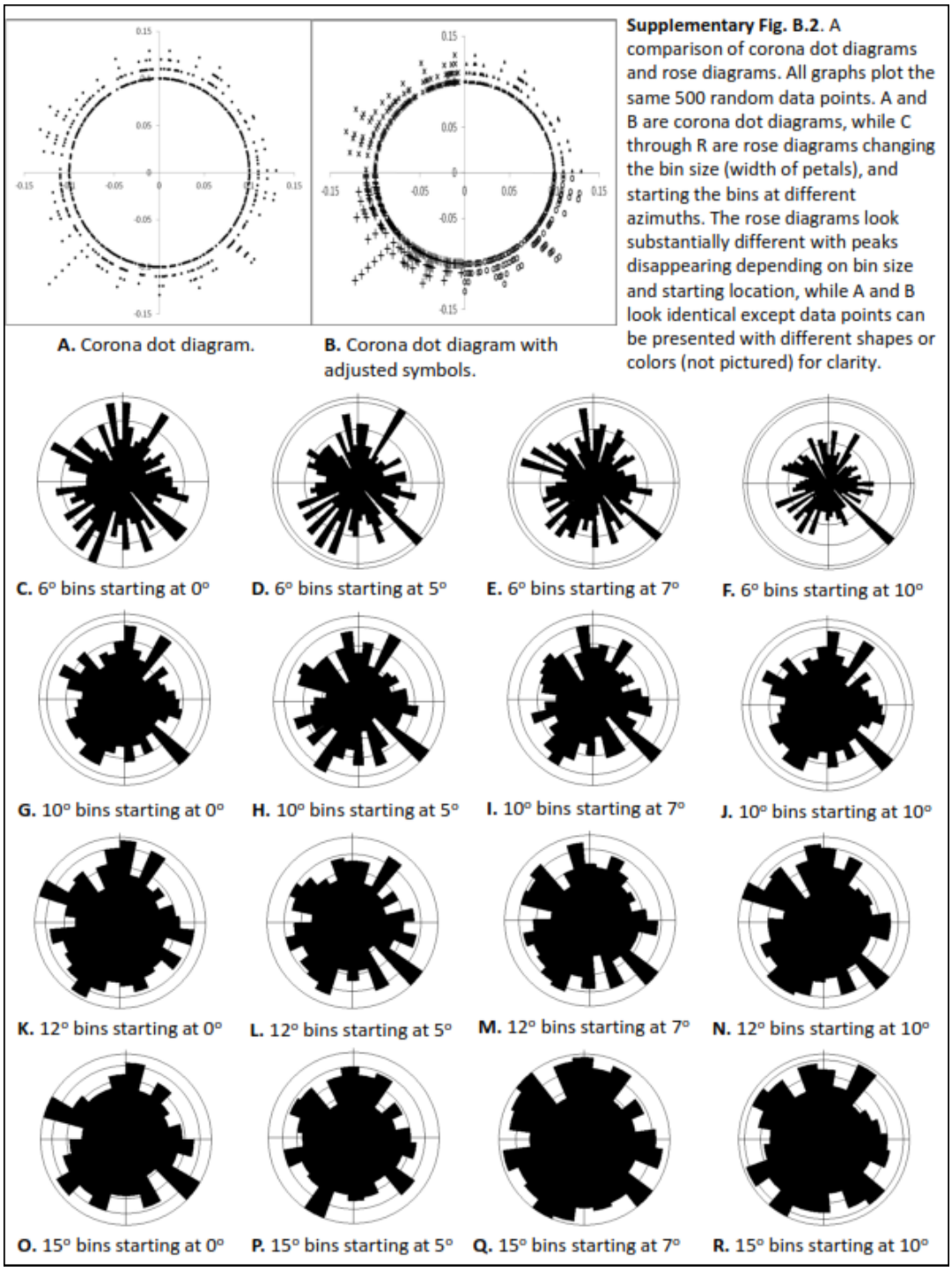

Figure A.2: A comparison of corona dot diagrams and rose diagrams. All graphs plot the same 500 random data points. A. and B. are corona dot diagrams, while C. through R. are rose diagrams changing the bin size (width of petals), and starting the bins at different azimuths. The rose diagrams look substantially different with peaks disappearing depending on bin size and starting location, while A. and B. look identical except that data points can be presented with different shapes or colors (not pictured) for clarity.

	A	B	C	D	E
1	Azimuth	Polar Coordinate Degrees (PCD)	Radius (R)	X	Y
2	#	=(-A2)+90	0.1	=(C2)*COS((B2)*(PI()/180))	=(C2)*SIN((B2)*(PI()/180))

Figure A.3: Column headings and equations used to calculate X and Y coordinates from polar coordinates in Excel.

Table 1
Flume studies reporting bone preferred orientations including the taxa, bones used, and the observed preferred orientations.

Citation	Taxon	Bone	General Shape	Observed Preferred Orientation
Blob 1997: 155, table 1	Spiny Softshell Turtle (*Apalone spinifera*)	Atlas	Irregular	Anterior down, ventral facing upstream
		Sternum	Flat	Lateral facing upstream
		Skull	Irregular	Palate facing up, nose facing upstream
		Atragalus/Calcaneum	Irregular	Random
		Free rib	Irregular	Angle facing upstream
		Posterior costal #7	Convex/Flat	Ventral up, lateral up or downstream
		Nuchal	Convex/Flat	Posterior facing upstream
		Hyoplastron	Convex/Flat	Ventral down, posterior facing upstream
		Cervical vertebra	Irregular	Anterior facing upstream
		Humerus	Elongate	Not reported
		Epiplastron	Convex/Flat	Head facing upstream
		Dorsal centrum #5	Irregular	Ventral facing down or dorsal up; angle, posterior, or anterior upstream
		Lower jaw	Irregular	Ventral facing up, symphysis upstream
		Anterior costal #3	Convex/Flat	Medial, anterior, or lateral upstream
		Pedal ungual phalanx	Irregular	Distal facing downstream
		Hypoplastron	Convex/Flat	Lateral facing upstream
		Radius/ulna	Elongate	Proximal facing downstream
		Entoplastron	Convex/Flat	Ventral facing down, anterior upstream
		Tibia	Elongate	Distal facing downstream
		Pedal phalanx V-2	Elongate	Distal facing downstream

Table 1 Continued

		Neural #3	Convex/Flat	Dorsal down, posterior upstream
		Femur	Elongate	Head facing upstream
		Pelvis	Irregular	Ilium 'dorsal', pubis facing downstream
		Scapulocoracoid	Irregular	Corocoid facing upstream
		Metatarsal IV	Elongate	Distal facing downstream
		Fibula	Elongate	Distal facing downstream
		Xiphiplastron	Convex/Flat	Ventral down, posterior upstream
Boaz and Behrensmeyer 1976: 56-57, table 2	Human (*Homo sapiens*)	Hemimandible	Irregular	Medial suface up, condyles downstream
		Molar	Irregular	Not reported
		Parietal	Convex	Medial or lateral surface up
		Patella	Irregular	Anterior or posterior surface up, inferior surface facing downstream
		Proximal radius	Elongate	Proximal end downstream
		Distal humerus	Elongate	Distal end downstream
		First rib	Irregular	Superior or inferior surface up
		Incisor	Irregular	Root facing downstream
		Atlas	Irregular	Superior facing up, posterior facing downstream
		Maxillary fragment	Irregular	Medial up, anterior or posterior facing downstream
		Femoral head	Irregular	Anterior or posterior surface up, head downstream
		Temporal fragment	Irregular	Medial or lateral surface up
		Scapula fragment	Irregular	Anterior or posterior suface up, medial downstream

Table 1 Continued

Edentulous hemimandible	Irregular	Medial or lateral surface up
Rib	Irregular	Superior or inferior up, inner surface downstream
Clavicle	Irregular	Superior facing up, medial surface downstream
Mandible	Irregular	Superior facing up, condyles facing downstream
Vertebra (T1)	Irregular	Superior suface up, body faces downstream
Proximal tibia	Elongate	Distal downstream, posterior facing up
Proximal radius	Elongate	Head downstream
Talus	Irregular	Superior facing up, variable surfaces downstream
Proximal ulna	Elongate	Constantly changing
1st Metatarsal	Elongate	Proximal downstream
4th Metatarsal	Elongate	Proximal downstream
Vertebra (T12)	Irregular	Superior up, posterior or proximal downstream
Proximal humerus	Elongate	Proximal downstream
Acetabulum	Irregular	Medial or lateral surface up
Calcaneum	Irregular	Constantly changing
Cuboid	Irregular	Constantly changing
Sacrum	Irregular	Posterior facing up, inferior facing downstream
Cranium	Irregular	Constantly changing

Table 1 Continued

		Unspecified	Flat	Flat on bed
		Unspecified	Elongate	Large end downstream
Coard and Dennell 1995	Mouflon sheep (*Ovis musimon*), pig-tailed macaque (*Macaca nemestrina*), and Alsatian dog (*Canis familiaris*)	Unspecified	Elongate	Parallel to current
		Innominate	Elongate	Parallel to current, illia downstream
Dodson 1973	Mouse (*Mus*), frog (*Rana*), toad (*Bufo*)	Unspecified	Elongate	Parallel to current
	Mouse (*Mus*)	Dentary	Convex	Convex up
Elder 1985	Rock Bass (*Ambloplites rupestris*)	Unspecified	Convex	Convex up
	White Sucker (*Catostomus commersoni*)	Rib	Elongate	Parallel and perpendicular to flow
		Spine	Elongate	Parallel and perpendicular to flow
		Pterygiophore	Elongate	Parallel and perpendicular to flow
		Unspecified	Flat	Flat on bed
		Unspecified	Elongate	Parallel and perpendicular to flow
		Unspecified	Convex	Convex up

Table 1 Continued

Elder and Smith 1988:586-588	Unspecified fish	Unspecified	Unspecified	Preferred orientations observed
Gifford 1977	Terrapin	Carapace	Convex	Convex up, long axis parallel to flow
	Crocodile	Mandible	Elongate	Perpendicular to flow
Gifford and Behrensmeyer 1977	Terrapin	Carapace	Convex	Convex up, long axis parallel to flow
	Crocodile	Mandible	Elongate	Perpendicular to flow
Morden 1991a	Human (*Homo sapiens*), chimpanzee (*Pan troglodytes*)	Humerus	Elongate	Parallel to flow
		Radius	Elongate	Parallel to flow
		Ulna	Elongate	Parallel to flow
		Femur	Elongate	Parallel to flow
		Tibia	Elongate	Parallel to flow
		Fibula	Elongate	Parallel to flow
		Unspecified	Cylinders	Parallel to flow
		Scapula	Convex/Flat	Convex up, spine parallel to flow
		Innominate	Irregular	Iliac crest upstream, pubic aspect inferior
Trapani 1996	Rock Dove (*Columbia livia*)	Sternum	Irregular	Laying on side
		Synsacrum	Convex	Convex up
		Rib	Convex	Convex up
		Unspecified	Elongate	Perpendicular to flow
Trapani 1998	Rock Dove (*Columbia livia*)	Sternum	Irregular	Laying on side
		Synsacrum	Convex	Convex up
		Rib	Convex	Convex up

Table 1 Continued

		Unspecified	Elongate	Perpendicular to flow
Voorhies 1969	Sheep, Coyote, Badger	Femur	Elongate	Parallel and perpendicular to flow, large end downstream (polarity)
	Sheep, Coyote, Rabbit	Tibia	Elongate	Parallel and perpendicular to flow, large end downstream (polarity)
	Sheep, Coyote, Badger	Humerus	Elongate	Parallel and perpendicular to flow, large end downstream (polarity)
	Sheep, Coyote, Man	Radius	Elongate	Parallel and perpendicular to flow, large end downstream (polarity)
	Cat, Wolf, Badger, Sheep, Deer	Dentary	Convex/Elongate	Convex up, parallel and perpendicular to flow
	Unspecified	Skull	Elongate	Perpendicular to flow
	Coyote	Innominate	Elongate	Dorsal down, ilia downstream, parallel to flow

Table 2

Expected preferred orientations for generalized bone shapes based on flume trials.

General Bone Shape	Example Bones	Hypothesized Preferred Orientations
Elongate	Humerus, radius, ulna, femur, tibia, fibula, etc.	Parallel to current Perpendicular to current Largest end downstream (polarity)
Convex/concave	Rib fragment, cranial vault fragment, etc.	Convex up/concave down
Flat	Turtle plastron, scapula without a spine, etc.	Flat on the bed

Table 3
Published studies that seeded skeletal material in natural fluvial systems, including the taxa seeded, and the (approximate) sample sizes.

Citation and Page Number	Taxa	Approximate Number of Seeded Bones	Number of Samples Recovered
Aslan and Behrensmeyer 1987	Mammal bones	Not reported	141
Aslan and Behrensmeyer 1996	Cow and Horse	311	142
Behrensmeyer 1975:496	Large bones, Cow	Not reported	Not reported
Bickart 1983	Rock Dove (*Columba livia*), Ring-billed Gull (*Larus delawarensis*), and Herring Gull (*larus argentatus*)	28 Carcasses	Not reported
Bickart 1984	Rock Dove (*Columba livia*), Ring-billed Gull (*Larus delawarensis*), and Herring Gull (*larus argentatus*)	28 Carcasses	11 partial or complete carcasses
Frison and Todd 1986	Indian Elephant (*Elephas maximus*)	23 (in 6 trials)	23
Hanson 1980	Domestic cattle	120	42
Harris 1978	Cattle	Smashed cattle bones	8
Korth 1978	Owl Pellets	Not reported	0
Korth 1979	Owl Pellets	Not reported	0
Schick 1984	Bones from the african landscape (see appendix)	296 (in 14 trials)	71 (from 11 of the 14 trials)
Schick 1986	Bones from the african landscape (see appendix)	296 (in 14 trials)	71 (from 11 of the 14 trials)
Schick 1987	Bones from the african landscape	Not reported	Not reported
Van Orden and Behrensmeyer 2010	Cow, Horse, Goat	Not reported	Not reported
This study	Deer, Elk, Pronghorn, Bison, Cow, Pig, + misc. medium sized mammal bones	6000+ (in 8 trials)	226

Table 4
The names, locations, approximate lengths, and number of visits to each river surveyed for naturally occurring skeletal material.

River	Location	~ Length Surveyed (km)	Dates of Visitation
Huzzah Creek	Missouri	4	5/22/2005
Tributary of the El Kejanero River	Kenya	0.7	7/27/2005
Unnamed Lugga	Kenya	1	7/31/2005
Lugga Maji Chumvi	Kenya	1.7	7/31/2005
Lugga Mbololo	Kenya	1.5	7/31/2005
Hamilton Creek	Missouri	1	5/28/2005
Heimos Cave (stream passage)	Missouri	0.25	7/7/2005
Middle Fork Snoqualmie River	Washington	8	2/26/2006
Caribou River	Canada	0.5	7/21/2007-7/22/2007
Unnamed River, Cave Ridge	Washington	0.5	8/3/2007
Big Beef Creek*	Washington	11	7/28/2009-7/31/2009, 8/8/2011, 7/5/2012-7/6/2012, 8/12/2013
East Fork Sevier River*	Utah	40	9/4/2009-9/6/2009, 5/30/2010-6/8/2010, 8/30/2011-9/5/2011, 6/18/2012-6/19/2012, 5/15/2013-5/22/2013
Levelock Creek	Alaska	3	6/27/2007, 7/13/09-7/22/09, 7/19/2011-7/23/2011
Escalante River	Utah	70	5/8/2012-5/9/2012

*Rivers that were also used for bone seeding trials.

Table 5
The iniation and observation dates of the eight bone seeding trials, and the (approximate) number of bones seeded in each trial.

River	Trial	Initiation Date	Approximate Number of Specimens Seeded	Dates of Observation
EFSR	Trial #1	9/7/2009	55	9/12/2010, 8/31/2011, 6/18/2012, 5/16/2013
EFSR	Trial #2	9/7/2009	112	9/14/2010, 9/15/2010, 9/1/2011, 6/18/2012, 5/15/2013
EFSR	Trial #3	9/7/2009	1429	9/12/2010, 9/13/2010, 8/31/2011, 9/5/2011, 6/18/2012, 5/16/2013
EFSR	Trial #4	9/18/2010	~200	8/31/2011, 6/18/2012, 5/16/2013
EFSR	Trial #5	6/19/2012	3625	5/24/2013
EFSR	Trial #6	6/20/2012	~200	5/20/2013
BBC	Trial #1	8/9/2011	One box (24 x 29x 46 cm) of small fragmentary bones	7/5/2012-7/6/2012, 8/12/2013
BBC	Trial #2	7/6/2012	~200	8/12/2013

Table 6
The total number of bones and articulated units found in each river surveyed, and number of observations providing useable orientation data

River	Articulated Units	Number of Articulated Units with Useable Orientation Data	Isolated Bones	Number of Elongate Bones with Useable Orientation Data	Number of Convex Bones with Useable Orientation Data
Huzzah Creek	3	0	1	0	0
Tributary of the El Kejanero River	0	0	5	0	0
Unnamed Lugga	0	0	9	0	0
Lugga Maji Chumvi	0	0	6	0	0
Lugga Mbololo	1	0	8	0	0
Hamilton Creek	0	0	1	0	0
Heimos Cave (stream passage)	0	0	1	0	0
Middle Fork Snoqualmie River	0	0	1	0	0
Caribou River	0	0	2	0	0
Unnamed River, Cave Ridge	0	0	1	0	0
Big Beef Creek	1	0	3	1	0
East For Sevier River	1	1	216	82	62
Levelock Creek	28	4	322	67	25
Escalante River	0	0	10	3	2

Table 7
The number of bones recovered from each bone seeding trial each year.

			Year of Observation			
River	Trial	Initiation Date	2010	2011	2012	2013
EFSR	Trial #1	9/7/2009	25	2	0	0
EFSR	Trial #2	9/7/2009	75	0	0	0
EFSR	Trial #3	9/7/2009	76	18	0	2
EFSR	Trial #4	9/18/2010	-	16	5	0
EFSR	Trial #5	6/19/2012	-	-	-	0
EFSR	Trial #6	6/20/2012	-	-	-	3
BBC	Trial #1	8/9/2011	-	-	1	0
BBC	Trial #2	7/6/2012	-	-	-	3

Table 8
Observed published bone hydration rates. From Evans (2013b, figure 6.2)

Citation	Time to Saturation or Sinking
Behrensmeyer 1973:31-32, figure 2	Hours, 70+ hours (time to saturation)
Behrensmyer 1975:485, figure 2, p. 486	Hours, 70+ hours (time to saturation)
Coard and Dennell 1995:442	5 to 7 days (time to saturation)
Dodson 1973:18	Few days to a month (time to sinking)
Gnidovec 1978:18, 20, table 3, p. 19, figure 8, p. 21	8 to 83 hours (time to sinking)
Gutierrez and Kaufmann 2007:155, figure 2, p. 158	Hours (time to saturation)
Trapani 1996:82-83, table 6.1, p. 84	2-13 days (time to saturation)
Young 1989:12,49	Bones released gas for over half an hour
Personal Observation	2.5 months (time to sinking)

Table 9
Reported observations of floating bones, including the elements, taxa, duration, and type of water remains were in. From Evans (2013b, figure 6.1)

Citation and Page Number	Floating Bones	Taxa	Duration of Floatation	Observation Made In
Alley 2007:39, 40, 42	Ribs, thoracic vertebrae, and articulated vertebrae	Pig (*Sus scrofa*)	1-2 weeks	Standing Water
Ayers 2010:37, table 3, p. 27, table 5, p. 35, appendix C, p. 82, 83, 92	Vertebra, phalanx, other bones	Pig (*Sus scrofa*)	1-2 days	Standing Water
Behrensmeyer 1973:31	Foot bones and vertebrae	Not reported	Hours	Standing Water
Behrensmyer 1975:485	Foot bones and vertebrae	Not reported	Hours	Standing Water
Boaz and Behrensmeyer 1976:57, figure 2	Cranium	Human (*Homo sapiens*)	Not reported	Flume
Coard 1999:1371	Thoracic and lumbar vertebrae, ribs, and sacrum	Mouflon sheep (*Ovis musimon*), Pig-tailed macaque (*Macaca nemestrina*), Alsatian dog (*Canis familiaris*)	7-30 meters	Flume
Coard and Dennell 1995:447	Cranium	Pig-tailed macaque (*Macaca nemestrina*)	Not reported	Flume
Dodson 1973:18	Nearly every bone in the body	Mouse (*Mus*) and Frog (*Rana*)	Few days (mouse), month (frog)	Standing Water
Evans 2010b:28	Not reported	Not reported	Month and a half	River, standing water
Frison and Todd 1986:67	Smaller elements'	Indian elephant (*Elaphas maximus*)	Minutes	River
Gnidovec 1978:18, 20, table 3, p. 19, figure 8, p. 21	Not reported	Mammals, birds, and herps	3 hours	Standing Water

Table 9 Continued

Gutierrez and Kaufmann 2007:155, figure 2, p. 158	Lateral tuberosity, head, distal epiphysis of humerus, femur, caudal vertebrae, sacral vertebrae, and others	Guanaco (*Lama guanicoe)*	Several hours	Standing Water
Kaufmann et al. 2011	Many, see Tables 1-3	Guanaco (*Lama guanicoe)*	Minutes	Flume
Morden 1991a:77	Cervical vertebra, thoracic vertebra, ribs, calcaneus, and metacarpal	Human (*Homo sapiens*)	5 days	Standing Water
Trapani 1996:116, 148	Cranium, most bird bones	Pigeon (*Columbia livia*)	Not reported	Flume
Trapani 1998:481, and table 1, p. 480	Cranium	Pigeon (*Columbia livia*)	Not reported	Flume
Voorhies 1969:67, text and footnote	Sacrum and sternum	Sheep, coyote (species not reported)	Not reported	Flume
Personal Observations	Nearly every bone in the body	Mammals, birds, frogs, salamanders, snakes, lizards	Seconds to 2.5 months	Buckets, rivers, settling columns, etc.

Appendix A: Collection of Orientation Data in the Field

Recording bone orientation data at the time of specimen collection is of paramount importance because once remains are collected their relative and absolute orientation information is permanently destroyed (Rogers, 1994). If orientation data are not collected, those data are irrevocably lost, preventing any future orientation analysis (Rogers, 1994).

Skeletal elements are three dimensional, thus a full description of their orientation includes at least three pieces of information. Written descriptions can be used by describing the direction in which three surfaces, ends, or parts face. These three orientation descriptions should be (approximately) mutually orthogonal. This method gives the investigator a qualitative description of bone orientation and is often satisfactory for answering some historical questions. More preferable than qualitative descriptions is the collection of quantitative orientation data. Traditionally, quantitative data has included measuring the trend and plunge of elongate bones with a compass (See Rogers, 1994:53, figure 3.3); (data taken with an azimuth compass makes data analysis easier than data taken with a quadrant compass), or the strike and dip of flat bones, and describing which side of a bone is facing up or down (Hunt, 1978; Rogers, 1994; Toots, 1965a). Again, the direction description should be approximately mutually orthogonal to the two measurements. Often a fourth descriptor is also needed, such as which side of a bone is up (e.g., lateral, medial, anterior, posterior, etc.). This method quantitatively constrains the orientation within two dimensions with a qualitative third and/or fourth descriptor, which is satisfactory for nearly all analyses a skeletal assemblage can be

subjected to. Consequently, it is prudent to measure the strike and dip or trend and plunge (whichever is appropriate) of as many bones as is reasonable given the irregular shapes of some bones and bone pieces because having a larger sample size strengthens the inferred conclusions. In addition, some bones provide different kinds of orientation data, for example, long bones provide orientation and polarity data, while convex bones only provide preferred orientation data.

When measuring the long axis of skeletal material, it is important to develop, explicitly state, and report the polarity conventions used during measurement (Toots, 1965b:220-221). Elongate bones (e.g., femora, tibiae, humeri, radioulnae, etc.) have distinct long axis orientations, however, reporting only an azimuth does not inform the reader which end faces which direction. The function of having a uniformly measured and reported polarity convention (e.g., measure tibiae orientations from distal to proximal ends) is to inform the reader which bone end faces which direction given your data presentation technique.

Similarly, it has been suggested that convex bones adopt a preferred orientation (convex up) when exposed to a current (Dodson, 1973; Elder, 1985; Gifford, 1977; Gifford and Behrensmeyer, 1977; Trapani, 1996, 1998; Voorhies, 1969). Presently there is no method for ‘measuring’ convex bone orientations, therefore, if convex bones are encountered (ribs, dentaries, etc.), a written description of the bone orientation suffices, noting if the convex surface is up or down.

In some instances, bones have parts (scapular spines, neural spines, etc.) or features (neurals on a turtle carapace) that have measurable orientations. In these cases,

bone orientations can be described in words, the orientation of identifiable parts measured, and the measurement method recorded. While orientation information on irregularly shaped bones is presently not useful for fluvial interpretations, such orientation information could be useful for future spatial analyses, thus this information should be collected and archived if possible.

When irregularly shaped bones (vertebrae, ribs, etc.) or bone fragments are encountered without distinct measurable long axes, a written orientation description is sufficient, because presently there is no way to correlate flow direction with the orientation of bones that are not elongate or convex.

Appendix B: Presentation of Skeletal Element Orientation Data

During field data collection, it should be apparent if the skeletal assemblage under study is within a horizontal or dipping plane. If the assemblage has a strong dip or plunge component (greater than approximately 10 degrees), then a method capable of presenting three dimensional data should be used (stereonet). Assemblages with little dip or plunge (less than approximately ~10 degrees) can be presented using a two dimensional presentation method (Fiorillo, 1988a), preferably a corona dot diagram or similar plot (Wells, 2000).

Three dimensional data should be plotted on a stereonet (Supplementary Figure B.1). A discussion of how to plot points on a stereonet is outside the scope of this review, though such a discussion is unnecessary since free software packages can be downloaded to graph data sets, or the interested reader can access one of the many textbooks (Johari

and Thomas, 1969; Lyman, 1994:181-183) or on line tutorials on the subject. Knowing when to use a stereonet to display the data and how to interpret the data is the primary focus in this appendix. A stereonet should be used whenever an assemblage has a significant dip or plunge component: usually greater than approximately 10 degrees. Plot all data sets on 360^{o} stereonets, rather than 180^{o} (half) plots, because bone polarities and preferred orientations are easier to identify on complete stereonets (Robson, 1994; Fiorillo, 1988a). Once a data set is displayed, a brief visual assessment shows any major preferred orientations; using a stereonet rather than a rose diagram makes the identification of preferred orientations easier (Fiorillo, 1988a:3, figure 2; Toots, 1965a; Voorhies, 1969:9, figure 9; Yamaji and Masuda, 2005:518, figure 7). If cryptic trends exist, then density contour maps may be useful to help identify any preferred orientations (Dominguez-Rodrigo et al. 2012: 2119-2120, figures 2 and 3; Eberth et al., 2007:303, figure 5.12; Fiorillo, 1987:29, figure 11b, 31, figure 13b; Fiorillo, 1988a:3, figure 2b; Fiorillo, 1988b:65, figure11b, 67, figure 13b; Scherzer and Varricchio, 2010:792, figure 14; Yamaji and Masuda, 2005:517, figure 5), however, if a density contour map is needed then any trends that exist may not be of any interpretive value.

Previous authors have described five idealized assemblages with identifiable orientations and depicted how each assemblage would look on a stereonet (Fiorillo, 1987, 1988a, b; Lyman, 1994; Rapson, 1990; Toots, 1965a, b). Supplementary Figure B.1 displays these five orientation types: random orientation, flat lying, one preferred orientation, perpendicular orientations, and vertical. On a stereonet, an assemblage that displays no preferred orientation is plotted with a random distribution of points across the

diagram (Figure 1a, Fiorillo, 1987:21, figure 9e; Fiorillo, 1988a:2, figure 1e; Fiorillo, 1988b:64, figure 9e; Lyman, 1994:182, figure 6.8d; Rapson, 1990:152, figure 22a; Toots, 1965a:59, figure 1a; Toots, 1965b:220, figure 2a; see also Shipman, 1981:74, figure 4.3; Shipman et al. 1981:66, figure 7), while a flat lying assemblage will appear as a ring around the stereonet rim (Figure 1b, Fiorillo, 1987:21, figure 9a; Fiorillo, 1988a:2, figure 1a; Fiorillo, 1988b:64, figure 9a; Lyman, 1994:182, figure 6.8b; Rapson, 1990:152, figure 22b; Toots, 1965a:59, figure 1b; Toots, 1965b:220, figure 2b). An assemblage with a single preferred orientation is represented as two clusters of points on opposite sides of the stereonet (Figure 1c, Fiorillo, 1987:21, figure 9c; Fiorillo, 1988a:2, figure 1b; Fiorillo, 1988b:64, figure 9c; Lyman, 1994:182, figure 6.8c; Rapson, 1990:152, figure 22d; Toots, 1965a:59, figure 1c; Toots, 1965b:220, figure 2d; see also Shipman, 1981:74, figure 4.3; Shipman et al. 1981:66, figure 7), and mutually perpendicular orientations appear as four clusters of points approximately 90^{o} apart (Figure 1d, Fiorillo, 1987:21, figure 9d; Fiorillo, 1988a:2, figure 1c; Fiorillo, 1988b:64, figure 9d; see also Shipman, 1981:74, figure 4.3; Shipman et al. 1981:66, figure 7). A preferred vertical orientation appears as a cluster of points in the center of the stereonet (Figure 1e, Fiorillo, 1987:21, figure 9b; Fiorillo, 1988a:2, figure 1d; Fiorillo, 1988b:64, figure 9b; Lyman, 1994:182, figure 6.8a; Rapson, 1990:152, 22c; Toots, 1965b:220, figure 2c). Other patterns are possible, but these idealized examples are most frequently described as expected. It should be noted that while these patterns are commonly expected, there is presently no concrete causal linkage between these preferred orientations and depositional processes.

Two dimensional data should be plotted on a corona dot diagram (Supplementary Figure B.2a, b) or similar plot (Wells, 2000). Corona dot diagrams are the two dimensional equivalent of a stereonet plot, with each data point plotted independently in one degree increments (no binning of data), which produces unique, non-arbitrary data presentations (Supplementary Figure B.2a, b). Briefly, a corona dot diagram is created by plotting the azimuth of a bone as a point an arbitrary distance from the origin on a Euclidean plane. For consistency, points can be assigned an arbitrary distance from the origin and any additional points with the same azimuth are plotted further out from the original arbitrary radius. Plotting is performed using polar coordinates converted to Euclidean ordered pairs (see below for detailed instructions). When using such a plot, preferred orientations are easily observed, no artifacts of data binning are introduced (Wells, 2000), and individual data points can be observed to give the investigator a realistic view of the data quality and any trends. Additionally, circular statistics can easily be calculated including measures of central tendency and variance (Andreassen, 1990; Krause and Geijer, 1987; Robson, 1994). Furthermore, different bones or data sets can be plotted with contrasting symbols, colors, or radii, allowing visualization of multiple trends based on skeletal element type or data set, which are two significant advantages over rose diagram use. For an excellent description of how to construct corona dot diagrams, see Wells (2000).

The use of rose diagrams to depict bone orientation data should cease because other more accurate and precise options are available (Wells, 2000). Since rose diagrams cannot depict dip or plunge data, information is lost when presenting three dimensional

data on a rose diagram (Toots, 1965b:220-221). Additionally, rose diagrams can only present orientation data in two dimensions (Toots, 1965a, figure 1, p. 59), and can do so only by binning data, which makes the final product an arbitrary data representation (Wells, 2000). Binning data causes problems during analysis since the bin sizes (how many degrees are in each bin or the petal width) and the bin starting numbers alter the resulting rose diagrams (Andreassen, 1990; Wells, 2000). It is possible to build 811 different rose diagrams with the same data (Wells, 2000), many of which look entirely different than the others (Supplementary Figure B.2c-r, Andreassen, 1990:628, figure 1; Wells, 2000:38, figure 1). There is enough ambiguity inherent in the creation of some rose diagrams to render them essentially useless during data interpretation (Wells, 2000). In addition, many rose diagrams are built incorrectly (Nemec, 1988; Wells, 2000), demonstrating that the method is both difficult to apply correctly and is less versatile and precise than corona dot diagrams. Since an alternative to rose diagrams is available (corona dot diagrams) without the flaws of rose diagrams, rose diagrams should no longer be used to present bone orientation data.

Finally, convex bone orientation data can be depicted easily on bar charts by plotting the absolute number or total percent of bones found convex up and convex down.

Plotting Azimuth Data

Plotting measured azimuth data in Cartesian space is a two step process: first, azimuths must be converted to polar coordinate degrees; and second, the polar coordinate degrees and an arbitrary radius must be converted to an ordered pair (x,y). Presented here is the math to perform this conversion manually to facilitate presentation in common

graphing programs (Excel), though some graphing programs will conduct this conversion automatically.

Azimuths are measured on a scale that starts from an arbitrary zero point, which is due north, or the positive y-axis on a Cartesian plane, with degrees increasing clockwise. Polar coordinates are also measured on a scale with an arbitrary zero point, however, that zero point is due east, or the positive x-axis on a Cartesian plane. Additionally, polar coordinate degrees increase moving counterclockwise. Since bone orientations are measured in azimuths, the angle measurement must be converted to polar coordinates to facilitate graphical presentation. The equation to convert azimuths to polar coordinate degrees is:

Eq. (A.1) $PCD = -A + 90^{o}$

Where PCD is polar coordinate degrees and A is azimuth (compass bearing).

Once azimuths are converted to polar coordinate degrees, each bone orientation now has the form of a polar coordinate; an ordered pair of direction (in degrees), and a radius (in this case the radius is arbitrary). To convert the polar coordinates to a Cartesian ordered pair, use the following two equations:

Eq. (A.2) $X = R\cos\theta$

Eq. (A.3) $Y = R\sin\theta$

Where R is the arbitrary radius, and θ is the polar coordinate degrees.

When plotting bone orientations on a corona dot diagram, assign all azimuths the same arbitrary radius (1, .1, whatever improves presentation). Additional points with the same azimuth should be assigned a longer radius. The convention used in this article is to

assign an arbitrary radius (0.1), then additional azimuths are assigned a 10% longer radius (0.11, 0.12, 0.13, etc.). Adjust the radii to generate a pleasing figure.

In Excel this process is easily accomplished in five columns with the equations in Supplementary Figure B.3. Using this format, the user can quickly alter the radius (R) of any point to facilitate the creation of corona dot diagrams by altering the radius of points with the same azimuth. The corona dot diagrams presented here were created using this method. In columns D and E the polar coordinate degrees are multiplied by □/180 to convert degrees to radians since Excel performs trigonometric functions in radians.

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CHAPTER FOUR

A CRITICAL ASSESSMENT OF THE ANALYTICAL USEFULNESS OF BONE SHAPE AND DENSITY FOR INFERRING FLUVIAL TRANSPORT

Contribution of Authors and Co-Authors

Manuscript in Chapter 4:

Author: Thomas Vincent Evans

Contributions: Provided the idea, provided near full funding through donating personal funds to support the research, performed the fieldwork, data analysis, writing, made all figures and tables, and proofread the final draft.

Manuscript Information Page

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The Paleontological Society

A critical assessment of the analytical usefulness of bone shape and density for inferring fluvial transport

Thomas Evans

Abstract

A common technique for inferring the fluvial transport of skeletal material is to qualitatively observe the shapes/sizes and density of bones in fossil or archaeological assemblages and develop interpretations based on the assumptions that smaller less dense bones move faster and farther in rivers than larger and denser bones. To test these assumptions, twenty-four bones from an adult domestic sheep (*Ovis aries*) were cast multiple times with a range of densities and seeded in three rivers: East Fork Sevier River, Utah; Levelock Creek, Alaska; and Big Beef Creek, Washington. Cast transport and deposition were tracked over space and time at annual intervals. In total, 3,686 bone casts were seeded in five trials, 520 casts were recovered for a total recovery rate of 14.1%. No visually apparent relationship was observed between bone cast shape and transport distance, while a weak relationship existed between bone cast density and transport. Denser casts of the same shape moved shorter distances than less dense casts, however, there was substantial overlap in the transport distances between low and high density casts of the same shape. The weak relationship between bone density and

transport may not be analytically useful because natural bones constantly change density through decay (grease loss and breakdown) and hydration. Thus, conservatively, bone shapes and densities should no longer be used to infer the transport and deposition of skeletal remains by rivers and a new technique should be developed and validated.

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Introduction

It is common at the beginning of a paleontological or archaeological skeletal assemblage analysis to determine if the remains under study were transported or reoriented by flowing water. If remains have experienced some fluvial transport or reorientation, then a taphonomic history reconstruction is needed to determine the temporal and spatial resolution of the assemblage (Badgley 1982; Behrensmeyer 1982a, 1982b; Behrensmeyer and Chapman 1993; Rogers 1993; Aslan and Behrensmeyer 1996) or to identify if any human behavioral information is still present in the locations and orientations of the remains (Turnbaugh 1978; Petraglia and Potts 1994). Historically, two common techniques have been used to assess fluvial interactions with remains, bone orientations (Voorhies 1969; Lyman 1994) and inferences based on the shape and density of individual skeletal elements recovered (Gifford 1981: pp. 401, 420-423; Shipman, 1981: pp.28-41; Dechant-Boaz 1982: p.63; Koster 1987; Behrensmeyer 1990: p. 233, 1991: p. 323; Lyman 1994: pp. 176-178; Rogers and Brady 2010: p.98). Bone orientation

analysis is thoroughly treated elsewhere (Evans submitted), so the focus here is the effects of shape and density on bone transport and deposition in fluvial systems. Generally it is assumed shapes that present less hydrodynamic surface area (smaller) and less dense (often stated as lighter) bones move farther and faster downstream (e.g., Rogers and Brady, 2010: p. 98). Neither of these intuitive assumptions have been directly tested, although these assumptions have been used for decades in the fields of paleontology (Wolf, 1973: p. 97; Hood and Hawksley 1975: pp. 11, 14; Rich 1980; Stojanowski 2002: p. 262; Work et al. 2005; Rogers and Brady 2010), archaeology (Benito-Calvo and de la Torre 2011; Morden 1991), and forensic science (Haglund and Sorg 2002; Evans 2013a). Therefore, a validation study is needed to determine if bone shape and density *primarily* control fluvial transport and deposition. And if so, is the relationship between shape or density and transport strong enough that it can be utilized to interpret paleontological or archaeological assemblages.

If a validation study determines that shape and density do indeed correlate with fluvial transport potential and the effects are large enough to use analytically, then no problem exists for present analytical practice because bone shape and density can be relied upon to provide consistent bone transport behaviors in fluvial systems. However, if bone shapes and densities do not provide consistent enough transport and deposition behavior in fluvial systems, then using bone shape and density to interpret skeletal assemblages would increase the analytical error of the assemblage analysis to an unknown extent. Consequently, if density and shape are not reliable predictors of bone fluvial transport behaviors, then present analytical practices in paleontology and

archaeology should change to reflect the new understanding of fluvial bone transport processes.

To test the two null hypotheses that there are strong enough relationships between bone shape and transport potential, and bone bulk density and bone transport potential to use analytically, bones from an adult domestic sheep (*Ovis aries*) were cast hundreds of times with variable densities and seeded in three natural river systems. The bone casts were tracked over space and time, and their transport distances plotted versus bulk density to reveal any relationships.

Background

Because of the logistical difficulties and frequent unpleasant odors associated with bones in water, little fluvial bone transport research has been performed in natural river systems with natural bones. Of those studies that have been performed by seeding skeletal material in rivers (Table 1), none have reported the density of the bones seeded in and recovered from rivers and the only shape information we have are the bone names, only sometimes in conjunction with the species they came from and their ontogenetic stage. Similarly, since few remains have been recovered from most river seeding trials (Table 1), the conclusions that can be drawn related to the effects of bone shape on transport are minimal and amount to a series of anecdotes (Table 1, Schick 1984, 1986; Frison and Todd 1986; Aslan and Behrensmeyer 1996). Generally authors report that smaller and lighter bones move faster and farther than larger and heavier bones (Table 1, Schick 1984, 1986; Frison and Todd 1986; Aslan and Behrensmeyer 1996). Similarly,

compact bone fragments move less than bone fragments with cancellous bone (Aslan and Behrensmeyer 1996; Dominguez-Rodrigo and Garcia-Perez 2013; Dominguez-Rodrigo et al. 2014). While these generalizations are intuitive, authors also noted that the variables size and density/mass are not sufficient to explain bone transport because light and heavy bones were frequently observed moving similar distances over the same time (Aslan and Behrensmeyer 1996). Bones were also frequently observed partially or completely buried (Aslan and Behrensmeyer 1996) or otherwise interacting with the bed (Bickart 1984; Schick 1984, 1986; Frison and Todd 1986), which dramatically altered bone transport, suggesting that interactions with the bed may be important during bone transport and deposition. Ultimately authors noticed that the heterogeneity in natural systems (e.g., changes in flow and bed conditions) interacted with bones in complex ways altering transport and deposition (Hanson 1980; Schick 1984, 1986). Because of the complexity of natural systems, small number of recovered samples, and that the variables size and mass are not equivalent to shape and density, it is difficult to develop hypotheses based on these anecdotal data sets. As such, flume derived data provides nearly all of the data used to infer the effects of shape and density on bone transport.

Voorhies (1969) performed the first flume trials utilizing skeletal material. After 15 flume trials with disarticulated skeletons of a sheep and a coyote, he divided the bones into three groups representing the most transportable (group 1), somewhat transportable (group 2), and least transportable (group 3). At no point does he attempt to explain causally why each bone ends up in each group, though he does note that some bones float, which cause them to end up in group 1. It is difficult to identify patterns in the

skeletal composition of each group because bones have variable shapes, different densities/masses, and a range of sizes. Unfortunately no raw data was published, so the sizes, densities, and masses of the bones are unknown. In addition, the age (juvenile or adult) of specimens was also not reported, as well as the preparation technique (e.g., boiling or beetle cleaning). Because preparation technique can alter bone density, the lack of reporting preparation technique further clouds the initial state of the samples. What is clear is that Voorhies never discusses density or shape in regards to bone transport potential. So the groups are not equivalent to shape and density categories because we do not know what the densities were of the bones utilized or how they changed during flume trials (through hydration and/or grease loss). As such, this pioneering work can only hint at density and shape as controlling variables in bone transport, which is not unexpected because Voorhies primarily described bone orientations caused by fluid flow and not the transport of skeletal elements. It was left to later researchers to explicitly investigate the effects of shape and density on bone transport.

Numerous authors have noted a correlation between bone shape and fluvial transport potential utilizing flume trials. Morden (1991) observed human bone transport in a flume and noted that bone shape was somewhat important in determining transport potential, particularly for bones greater than 10 g in mass. Coard and Dennell (1995) reported articulated skeletal units moved faster than isolated bones in a flume, suggesting that the shape of the transported object alters transport potential, a result also found by Trapani (1996, 1998). Similarly, Coard (1999) found that articulated skeletal units were more transportable than single bones, which was explained by the bigger shape projecting

higher into the flow and experiencing greater flow velocities (more accurately, greater bed shear stress).

Other authors have reached opposite conclusions however. For example, Boaz and Behrensmeyer (1976) reported broken human bone transport in a flume was primarily governed by density and not shape, because shapes were idiosyncratic and hydrodynamic shape was largely a function of bone orientation. Similarly, Trapani (1996, 1998) concluded that metrics of bone shape did not correlate with bone transport behavior however he did note that shape did alter transport behavior for numerous bones. Blob (1997) also found no correlation between bone shape and transport potential using turtle remains in a flume, largely because of orientation effects. Conversely, he noted shape does matter for the transport of irregularly shaped bones.

Other authors have suggested bone density is more important in determining bone transport potential than shape. Dodson (1973) found that changes in buoyancy (a function of density) yielded considerable differences in transport potential, often in the form of floatation. Behrensmeyer (1973, 1975) concluded that density is more important in determining bone transport behavior than size and shape, though she noted that shape becomes important for skeletal elements with high surface area to volume ratios (e.g., scapulae and ribs). Similarly, Boaz and Behrensmeyer (1976) found that bone density was a better predictor of bone transport potential than shape. Blob (1997: p. 159) reported that density had a greater influence on transport potential than shape while investigating the fluvial transport of turtle remains. In manipulative trials, Morden (1991) observed that mass was the best indicator of bone transportability, with density important in the

transport of bones greater than 10 g. Coard (1999) reported that dry bones moved faster than saturated bones (largely due to floatation), which suggests that density is important in governing bone transport. It was noted that density was one of a number of variables that also partially predicted bone transport behavior. Pante and Blumenschine (2010: p. 851) found lower density epiphyses were transported at lower current velocities than higher density epiphyses. Likewise, Kaufmann et al. (2011) investigated the effects of hydration and animal age on transport potential. They found that more water saturated (denser) bones traveled slower and shorter distances than dry bones.

Results of the preceding flume studies (a synopsis of which is in Table 2) have unknown applicability to the real word because the simplifications inherent in using a laboratory flume may make the results unrealistic (Dominguez-Rodgrigo et al. 2014). Natural river systems are heterogeneous with nearly constantly changing conditions (e.g., slope, discharge, bed composition, etc.). Using flumes with uniform smooth beds (Morden 1991; Coard and Dennell 1995; Blob 1997; Pante and Blumenschine 2010; Kaufman et al. 2011) with no slope (Boaz and Behrensmeyer 1976; Morden 1991: Coard and Dennell 1995; Coard 1999) is not analogous to natural fluvial systems with variable composition and size bed loads. Similarly, running flumes with a constant discharge in a uniformly shaped channel produces relatively homogenous bed shear stresses, a condition which is rarely found or sustained in natural fluvial systems with variable depth, discharge, and channel morphology. In addition, many of the flume trials soaked their samples until they became saturated (Boaz and Behrensmeyer 1976; Coard and Dennell 1995; Trapani 1996, 1998; Blob 1997; Coard 1999; Pante and Blumenschine 2010), thus

reducing sample transport potential variability. Natural skeletal material hydrates at variable rates, often slowly hydrating over weeks and months. Consequently, results from flume trials utilizing uniform conditions and artificially homogenous samples may not yield results that can be extrapolated to the real world without significant error.

As a result of the reviewed research, the assumptions that correlations exist between bone shape and density and transport potential has permeated the historical science community with the result that authors have uncritically utilized these assumptions to analyze skeletal assemblages. Even important and high profile assemblage analyses have been performed using these assumptions overtly, for example in paleoanthropology (Louchart et al. 2009), archaeology (Benito-Calvo and de la Torre 2011), and paleontology (Eberth 1990: p. 15). While these assumptions seem intuitive, without validation, there is no a priori reason why they should accurately reflect the behavior of bones in natural fluvial systems. Therefore, a validation study is necessary to determine if there is a relationship between fluvial transport potential and bone shape (with constant size and density), as well as between transport potential and bone density (with constant shapes), to determine if the relationships are strong enough to use analytically.

The research presented here is a suite of hypothesis driven empirical trials that held density constant and compared transport potential between different bone shapes and in the same trials held bone shape constant and compared transport between different densities. By utilizing efficient empirical research design, two hypotheses could be tested simultaneously, thus leveraging physical resources and field time.

Field Localities

The choice of rivers used was based on three factors: 1. A river small enough that working in the river would not present a prohibitive risk of drowning, 2. A river large enough that transport was likely to occur in the timeframe of a PhD thesis, and 3. The river was owned by one entity, making permitting long stretches of river logistically possible. Three field localities met these criteria: the East Fork Sevier River, Utah; Levelock Creek, Alaska; and Big Beef Creek, Washington.

The East Fork Sevier River (EFSR, Fig. 1A), Utah is free flowing on Forest Service land in the drainage on the west side of Bryce Canyon National Park. The permitted reach (Special Use Permit# PWL018901) extends from the headwaters in the south to the Tropic Reservoir in the north for a total of approximately 40 km (25 miles). Seeding trials took place in the reach between the Podunk Guard House and approximately 600 m (2,000 ft) upstream of the established campsite #9 (see Fig. 2A). The headwaters of the EFSR is straight and channelized and displays chute and pool morphology with a coarse sand to gravel bed. Down valley, the river begins to meander, the channel widens, deepens, and the bed composition becomes sandy to muddy. Seeding trials took place in reaches that were transitional between a sand and gravel bed to a mud and sand bed. When seeding trials were initiated in the early or late summer the flow was low, between roughly 5 and 10 cfs. Generally the river has a low discharge in the winter due to constant snow cover, but rises in the late spring during snow melt, then falls by the middle to end of the summer once the snowmelt has run off. During storms or rainfall events the river rises gradually, and is not prone to flash flooding.

Levelock Creek (LC. Fig. 1B), Alaska is a highly sinuous sand to gravel bed river, flowing through land owned by the Levelock Village Council. Research was performed under Alaska Department of Natural Resources land use permit# LAS27208, with access permission through the Levelock Village Council. The seeding trial was initiated at the downstream end of the foot bridge crossing the creek on the north side of the Levelock Airstrip and ran to the confluence with the Kvichak River, Alaska (approximately 3 km, or 2 miles) (see Fig. 2B). Generally the river flows with between about 10 and 100 cfs as it drains a saturated portion of tundra. During periods of constant rainfall the river fills to bank full with a slow rise and fall in discharge.

Big Beef Creek (BBC, Fig. 1C), Washington flows through the Big Beef Creek Research Station owned by the University of Washington. Permission to use the facility was granted by the research station manager. BBC is a gravel to cobble bed braided river with episodic seasonal flow. The seeding trial was initiated a few hundred feet upstream of the USGS gauging station on the river and extended to the confluence with the Hood Canal (see Fig. 2C). During summer months discharge is low, around 4 to 8 cfs, and flow increases with fall and winter storms. In winter months discharge is high averaging around 100 cfs, but rises to ~1,500 to ~2,100 cfs during large winter storms. Discharge falls in April, May, and June back to low summer flow. Detailed flow data can be obtained from the USGS from the Big Beef Creek, near Seabeck Washington gauging station (#12069550).

Materials and Methods

An adult domestic sheep (*Ovis aries*) was killed as part of normal herd maintenance at Fort Ellis, a Montana State University research farm. The body was flensed, the bones dried, and cleaned with dermestid beetles. After washing and drying, twenty-four bones were selected that represent a range of sizes and shapes that were easy to cast (Table 3). Each bone was molded and cast numerous times. The primary casts of each bone were then used to make production molds that made it possible to pour many casts of each bone at the same time. Production molds were used to make hundreds of casts of each bone. Three cast recipes were used to create a light, medium, and heavy suite of bone casts. However, because it was impossible to achieve even mixing of casting resin and the additives, a range of cast densities were produced rather than three consistent densities. Instacast casting resin was used incorporating silica additives to modulate cast density and atomized steel was added so casts could be recovered, even if buried, utilizing a metal detector.

In the field, a datum point was established for each seeding trial then casts were placed in arrays on the river bed with known initial locations (relative to the datum) and orientations (Fig. 3). The casts seeded in each trial and the recipes used to make them are reported in Table 4. Rivers were observed annually; casts were searched for visually and with a metal detector from the datum point downstream until a major competence drop was reached (ocean, beaver dammed lake, etc.). When casts were found data was recorded on bone location (tape measure deployed in the thalweg from a known datum point), orientation (measured and described), burial, geomorphology at location of

deposition, sediment description, bed forms, flow direction, water depth, presence of obstructions and woody debris, pictures were taken, and the casts collected. The year trials started, the number of casts seeded, when observations occurred, and how many casts were recovered at each observation is presented in Table 5. For clarity, the term "trial" indicates a group of casts seeded in a river simultaneously, while the term "observation" is used to denote the data taken at annual intervals on casts in individual trials. Presented here will be the distance of transport relative to shape and density results; the remaining observations will be reported elsewhere.

In the lab, recovered casts were washed, dried, and weighed. Wet masses were measured by placing casts in a vacuum chamber full of water for 15 minutes at -690 torr; the mass of the cast was measured while suspended in water with a known temperature. Cast bulk densities were calculated using the equation:

$$\rho_c = \frac{D_m}{\left(\frac{D_m - W_m}{\rho_w}\right)}$$ Butler and Chatters (1994).

Where bone cast density is ρ_c, W_m is cast wet mass, D_m is cast dry mass, and ρ_w is water density based on water temperature (CRC Handbook of Chemistry and Physics 2013-2014).

Shape classes for casts were designated as the bone name (i.e., humeri, femora, etc.) because each bone has a unique shape. Rather than utilize common shape classifications that have questionable physical meaning for fluvial bone transport, the unit of analysis is an individual bone shape under the assumption that each bone could potentially behave differently when exposed to a flow.

Cast transport distances were calculated by subtracting the starting location from the end location based on starting and ending distances relative to the trial datum.

During data analysis it was assumed that cast movement was primarily the result of fluvial transport and not a result of other processes. This assumption is probably valid because all three locations are remote however human interaction is more likely for trials in the EFSR. Because the valley the EFSR flows through is used for cattle grazing, hunting, and human recreation, it is possible that other processes moved some or all of the casts. To prevent human and animal interaction with the casts, seeding trials were initiated in locations far away from heavy recreational utilization, but human alteration of the data is still possible.

Ultimately the goal here is to determine if the relationships between bone shape/density and fluvial transport potential are strong enough to use analytically in paleontological or archaeological assemblage analysis. This is a *practical assessment* of the magnitude of an effect, which cannot be measured using conventional statistics. In other words, a calculated statistic is not used when determining if an assemblage has enough light or less dense bones to infer fluvial transport. Rather the analyst makes an informed judgment based on understanding the taphonomic processes operating on an assemblage with an understanding of the magnitude of the effects produced by a taphonomic agent. Numerous examples of this kind of thinking abound in the historical sciences. For example, no statistic is used to determine if a newly excavated fossil is a new species or not; no statistic is used to infer that crosslaminae are ripples; and no statistic is used to determine if an archaeological site is disturbed too much to make

human behavioral inferences. As such, statistical analysis of shape/density data does not provide the information analysts use to interpret skeletal assemblages. Rather, what is needed is a depiction of the magnitude of the effects on transport of bone shape and density. Consequently, rather than calculating descriptive statistics for each data set observed, the raw data is plotted so that analysts can decide if the relationships are strong enough to utilize with their own unique data sets.

Data was subdivided by trial, year of observation, and bone name. By plotting bones that were deployed simultaneously and spent the same amount of time in the river, any environmental effects should be normalized (e.g., all casts experienced the same river discharges, so discharge can be removed as a confounding variable). Plots were made depicting density versus transport distance for both aggregate data and individual classes of bone casts (e.g., femora, humeri, etc.), but only for trials in which there were multiple cast shapes with five or more samples recovered. A minimum of five samples was deemed an absolute minimum sample size to identify a rough transport behavior. Consequently, many recovered casts were not used in density versus transport distance plots because not enough samples were present to provide meaningful comparisons. In addition, comparison plots were made showing the transport distances of individual cast shapes (e.g., bone names) relative to other shapes, utilizing data from casts with similar densities. Samples were divided into three density ranges by plotting the rank order density of each sample and observing the plot for natural breaks in the data. Two natural subdivision points were identified yielding density ranges of 1.10-1.31 g/cm^3, 1.32-1.50 g/cm^3, and >1.50 g/cm^3. Plots were aligned horizontally with the same y-axis so the

relative transport potential of each bone shape could be identified visually. Because of cast loss, the requirement of five or more samples dramatically reduced the number of possible comparisons.

Plots of density versus transport distance were regressed to potentially describe any patterns observed. Linear, logarithmic, exponential, power functions (second through seventh order), LOWESS, and LOESS regressions were calculated in Excel.

Results

Without the benefit of gauging stations at the EFSR and LC the only information available about discharge during the seeding trials was available during site visits. During all seeding events and observations of the EFSR, the flow was low, around 20 to 30 cfs. Otherwise, the summer of 2011 was a wet year for southern Utah, so higher than normal flows were likely. The seeding trial at LC was initiated when flow was near bank full conditions, and the observation took place at low flow, at a few cfs. Discharge at BBC was consistently seasonal with low flows in July and August (20 to 50 cfs), rising in September to around 100 cfs, then falling in the spring.

In total, five river seeding trials were performed, three in the EFSR, one in LC, and one in BBC with a total of 3,686 casts seeded; 520 casts were recovered for a total recovery rate of 14.1% (Table 5). Table 5 also displays the number of seeded casts for each trial, the number of casts recovered at each observation, and the recovery rates of each trial. Supplementary Tables 1-9 present all raw data on bone casts including the

trail, observation, element, density, presence and extent of burial, and transport distance for all bone casts recovered.

Most bone casts were not recovered so their fate is impossible to determine. It is expected that most were simply buried deep enough that they were not located by the metal detector. Two lines of evidence support this interpretation. Between 40% and 100% of casts recovered in a given trial were found with either partial or complete burial, and additional material was found in searched river reaches in subsequent years. Casts found in later years had not moved out of the study reach because they had been buried. Unfortunately patterns of burial in the recovered remains are largely a function of bone size because larger casts were preferentially recovered because they had more iron within them and were easier to locate with the metal detector.

A total of four out of nine observations of all five trials met the criteria of having multiple bone shapes of the same density with five or more casts recovered. For each of these observations, plots were made of the transport distances of each bone cast shape, side by side with the other shapes observed to facilitate direct comparisons. The results are depicted in Figure 4: 1. EFSR Trial #1, 2011 observation, 1.10-1.31 g/cm^3 density casts (Fig. 4A), 2. EFSR Trial #3, 2013 observation, 1.10-1.31 g/cm^3 density casts (Fig. 4B), 3. LC, 2011 observation, 1.10-1.31 g/cm^3 density casts (Fig. 4C), and 4. LC, 2011 observation, 1.32-1.50 g/cm^3 density casts (Fig. 4D). It can be seen by casual observation that bone casts with wildly different shapes but with the same densities, were transported similar distances. This means that bones like scapulae (wide and flat) were transported similar distances to vertebrae (irregularly shaped) and limb elements (primarily elongate).

No patterns of transport are observed based on bone shape between the four observations. The same figure is shown as a series of box and whisker plots which show there is dramatic overlap between the transport potentials between bone shapes with the same density (Fig. 5). As such, no division in transport potential is observed between bone casts with the same density but with wildly different shapes, in fact, there is substantial overlap in transport properties between bone shapes with the same density.

There were a total of nine observations of all 5 seeding trials, and for each observation a plot of bone cast density versus transport distance was made, with each bone shape depicted by a different icon (Fig. 6). Generally a triangular pattern is observed where denser casts move shorter distances than lighter casts which move farther distances. However, it is important to note that even low density casts were observed moving short distances. This trend is best shown in the figures with larger sample recovery (Fig. 6A, 6G, and 6H). To determine if this same trend is observed in the transport of individual shape classes, density versus transport plots were graphed for those observations in which more than two bone shapes were recovered with greater than 5 samples. Figure 7 depicts the results from the EFSR Trial #1, 2011 observation, Figure 8 the results from EFSR Trial #2, 2011 observation, Figure 9 the results from EFSR Trial #3, 2013 observation, and Figure 10 depicts results from LC, 2011 observation. It is clear that the triangular shape is not depicted in all the individual density versus transport plots however those with larger numbers of samples tend to show this relationship. As such, because of small sample sizes, it is unclear if this trend is also observed in the transport of individual shape classes, but Figures 7-10 do seem to suggest this may be the case.

Consequently, it is possible a causal link between bulk density and transport potential exists however there is substantial overlap in the transport behaviors of less dense casts and denser casts making this link weak.

None of the regressions attempted yielded statistically significant correlations, as expected from simple observation of the data plotted in a triangular shape. A single curve is insufficient in describing data in which there are multiple possible y values for a given value of x. For those plots that appear linear, adjusting the y axis values creates a graph of points that are spread out, so the linear appearance is a function of axis choice, not of a relationship between density and transport.

Discussion

Generally smaller casts were recovered at a lower rate than larger casts, which is a trend in recovery observed by those who have performed river seeding trials with natural bones (Aslan and Behrensmeyer 1996; Schick 1984, 1986). Previous authors have attributed bone loss to transport out of the study reach, or burial, and both options are possible here as well. In addition, a third option exists with smaller size leading to lower recovery rates because smaller objects are harder to locate in a flow. Determining which of these three mechanisms is operating is difficult, and ultimately impossible to identify. If casts were transported out of the study reach, visual inspection of the river downstream should produce occasional cast sightings. However, none were found in searches downstream of study reaches, even past large competence drops, often for many miles. This suggests that finding fewer small less dense casts is less likely from transport out of

the system. If casts were transported out of the system they would have been transported miles, and in those miles, no bone casts were observed which suggests shorter transport distances. As such it is more likely that missing casts, including the smaller lighter ones, are simply buried somewhere in the system and are not being found utilizing a metal detector. This interpretation is supported by finding additional material, including some smaller casts, in searched river reaches in subsequent years.

Ultimately, missing casts provide no useful transport information because many possible processes could have removed them from the observed sample. In other words, the equifinality problem inherent in interpreting missing data is sufficient to make any further analysis of these samples superfluous. For example, the size or element bias in recovering larger samples could be attributable to larger material not moving, so they were easier to find. Or their large size made visual relocation much easier. Or larger clasts were temporarily buried but were easier to find with the metal detector, even at greater depths, because they contained more atomized steel than smaller casts. Or larger sizes and shapes made burial more likely (preferential burial) which slowed transport. Similar problems affect interpreting small cast recovery rates. The lack of small casts or specific elements recovered could be due to (1) transport out of the system, (2) burial and lack of relocation with the metal detector (not enough steel), or (3) they were small enough that they were not located on visual inspection. As such, any trends in which casts are recovered can be explained numerous ways, thus constitute an unreliable data set for analytical purposes.

Because no clearly observable difference exists in transport behavior of differently shaped bone casts with the same or different densities (Figs. 4-5), conservatively bone shape alone should no longer be used to infer the past presence or absence of fluvial interaction with a skeletal assemblage. It should be noted that this conclusion is based on relatively small sample sizes, and from bones that include elongate limb elements compared to ribs, scapulae, and innominates. It is possible that other bone shapes would yield different results, but that would require much larger seeding trials. In addition, because the elements with poor recovery provide limited data, it is impossible to compare their relative transportability as well.

While bone shape certainly alters the transport potential of remains, the variable of shape alone does not control transport enough for shape to be used to interpret skeletal assemblages. In other words, other variables control transport far more, so shape is not a dominant controlling variable during natural fluvial transport. So, while previous flume studies have suggested that bone shape is important in bone transport (Morden 1991; Coard and Dennell 1995; Trapani 1996, 1998; Coard 1999), shape was not a controlling variable in natural fluvial systems, possibly because cast transport and deposition was governed more by interactions with the bed (short term deposition and burial) or orientation, rather than cast shape (Evans 2010, 2013b, c). Because we have so little information from river seeding trials utilizing natural bones, no direct comparison can be made between the data presented here and observed bone transport in natural fluvial systems. In addition, because flumes typically have homogenous flow and bed

conditions, they are expected to yield results of questionable applicability to the heterogeneous and constantly changing conditions of natural fluvial systems.

While, on average, denser casts moved shorter distances than less dense casts of the same shape, there is substantial overlap between transport of denser and less dense casts of the same shape (Figures 6-10). The presence of such overlap suggests the relationship between density and transport potential is weak, most likely due to partial or complete short term burial or temporary deposition due to bed obstructions, leading to a temporary halt in transport.

Generally, Aslan and Behrensmeyer (1996: 414-415) observed longer distance transport of lighter smaller bones (e.g., vertebrae, phalanges, sacrum), and less transport of larger heavier bones. A similar pattern was observed by Frison and Todd (1986), with Schick (1984, 1986) also reporting lighter bones moving farther than heavier remains. The data here generally show less dense casts moving farther than denser casts, but the trend is not observed consistently. Frequently less dense casts moved the same or similar distances to larger, denser casts. Because density is not the same as mass, no direct comparison to the observations of previous authors can be made, but the suite of observations is suggestive.

Directly comparing the results of this study to previous work is problematic because previous research has not reported bone shapes and densities sufficiently to make comparisons meaningful. For example, what knowledge we have of bone shapes usually comes from knowing the taxon used and the bones recovered, with no description of animal size or ontogenetic stage (e.g., adult vs juvenile). This means that bone size

reported in previous work can only be estimated, and with considerable possible error. Similarly, bone densities have not been reported. This becomes exceptionally problematic when considering extremely large bones (e.g., bison femur) which can be heavy, and yet still have a density below 1.0 g/cm^3 and float. This means that when investigators report "heavy" and "light" bones, there is no way to know if even the "heavy" bones float or not. This becomes even more problematic when considering the effects of bone preparation technique. For example, boiling bones often breaks down collagen, and removes much of the grease, thereby reducing bone density and making it more porous. Not knowing bone preparation methods means we cannot tell if a suite of bones used for empirical trials is more likely to be high or low on the density scale, making comparison between this study and previous work hand waving at best. Similarly, some studies simply report very few observations and conclusions, making comparisons virtually impossible because they amount to a series of anecdotes. For example, Behrensmeyer (1975:496, footnote) reports "Experiments in a natural stream show that large bones (e.g., a cow tibia) on a sand and gravel bottom may not move even at mean flow velocities of 150 cm/sec." Such reporting suggests a bone that is large, but of unknown ontogeny and density. Therefore, a comparison can only state that a big bone may not move, which was observed in these trials; some large casts did not move much after experiencing high flows. Such shallow comparisons simply state the obvious, are unrelated to bone density or shape transport trends, but are often the only comparisons possible.

Bickart (1983, 1984) reported avian bones both reoriented due to flooding and fully or partially buried from fluvial activity. Bone casts were reoriented due to fluvial

flow, and many did display partial or full burial. Notably, Bickart (1984) reported that avian bones were "glued" to the bed by decay fluids, which was not observed in cast behavior because no decay fluids were included while placing synthetic bones. Neither comparison relates to bone shape or density transport trends, however.

Korth (1978, 1979) observed the degradation and transport of owl pellets in a river. He observed small bones falling out of owl pellets and continuing to move downstream, ultimately being lost due to the irregular bed. Similar to the recovery rates reported here, small bones were difficult to relocate against a backdrop of an irregular bed, a comparison between studies unrelated to bone density or shape transport trends.

Harris (1978) seeded an unknown number of bones and bone fragments in a river and recovered only eight specimens at the end of his study. He concluded that smaller bones move more readily than larger bones (pg. 431), however, it is unclear what his initial and final samples were, and what "large" and "small" bones are given that all his recovered bones and bone fragments were relatively small. With such meager sample sizes of "small" and "large" bones, Harris (1978) can only report bone transport anecdotes, rather than generalizable bone transport behaviors. The study here did not investigate the effects of cast size, which is fortunate because few smaller casts were recovered. As such, the data set presented here is inadequate to address the issue of the relative transportability of small versus large bones. However, the limited data suggest that smaller bones show a similar transportability to larger bones, contrary to the anecdotes reported by Harris (1978). Neither study reports enough samples to form well

supported conclusions on the issue however, nor was this study designed to approach this question.

Van Orden and Behrensmeyer (2010) report results of bone surface medication for 27 bones that experienced up to 10 years of fluvial transport and up to 5 km of transport. They report that transport distance did not correlate with bone surface abrasion state. However, they did report that Voorhies Group 1 bones (e.g., vertebrae) traveled farther than Voorhies Group 2 bones (e.g., limb bones), which moved even shorter distances than Voorhies Group 3 bones (e.g., mandibles). It is unclear how Voorhies Group assignments were developed given that the bones recovered were from cows, horses, and goats, while Voorhies Groups were developed using sheep remains. Further research has conclusively demonstrated that the bones contained in Voorhies Groups vary depending on the animal and ontogenetic stage (e.g., adult vs juvenile), and they did not report the skeletal ages of bones recovered, or if they developed species specific Voorhies Groups for utilization in their study. More importantly Voorhies Groups have no correlation to the variables of shape and density, though those two variables are part of a complicated semi-quantitative transport relationship potentially described by the concept of Voorhies Groups. In other words, Voorhies Groups are a description of transport behaviors which incorporates the interrelationships between transport variables which could include shape and density, to an unknown degree. As such, no direct comparison can be made between the data presented here to Van Orden and Behrensmeyer's work other than to say bones they expected to move farther did, and some (not all!) less dense bone casts moved longer distances as expected.

Schick (1984, 1986) seeded the African landscape with bones and lithic artifacts and observed the transport, reorientation, and deposition of these materials in 43 simulated archaeological sites over time. Because her bone recovery rates were so low for each simulated site, her observations of bone transport behaviors amount to a suite of exceptionally well documented anecdotes. The bones used had been defleshed, but many still had some soft tissue adhering and over the course of her observations many weathered substantially. Consequently we know bones probably started with higher densities that reduced over time due to weathering. Generally she reports that bones were far more transportable than lithic artifacts, with 100% bone loss in many of the observed sites. Her observations were mixed, making generalizations difficult to develop. For example, after fluvial interaction some sites were observed with both transportable and non-transportable elements remaining (e.g., site 25, pg. 248) like a cranium, tibia fragments, and vertebrae in place, while non-transportable elements like a hemimanible, and tibia fragments moved downstream. Similarly, some sites showed highly transportable elements (ribs and vertebrae) recovered in place, but non-transportable skeletal material recovered many meters downstream (e.g., giraffe skull, pelves) (site 36, pg. 275). It is unclear how transportable versus non-transportable skeletal elements were identified. It was also common for both small and large bones to remain in place, making transport generalities difficult to develop. Over all, bones were observed buried in place, transported short distances and buried, or transported downstream with no burial, sometimes with bones re-accumulated downstream in new transported skeletal assemblages. Ultimately she concludes that the spatial and temporal variability in

locations is profound and over small spatial scales (cm's). Her observations are entirely consistent with the observations of bone cast transport and deposition observed in this study (observations not reported here). While Shick's pioneering and influential work is tremendously important in understanding the spatial and temporal variability in bone transport, none of her results relate to the variables of bone shape or density relative to transport potential, making her work less applicable to this study.

Frison and Todd (1986) report the transport of skeletally mature Indian elephant (*Elephas maximus*) bones in a series of simulated flooding events in a small creek. They note that each subsequent trial led to less transport of given bones. This effect could be from hydration increasing bone density or bones getting stabilized by the bed, both interesting effects not investigated here, though casts did interact with the bed during deposition. They also observed bones getting caught by the bed or other bones, dramatically altering bone transport. A fluvial transport index was calculated with highly transportable elements including the sacrum, patella, astragalus, calcaneus, and all the vertebrae. Some of these bones floated when they entered the stream, suggesting that the unreported preparation method used (boiling?) removed grease from the remains. They plotted scaled saturated wet weight versus scaled transport distance (pg. 69) which roughly shows a triangular shaped plot similar to figures reported here. Unfortunately the scaled transport distance and wet weights are not equivalent to the observed transport distances and densities reported here, so a comparison between their figure is unwarranted, though the similar shapes are interesting. Similarly, it is unclear what the bone preparation technique was, and how fast bones were changing density during the

study, making their results difficult to compare to the results presented here based on clasts with a static density. However, their observations (really a series of well documented anecdotes) may suggest that less dense bones are more transportable, though with many caveats related to bone interactions with the bed. A conclusion similar to that presented here with low density bones moving both short and longer distances relative to denser bones.

Dominguez-Rodrigo et al. (2014) generally reported the results of juvenile goat bone fragment movement in a river. Their results are not directly applicable to the results here because they utilized bone fragments with unknown preparation technique (density), and transport distances are not reported, they simply note if the fragments moved out of their study reach. They did note that long bone fragments moved shorter distances than compact bones, but it is unclear what compact bones are, and under what state of development they are in. Generally smaller limb shaft fragments moved "away" from larger ones, but the sample size is not reported, so how this statement can be generalized is unknown. In addition, these trials lasted only 15 minutes, so remains experienced only a short transport history, certainly not long enough for remains to experience a heterogeneous fluvial environment or to change density fully. They report that 28% of an unknown number of bones moved out of the study reach, with 100% of compact bones, 62% of the pelves, 50% of the vertebrae, 30% of the ribs, 25% of the scapulae, and 18% of the limb bones moved out of the study reach. These numbers have no generalizability because it is unclear how many samples there were (less than 132 total bone fragments though), so these numbers are fraught with small sample size problems. They do report

that there was a bias toward epiphyseal ends moving out of the study reach, but this observation was not quantified, again based on an unknown number of observations. In a second set of trials using 132 bone fragments, the densest bones were intentionally placed in deeper faster flow. Consequently, the results of these trials are biased by the poor study design (pg. 48), and are not directly comparable to the first suite of trials. They note that 100% of the compact bones, 75% of scapulae, 57% of the pelves, 50% of the ribs, 50% of the vertebrae, and 40% of long bones moved out of the study reach. Comparing the results from these trials to the first suite by ignoring the differences in initial conditions, it is unclear if there are any trends. More importantly, the sample sizes are too small to generalize even if there were trends. They do note that 81% of epiphyses from small carcasses, and 60% of epiphyses from large carcasses moved out of the study reach, but stated that no size trend was evident due to small bones from larger animals being buried and not moving. Because transport distances and densities were not reported for any samples, only a general comparison with the work reported here is warranted, particularly because of the obviously flawed study design. Generally it seems bones we assume are denser moved shorter distances than those we assume are less dense, a conclusion broadly comparable to the results here.

Hanson (1980) calculated a theoretical relative transportability index for bones, and partially tested it with observations of 42 bones transported in a river. He noted that most higher transportability bones had moved from the initial study sites, but some high transportability bones were held in place by vegetation or stabilized by scour or burial. However, he noted that: “The transported assemblages included some elements which

should be among the most difficult to transport,…", which suggests that his model was incomplete in describing bone transport. Further, he suggests that obstructions and "unpredictable temporal and spatial variations" caused bone transport to deviate from his predictions. While this is the most mathematically rigorous study of bone transport, his results are not directly comparable to those here because no densities or transport distances were reported. However, broadly he came to a similar conclusion, which is that theory may predict bone transport, but in practice there is considerable overlap between the transport behaviors of highly transportable and low transportability elements, because of interactions with the bed, and spatial and temporal variability in natural fluvial systems. It is important to note, that the theory he was utilizing is wildly different than that investigated here.

Aslan and Behrensmeyer (1996), report the results of tracking the movement of 142 bones seeded in the East Fork River, Wyoming for over a decade. Generally they report that over time fewer bones were recovered from a given seeding event, and there was a recovery bias toward larger materials. Both observations were also made in the recovery rate of bone casts. However, Aslan and Behrensmeyer (1996) report bones preferentially deposited on point bars, an observation not seen in bone casts which were deposited more or less equally distributed across the river. Generally they report that lighter bones moved farther than heavier bones, however, the preferential separation of light and heavy bones was more a function of where the bones were initially deposited. For example, if bones were placed in a straight channel with separation between bones, lighter bones moved downstream farther than heavier bones. However, when bones were

placed in channel bends there was less separation because both light and heavy bones were not transported, even after years of residence in a river. They described these channels as either “scouring” or “filling”, with bones showing light and heavy bone separation when placed in “filling” channels, and very little separation when placed in “scouring” channels. These results reconfirm the observations of Schick (1984, 1986) and Hanson (1980) indicating that the temporal and spatial variation in river channels plays an important role in determining bone transport. In addition, they did note that some light elements (ribs) were not transported as far as expected. Similarly, some of the limb bones transported the farthest distances were among the heaviest bones in the study, thus confirming that there was considerable variation in transport not accounted for by the amorphous categorization of bones as “light” or “heavy”. They explained the downstream movement of heavy bones as more a function of preferential collection bias toward large bones, though it is equally parsimonious to suggest these larger bones had reduced densities so they floated or moved as neutrally buoyant clasts downstream. Ultimately they concluding that bone size and density did not solely control bone transport potential, a surprising conclusion because no effort was made to quantify bone size, mass, or density. Most analysts have internalized the message that lighter and more porous bones move faster than heavier and denser bones, and have ignored that this relationship disappears in some portions of a river system. An intuitive interpretation, however not backed with any quantification or statistical measures of mass, density, or size. More importantly, because their study focused on the effects of mass on transport their results are logically not comparable to those presented here based on measures of shape and

density. Because the variable of mass is decoupled from density, objects can be massive with low net densities (e.g., oil tankers), or light and dense (e.g., a sand grain of lead). In addition, their study suffers from problems associated with small sample sizes, with bones crossing species, skeletal elements, and potentially ontogenetic stage, reducing their observations to well constrained anecdotes. Further, many of their conclusions are based on some bones not moving, as in the bones staying in place for the duration of the study. The research reported here only involves casts that had moved, so are by definition a transported assemblage. Consequently a direct comparison of the two data sets is not appropriate past the observation that lighter bones tend to move more readily than heavier bones, which can sometimes parallel the observation that denser casts move less readily than lighter casts (an observation discussed above).

Ultimately the data reported here coupled with observations of floating bone transport (Table 6) suggest that bulk density is the most important variable in determining bone transport potential, yet density does not correspond with transport distance. In other words, there is a strong relationship between density and transport, but the variable of density only partially predicts the resulting transport. For example, when bone density changes to make a bone float, the bulk density drastically increases transport potential, but the bulk density also does not correspond with transport (personal observation). In other words, as long as a bone is floating it does not matter what density it is, so long as it is floating. However, the change from bedload to floating radically alters transport potential. So the variable of density in isolation does not control much bone transport in a system, but a change in its value causes the system to reach a tipping point.

Consequently, bone density is probably the most important variable in bone transport, but bone density in and of itself is a poor predictor of transport potential.

What remains is the question of if there is a large enough difference in transport potentials between less dense and denser bones, that the difference can be used analytically. Statistics cannot answer this question, as it is a practical concern, rather than a test of the mathematical differences between numerical data sets, because it requires investigators to decide for themselves if a relationship between two variables is strong enough that it applies to the assemblage they are interpreting. As such, individual investigators can make informed decisions based on the graphs presented here, and if the relationship is strong enough for their personal comfort, the relationships can be utilized for assemblage analysis. This same logic is used when Voorhies Group analyses or bone orientation analyses are performed. When both methods are utilized, practitioners invoke an unquantified taphonomic process analog, and perform no statistics to verify the accuracy of the interpretations provided or compare their assemblage to the method description. As such, the data presented here is presented in the same format as multiple methods commonly utilized for analytical purposes in paleontology and archaeology assemblage analysis.

While the weak relationship between density and transport presented here could potentially be used for assemblage analysis, there are still some barriers to use. Using this relationship between bone density and transport potential for analytical purposes requires the analyst to make assumptions about the density of bones in fossil or archaeological assemblages. To do this requires knowing the range of densities found in natural skeletal

material, and the assumption that the density remains more or less constant. A brief literature review demonstrates that natural bone densities (~1.1 g/cm^3 to 2.245 g/cm^3) (Table 6) frequently fall outside of the range of densities tested here, and that bone densities change over time when placed in water (Table 7). As such, this weak relationship between bone density and transport potential is insufficient to describe realistic natural bone transport, and consequently, it is also insufficient for interpretation of fossil or archaeological skeletal assemblages. So the development of a correlation between a static density and transport potential may not be appropriate for clasts whose densities change continuously. Therefore, a bone transport model would require a component that incorporates how bone density changes through time for each skeletal element, with some bones changing density at different rates (and with changing rates), and both increasing (e.g., hydration) and decreasing (e.g., build up decay gases in a bone) in density. Such a model would be tremendously complicated and require element specific hydration rates given initial bone conditions (e.g., fully fleshed, heavily weathered and cracked, etc.), because each bone condition would require a separate hydration rate. Therefore, a transport model developed with the changing rate of bone hydration would require copious detailed empirical observations prior to development.

By seeding synthetic clasts and tracing their transport and deposition over space and time it was possible to remove some confounding variables complicating the understanding of transport and deposition of bones in rivers. While shape was successfully controlled by using consistent molds, density was difficult to hold constant using a single casting resin and mixing additives. The additives were rarely distributed

evenly in the casts, making it difficult to manufacture casts with exactly the density desired. More frequently the casts were poured with a narrow range of densities, which is somewhat realistic for natural bones, but less accurate for a study attempting to hold density constant. More consistent bone cast densities could have been obtained using different casting resins of different densities however this was impossible due to insufficient funding.

Conclusions

The lack of a clear relationship between bone shape and transport potential of a limited suite of bone shapes and densities, if interpreted conservatively, suggests that the shapes of bones in an assemblage should no longer be used to infer the presence or absence of fluvial interactions with the skeletal assemblage under analysis. Similarly, the weak relationship between bone density and transport potential, suggests that density should also no longer be used to infer fluvial interactions with skeletal assemblages. This study design is restricted in applicability to the relationship of shape and transport or density and transport. As such, it is possible that *other variables* (e.g., size, weight) or *combinations of variables* (e.g., size and weight) could yield consistent patterns. For example, it is possible that small shaped bones with low densities consistently travel faster and farther than larger denser bones. However, this study did not collect enough data, and of the appropriate kinds, to approach these questions. Considerably more casts and observations would be required to tease out these relationships. What is clear is that

the variable of shape alone shows no relationship to transport distance, and density alone shows a weak relationship to transport with considerable overlap at lower densities.

These results reconfirm that it is important that, as a community of historical scientists (paleontologists and archaeologists), we recognize that we should test our methods before we use them for extended amounts of time. Validating methods before use will lead to more efficient science of higher quality and waste fewer resources reanalyzing assemblages when it becomes clear interpretations were generated utilizing flawed techniques or assumptions.

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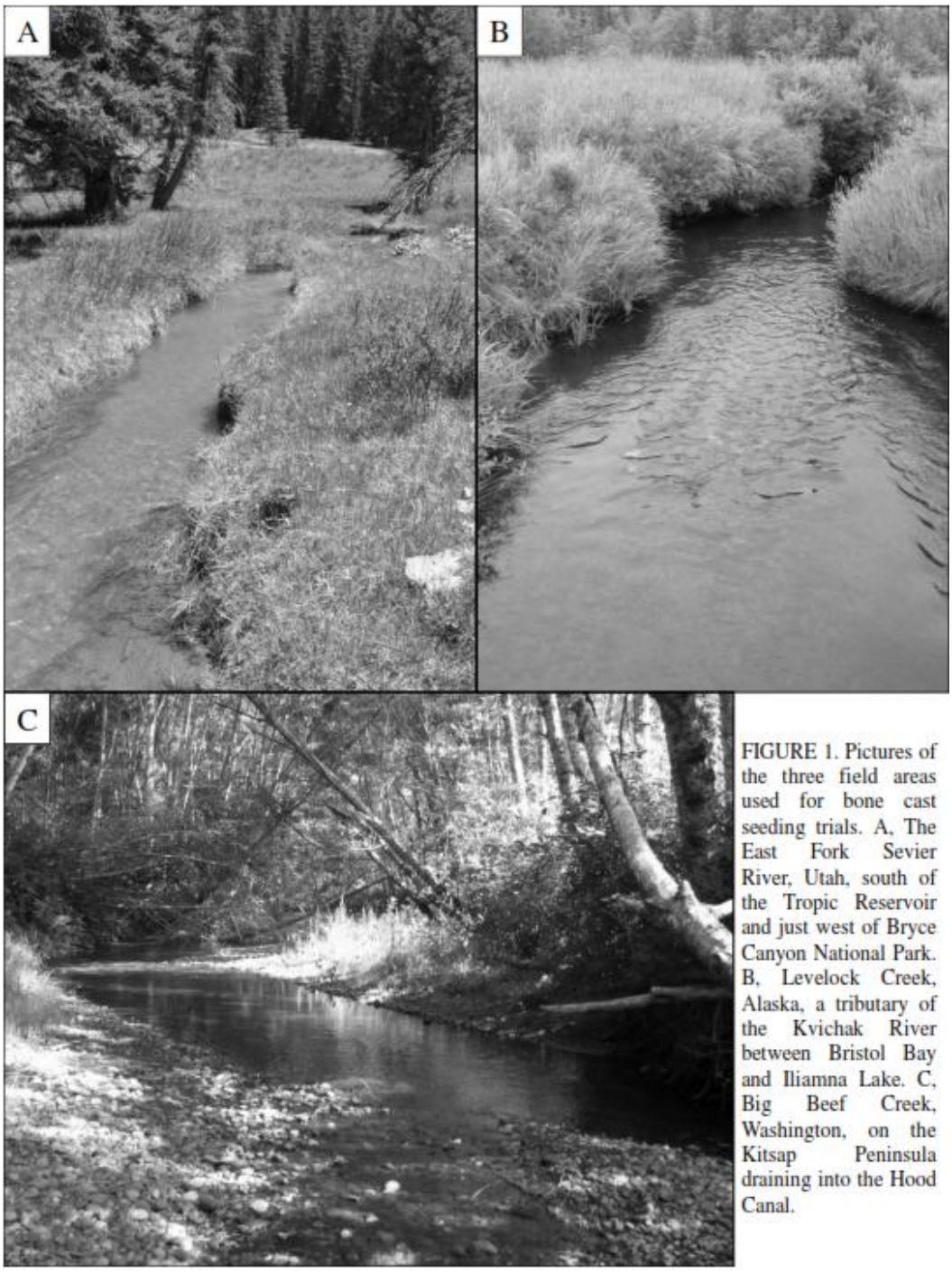

FIGURE 1. Pictures of the three field areas used for bone cast seeding trials. A, The East Fork Sevier River, Utah, south of the Tropic Reservoir and just west of Bryce Canyon National Park. B, Levelock Creek, Alaska, a tributary of the Kvichak River between Bristol Bay and Iliamna Lake. C, Big Beef Creek, Washington, on the Kitsap Peninsula draining into the Hood Canal.

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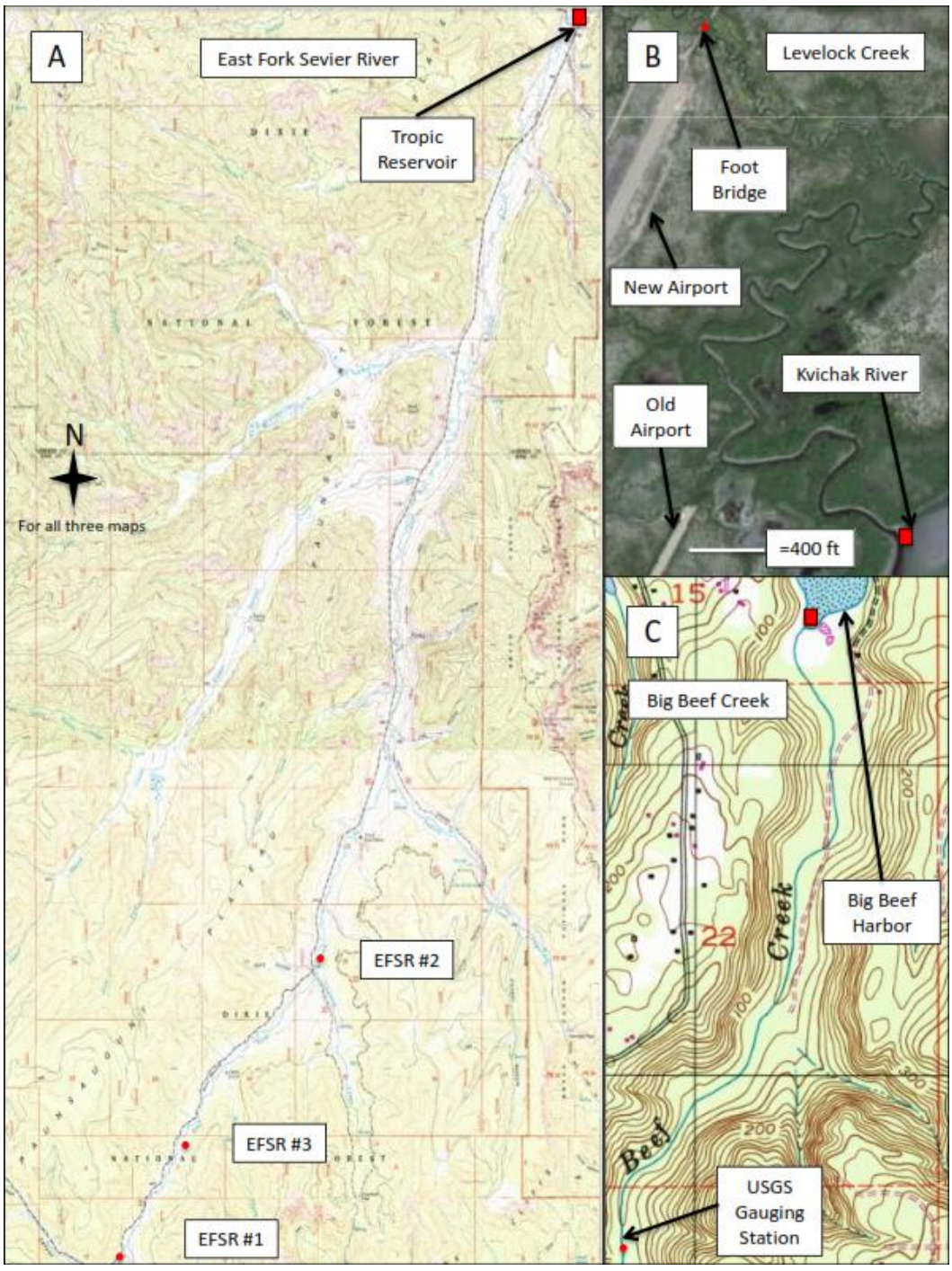


FIGURE 2. Maps and satellite images of the rivers used for seeding trials. Circles represent locations where seeding trials were initiated, and rectangles depict the end of the study reaches, usually at large competence drops. A, East Fork Sevier River, UT. B, Levelock Creek, AK. C, Big Beef Creek, WA. [Full page figure]

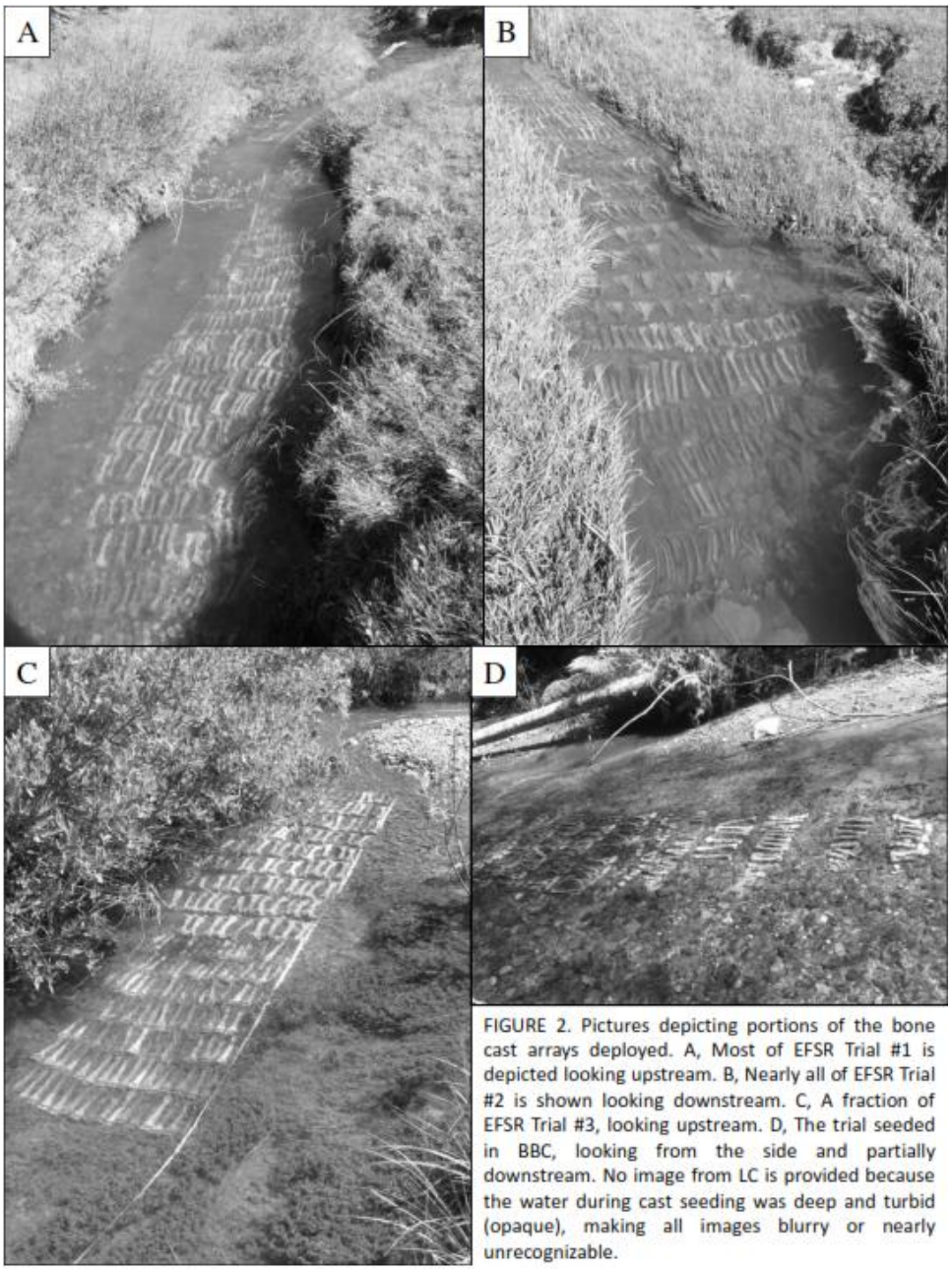


FIGURE 2. Pictures depicting portions of the bone cast arrays deployed. A, Most of EFSR Trial #1 is depicted looking upstream. B, Nearly all of EFSR Trial #2 is shown looking downstream. C, A fraction of EFSR Trial #3, looking upstream. D, The trial seeded in BBC, looking from the side and partially downstream. No image from LC is provided because the water during cast seeding was deep and turbid (opaque), making all images blurry or nearly unrecognizable.

FIGURE 3. Pictures depicting portions of the bone cast arrays deployed. A, Most of EFSR Trial #1 is depicted looking upstream. B, Nearly all of EFSR Trial #2 is shown looking downstream. C, A fraction of EFSR Trial #3, looking upstream. D, The trial seeded in BBC, looking from the side and partially downstream. No image from LC is provided because the water during cast seeding was deep and turbid (opaque), making all images blurry or nearly unrecognizable. [Full page figure]

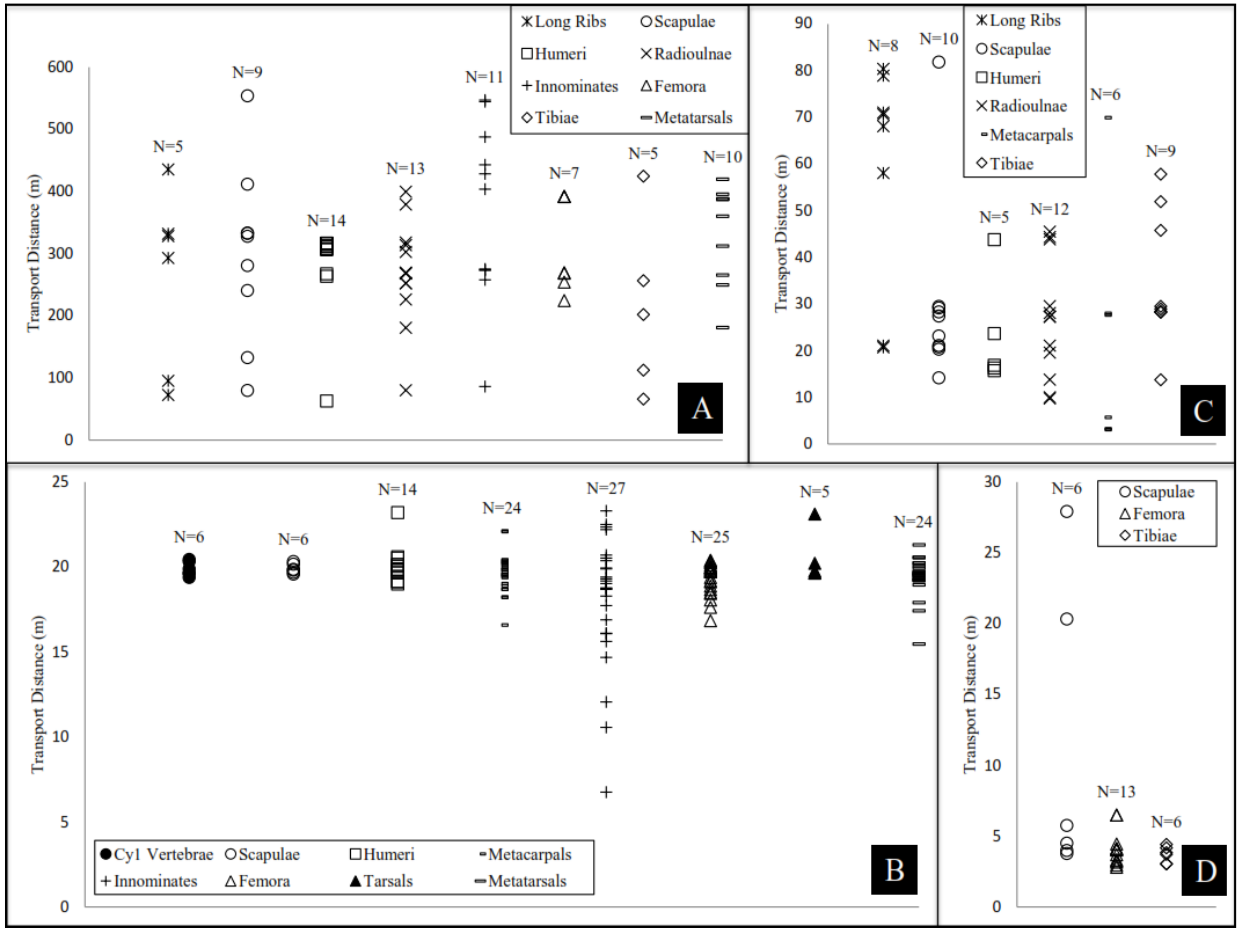


FIGURE 4. Shape versus transport distance plots depicting each data point for: A, EFSR Trial #1, 2011 observation, 1.10-1.31 g/cm^3 density casts. B, EFSR Trial #3, 2013 observation, 1.10-1.31 g/cm^3 density casts. C, LC, 2011 observation, 1.10-1.31 g/cm^3 density casts. D, LC, 2011 observation, 1.32-1.50 g/cm^3 density casts. [Full page figure, landscape orientation]

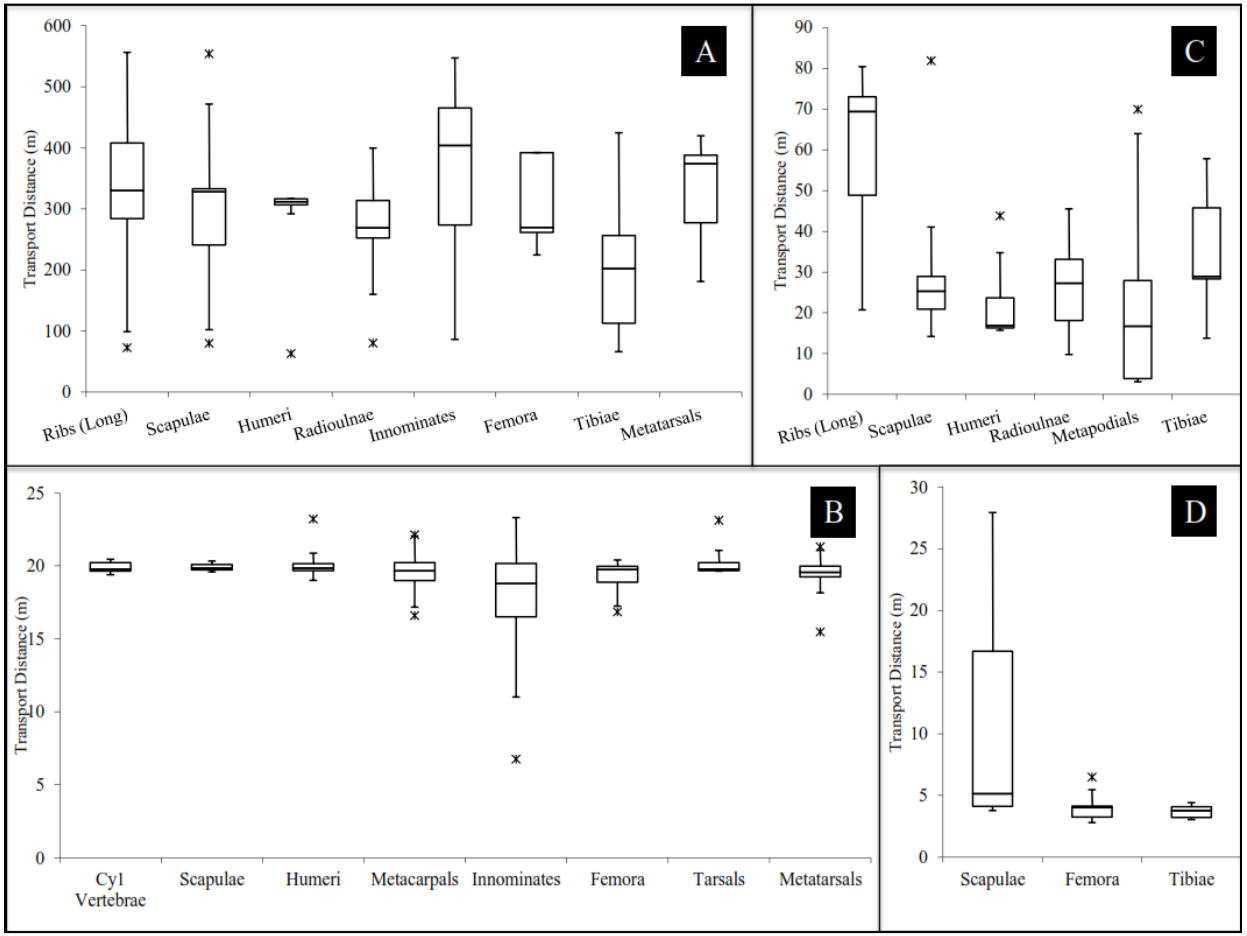
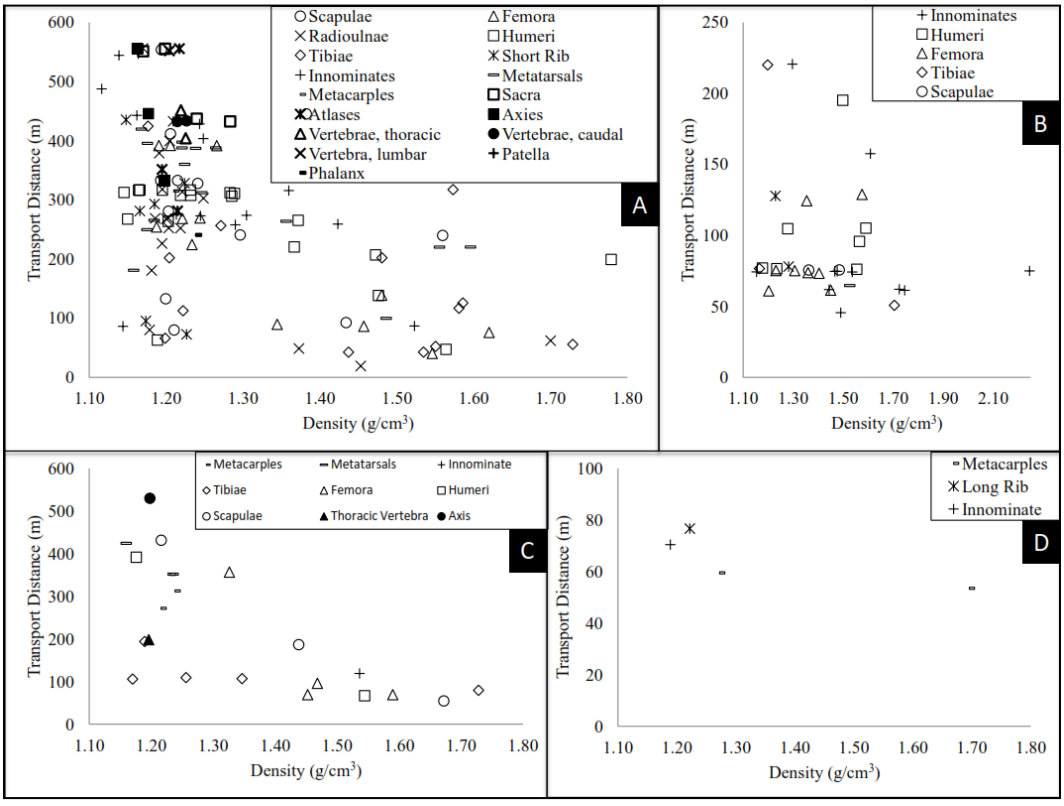
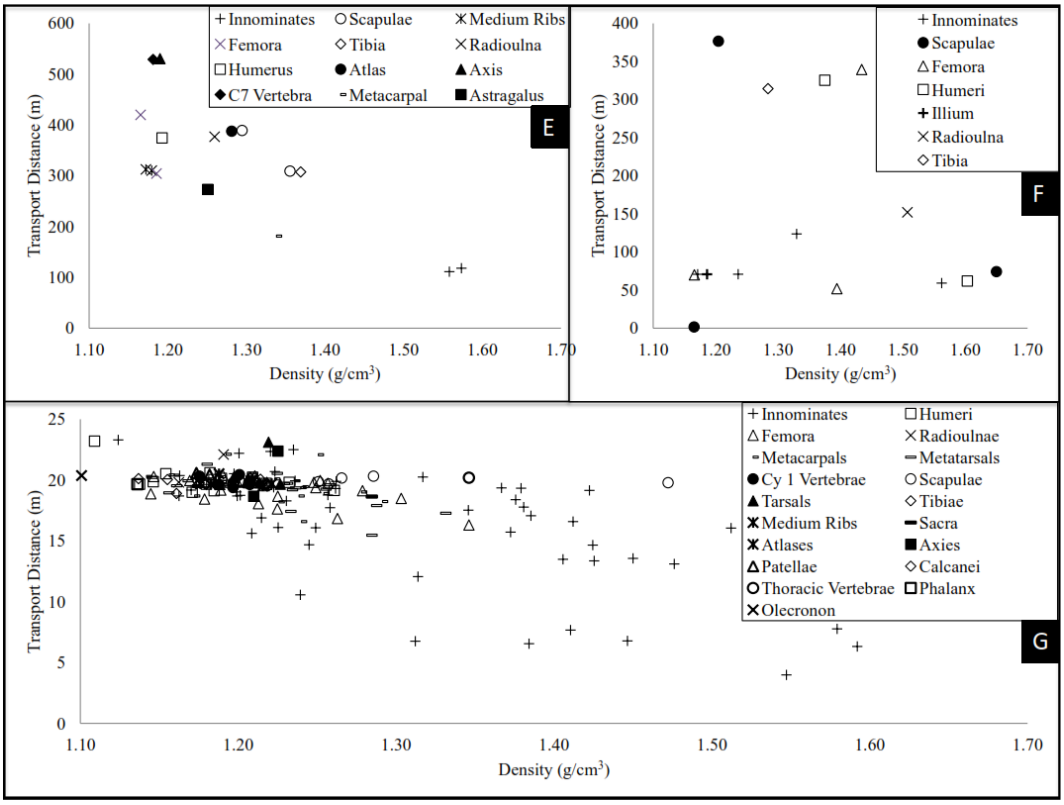


FIGURE 5. Summary shape versus transport distance plots depicting box and whisker plots for: A, EFSR Trial #1, 2011 observation, 1.10-1.31 g/cm^3 density casts. B, EFSR Trial #3, 2013 observation, 1.10-1.31 g/cm^3 density casts. C, LC, 2011 observation, 1.10-1.31 g/cm^3 density casts. D, LC, 2011 observation, 1.32-1.50 g/cm^3 density casts. [Full page figure, landscape orientation]


A
Scapulae
Radioulnae
Tibiae
Innominates
Metacarples
Atlases
Vertebrae, thoracic
Vertebra, lumbar
Phalanx
Femora
Humeri
Short Rib
Metatarsals
Sacra
Axies
Vertebrae, caudal
Patella
Transport Distance (m)
Density (g/cm3)
B
Innominates
Humeri
Femora
Tibiae
Scapulae
C
Metacarples
Metatarsals
Innominate
Tibiae
Femora
Humeri
Scapulae
Thoracic Vertebra
Axis
D
Metacarples
Long Rib
Innominate


E
Innominates
Scapulae
Medium Ribs
Femora
Tibia
Radioulna
Humerus
Atlas
Axis
C7 Vertebra
Metacarpal
Astragalus
Transport Distance (m)
Density (g/cm3)
F
Innominates
Scapulae
Femora
Humeri
Illium
Radioulna
Tibia
G
Innominates
Humeri
Femora
Radioulnae
Metacarpals
Metatarsals
Cy 1 Vertebrae
Scapulae
Tarsals
Tibiae
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Sacra
Atlases
Axies
Patellae
Calcanei
Thoracic Vertebrae
Phalanx
Olecronon

Figure 6 Continued

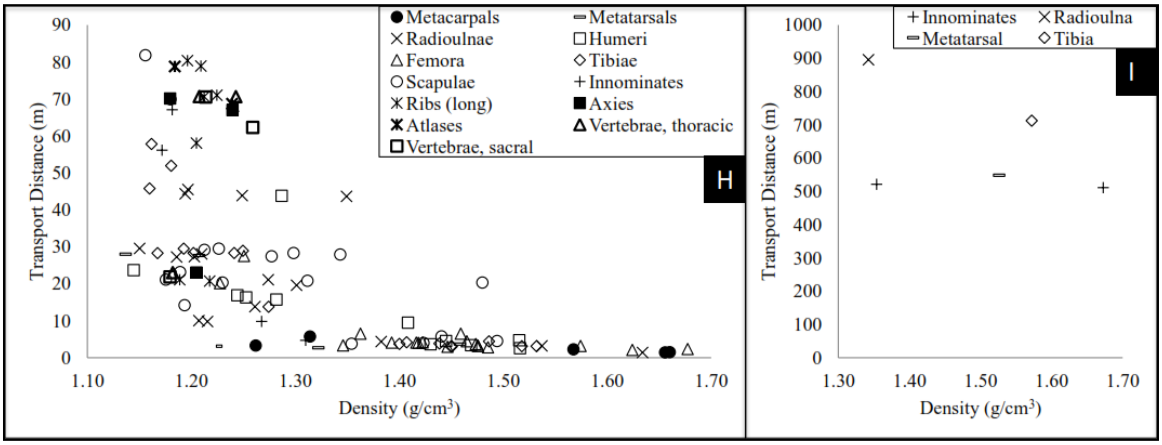

FIGURE 6. Summary density versus transport distance plots for each of the nine trial observations. A, EFSR Trial #1, 2011 observation. B, EFSR Trial #2, 2011 observation. C, EFSR Trial #1, 2012 observation. D, EFSR Trial #2, 2012 observation. E, EFSR Trial #3, 2013 observation. F, EFSR Trial #2, 2013 observation. G, EFSR Trial #1, 2013 observation. H, LC, 2011 observation. I, BBC, 2012 observation. [Full page figure]

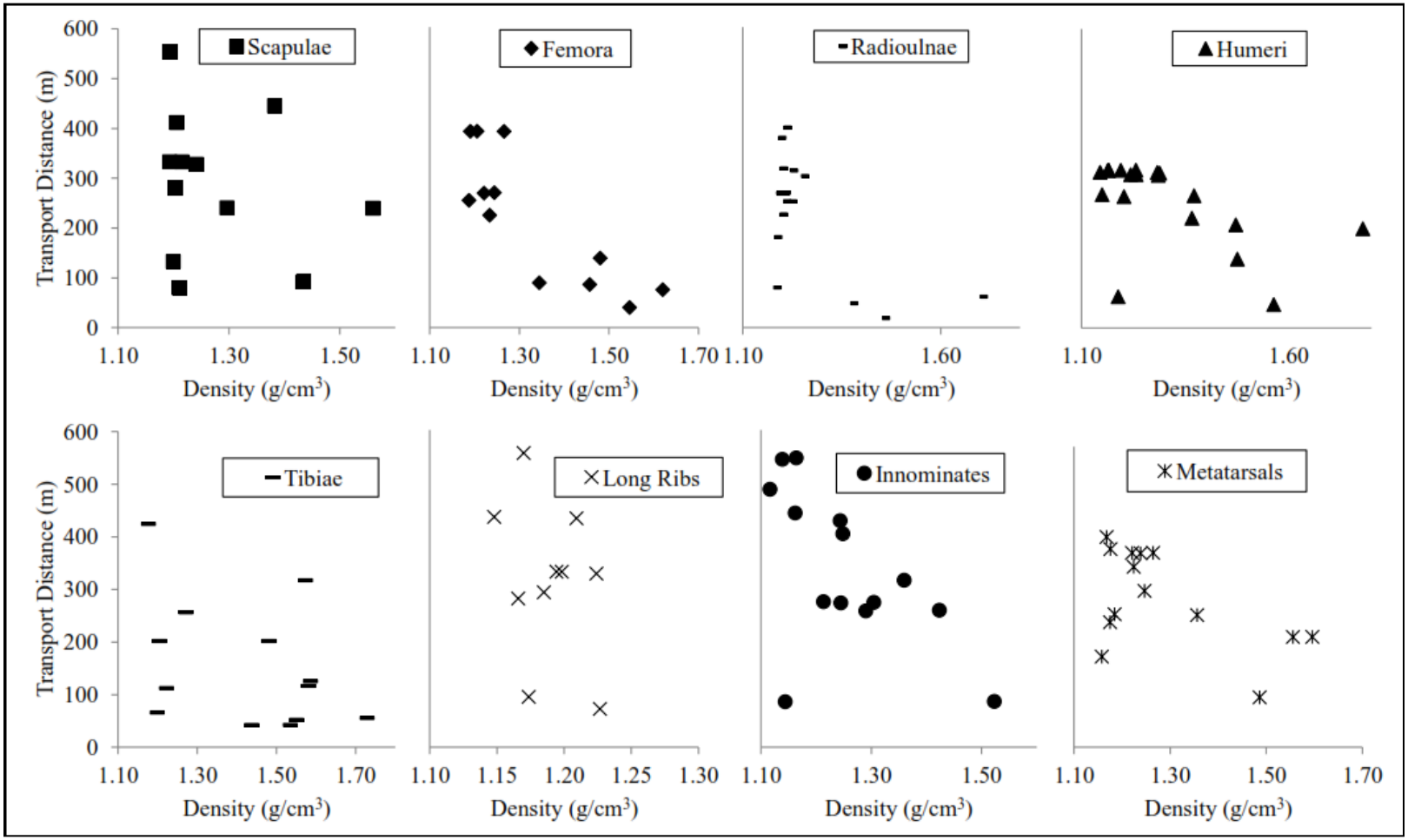

FIGURE 7. Element specific density versus transport distance plots for EFSR Trial #1, 2011 observation, 1.10-1.31 g/cm^3 density casts. [Full width of portrait oriented page]

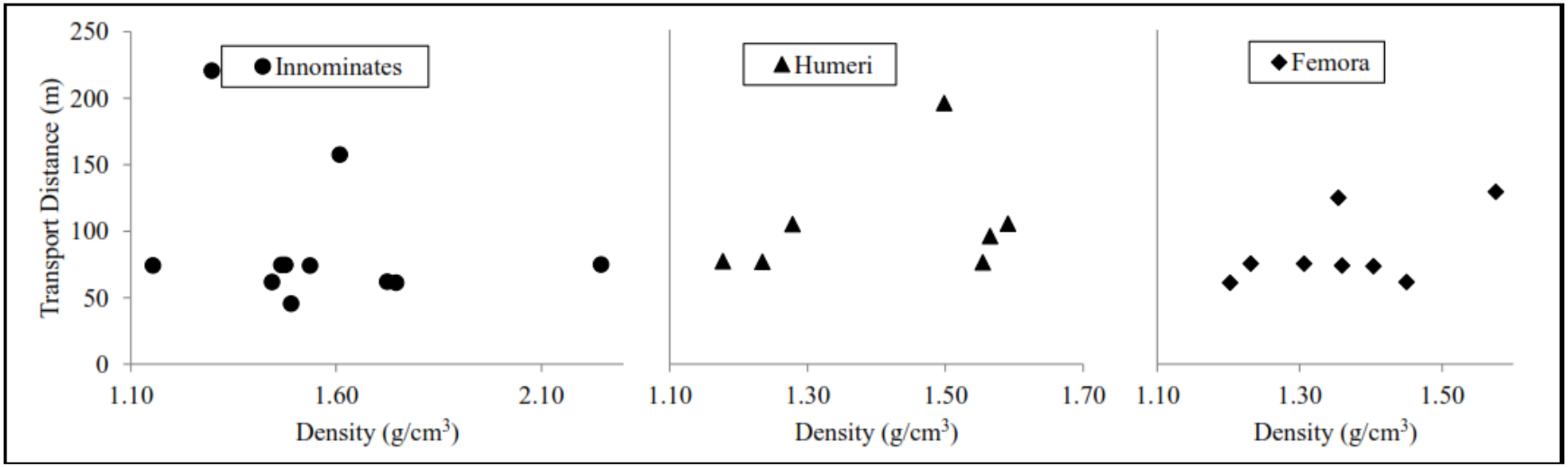

FIGURE 8. Element specific density versus transport distance plots for FSR Trial #3, 2013 observation, 1.10-1.31 g/cm^3 density casts. [Full width of portrait oriented page]

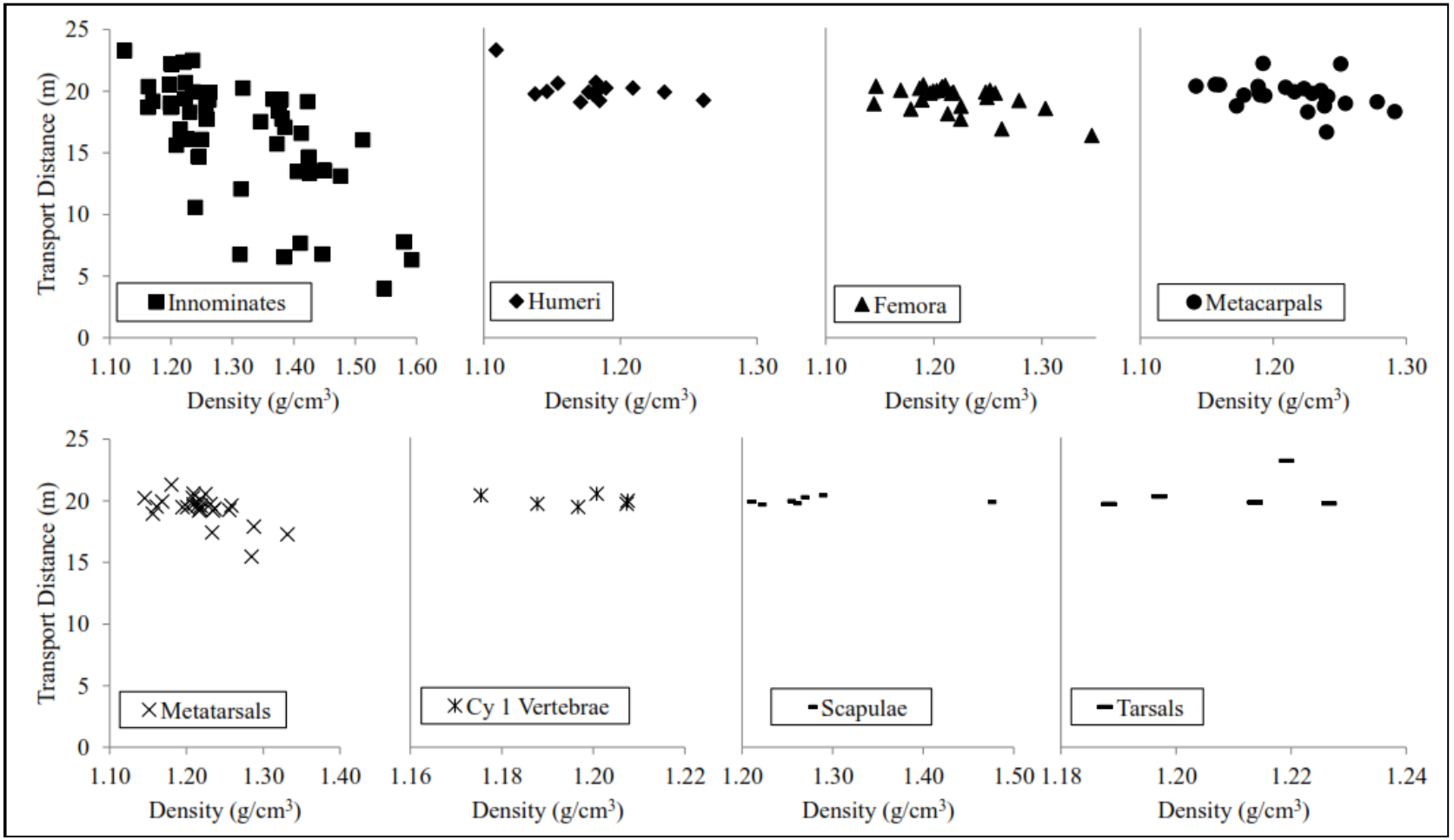

FIGURE 9. Element specific density versus transport distance plots for LC, 2011 observation, 1.10-1.31 g/cm^3 density casts. [Full width of portrait oriented page]

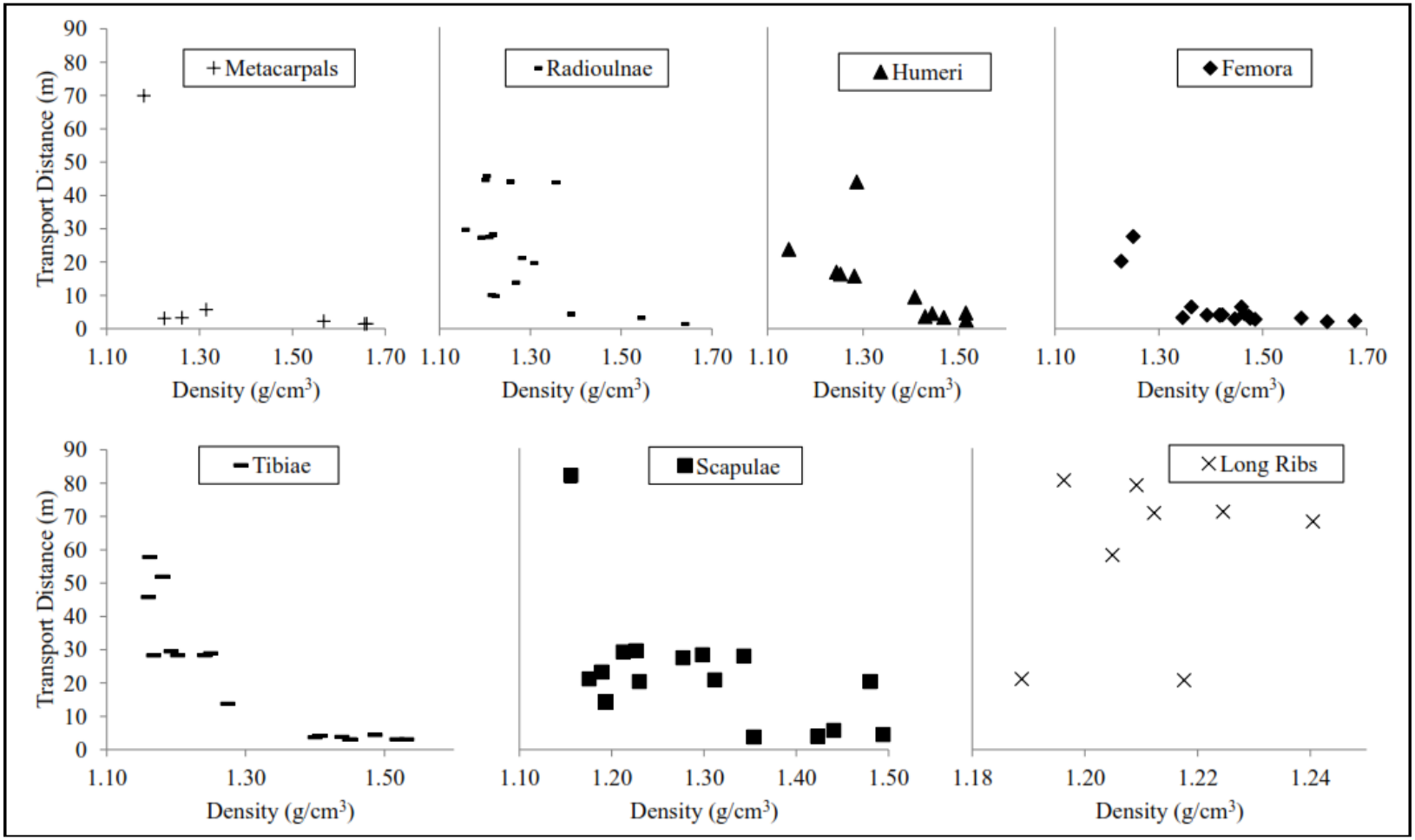

FIGURE 10. Element specific density versus transport distance plots for LC, 2011 observation, 1.32-1.50 g/cm^3 density casts. [Full width of portrait oriented page]

Table 1. Published studies that seeded skeletal material in natural fluvial systems, including the taxa seeded, the (approximate) sample sizes, and general results.

Citation and Page Number	Methods	Taxa	Approximate Number of Seeded Bones	Number of Samples Recovered	Results	Observations Relavent to Bone Transport Mechanisms
Aslan and Behrensmeyer 1987, 1996	Five sets of bones were seeded in grid arrays at four locations and their transport and deposition observed over time.	Cow and horse	311	142	Fewer bones were found the longer the trial continued. Generally larger bones were found more often than smaller bones, and bones were frequently concentrated on point bars. Over time bones did show signs of abrasion. Lighter and more porous bones moved father downstream than heavy bones, except for ribs wich moved less given their weight. Bones from each trial did show hydraulic sorting according to channel position, and original spacing. Assemblages placed in channels showed lighter bones transported faster than heavier bones, while assemblages placed on point bars showed less sorting. While sorting was observed based on weight, light and heavy bones were transported similar distances. Generally heavier and denser bones moved shorter	Because both light and heavy bones were transported similar distances (often some of the longest), bone size and density alone do not control bone transport and deposition. Partial burial prevented transport frequently.

Table 1 Continued

					distances than lighter and more porous bones.	
Behrensmeyer 1975:496	Bones were seeded in a river and their transport and deposition observed over time.	Cow large bones	Not reported	Not reported	Large bones may not move at current velocities expected from flume trial results.	
Bickart 1983, 1984	Carcassess were placed in a stream channel and their decay and transport observed over time.	Rock Dove (*Columba livia*), Ring-billed Gull (*Larus delawarensis*), and Herring Gull (*Larus argentatus*)	28 Carcasses	11 partial or complete carcasses	Decay fluids glued carcasses and bones to the bed so strongly that flood flows rarely moved bones, and only short distances.	An interaction with the bed dramatically altered bone transport potential.
Dominguez-Rodrigo et al. 2014	20 pieces of fresh hammerstone broken femur and tibia fragments plus 11 compact bones were seeded in a modified river channel (boulder to cobble bed)for 15 minutes and bone orientation and transport observed.	Juvenile goat	20	Not reported	Compact bones moved faster than elongate bone fragments, and smaller bones moved farther than larger bones.	Smaller bones move farther than larger bones, and compact bones move quickly relative to other bones.

Table 1 Continued

	132 bone fragments were seeded on a river point bar with random orientations with the least dense fragments in the shallowest flow, and the most dense fragments in the deepest flow, and their orientations and transport observed for 30 minutes.	Juvenile goat	31	Not reported	Compact bones moved more than limb bones.	Compact bones transport more readily than limb bones.
	132 bone fragments were seeded on a river point bar with random orientations with all bonnes in the deepest flow, and their orientation and transport observed for 60 minutes.	Two goats, one deer, one horse, and one cow	132	Not reported	Bone fragments with cancellous bone (epipheseal ends) moved faster than bone fragments of compact bone (long bone shafts). Smaller specimens were lost more frequently than larger specimens, though no size sorting was observed of long bone shaft fragments. Generally denser flatter bones did not move as readily as tubular or cube shaped bones.	Size sorting was observed with smaller bones transported farther than larger bones which caused selection based on anatomical units, however, size was not as important as bone structure (compact vs cancellous) in determining transport potential.
Dominguez-Rodrigo and Garcia-Perez 2013	Complete bones were dropped into a river along a 4 meter transect and their orientation and	Adult deer, pig, subadult cow	136	82	Trabecular bones were transported more frequently than compact bone. Only some elongate bones consistently adopted prefered orientations	Trabecular bones are more transportable than compact bone.

Table 1 Continued

	transport observed for two hours.				relative to flow direction.	
Frison and Todd 1986	A small river was dammed, bones placed in the channel, and flash floods simulated by removing the dam.	Indian Elephant (*Elephas maximus*)	23 (in 6 trials)	23	After a bone moved it was more difficult to initiate movement again. Bone orientation altered bone transportability. Frequently bones captured other bones. Smaller elements moved more easily often due to floatation, and heavier bones moved shorter distances than lighter bones.	Once a bone is deposited, further movement is more difficult probably from bone hydration and stabilization in sediment. Smaller bones are more transportable than larger bones, and heavier bones move less than lighter bones.
Hanson 1980	Bones were placed on a sandy and gravely river bed and their transport distances observed over time.	Domestic cattle	120	42	During bone transport bed and flow conditions were constantly changing. Vertebrae moved farther downstream than metatarsals, or femora and humeri.	Natural systems have heterogenious flow and bed conditions which caused scatter in bone deposition largely due to bed obstructions.
Harris 1978	Bone fragments were laid in meter square plots in different geomorphic locations on a river bed and	Cattle	Not reported	8	Generally bones moved faster than stone artifacts, and some bones were partially buried when recovered.	Bone burial is common between periods of transport.

Table 1 Continued

	bone transport and orientations were observed over time.					
Korth 1978, 1979	Owl pellets were released in a small stream and bone and pellet transport observed.	Owl Pellets	Not reported	0	Owl pellets saturaed with water in ~10 seconds but floated for the duration of the trial. After ~20 meters of transport bones started to fall out of the pellets and continued transport but were lost due to their small size and large bed material.	
Schick 1984, 1986	Bones, bone fragments, and lithic artifacts were placed in numberous places on the landscape and their transport and burial observed over time.	Bones from the african landscape (see appendix)	296 (in 14 trials)	71 (from 11 of the 14 trials)	Bones are far more transportable than lithic artificats with bones having similar recovery rates to debitage. Simulated sites stretch out with fluvial interaction and local topography alters flow causing local deposition. Often bones and artificats were deposited and partially or fully buried in new concentrations around obstacles, gravel bars, and topographic highs in the river channel. There is significant spatial and temporal heterogeneity in real rivers.	Alterations in flow around obstacles creates loci of deposition and burial that slow down bone transport which is a function of real world channel and flow heterogeneity.
Schick 1987	Bones were seeded on a landscape and their transport observed over time.	Bones from the african landscape	Not reported	Not reported	Bones are more transported than lithic material and show similar transportability to debitage.	

Table 1 Continued

Van Orden and Behrensmeyer 2010	Bones were seeded in a river and their abrasion states compared to their transport distances.	Cow, horse, goat	Not reported	Not reported	The abrasion observed on bones recovered from fluvial contexts does not correlate with transport distance.	Bones that were transported shorter distances often showed more abrasion from sandblasting in place during temporary partial burial.
Evans (submitted)	Bones were seeded in river channels and their orientation, transport, and deposition observed over time.	Deer, elk, pronghorn, bison, cow, pig, + misc. medium sized mammal bones	6000+ (in 8 trials)	226	Elongate skeletal elements do not adopt consistent orientations relative to current direction because bones orient relative to obstructions and bed features.	Bone densities change frequently, and interactions with the bed strongly control transport and deposition.

Table 2. Synopsis of flume results related to the effects of bone shape and density on fluvial t

Citation	Shape Results	Density Results	Taxa
Behrensmeyer 1973	Shape is important for bones with high surface area to volume ratios.	Density is more important in governing transport potential than shape.	Hippopotamus, zebra, large and small antelope (*Redunca, Damaliscus*), pgi (*Hylochoerus*) crocodiles, fish, sheep.
Behrensmeyer 1975	Shape is important for bones with high surface area to volume ratios.	Density is more important in governing transport potential than shape.	Hippopotamus, zebra, large and small antelope (*Redunca, Damaliscus*), pgi (*Hylochoerus*) crocodiles, fish, sheep.
Blob 1997	No correlation between shape and transport exists, largely due to orientation effects.	Density has a greater influence on transport potential than shape.	*Apalone spinifera* (Trionychine turtle)
Boaz and Behrensmeyer 1976	Bone hydrodynamic shape is a function of orientation, so shape controls transport less.	Density is a better predictor of transport potential than shape.	*Homo sapiens*
Coard 1999	Shape alters transport potential.	Dry bones (less dense) move faster than saturated bones, often due to floatation.	Mouflon sheep (*Ovis musimon*), pig-tailed macaque (*Macaca nemestrina*), and alsatian dog (*Canis familiaris*)
Coard and Dennell 1995	Shape alters transport potential.	-	Mouflon sheep (*Ovis musimon*), pig-tailed macaque (*Macaca nemestrina*), and alsatian dog (*Canis familiaris*)
Dodson 1973	-	Changes in buoyancy (density) drastically change transport potential.	Mouse (*Mus*), frog (*Rana*), toad (*Bufo*)
Kaufmann et al. 2011	-	Water saturated (denser) bones traveled slower than dry bones.	*Lama guanicoe*
Morden 1991	Shape is somewhat important in governing transport behaviors.	Mass (part of density) is most important in determining bone transportability.	*Homo sapiens*
Pante and Blumenschine 2010	-	Lower density bones moved faster than less dense bones.	Bovid

Table 2 Continued

Trapani 1996	Bone shape alters transport potential, but bone shape does not correlate with transport potential.	Domestic pigeon (*Columba livia*)
Trapani 1998	Bone shape alters transport potential, but bone shape does not correlate with transport potential.	Domestic pigeon (*Columba livia*)

Table 3. Bones molded and cast.

Axial	Appendicular
Atlas	Scapula
Axis	Humerus
C7 Vertebra	Radioulna
Lumbar Verebra	Carpals
Thoracic Vertebra	Metacarpals
Sacrum	Innominate
Cy1 Vertebra	Femur
Cy2 Vertebra	Patella
Short Rib	Tibia
Medium Rib	Calcaneus
Long Rib	Astragalus
	Metatarsal
	Phalanges

Table 4. The number and recipe of bone casts seeded in each trial.

Bone	EFSR Trial #1			EFSR Trial #2		EFSR Trial #3		Levelock Creek			BBC	
	Light	Medium	Heavy	Light	Unknown*	Light	Unknown**	Light	Medium	Heavy	Light	Unknown***
Atlas	36	0	0	1	-	5	-	39	0	0	20	-
Axis	36	0	0	4	-	5	-	37	0	0	9	-
C7 Vertebra	36	0	0	1	-	2	-	25	0	0	2	-
Lumbar Verebra	36	0	0	0	-	3	-	21	0	0	5	-
Thoracic Vertebra	36	0	0	1	-	0	-	23	0	0	2	-
Sacrum	36	0	0	3	-	6	-	36	0	0	8	-
Cy1 Vertebra	36	0	0	0	-	17	-	14	0	0	4	-
Cy2 Vertebra	36	0	0	0	-	4	-	38	0	0	4	-
Short Rib	36	0	0	2	-	1	-	25	0	0	0	-
Medium Rib	36	0	0	3	-	2	-	16	0	0	0	-
Long Rib	36	0	0	9	-	3	-	24	0	0	14	-
Scapula	36	36	36	-	33	-	54	36	37	38	-	61
Humerus	36	36	36	-	34	-	71	28	36	22	-	8
Radioulna	36	36	36	-	33	-	59	36	36	36	-	18
Carpals	36	0	0	0	-	14	-	48	0	0	5	-
Metacarpals	36	36	36	-	34	-	61	47	44	0	-	29
Innominate	36	36	36	-	51	-	97	37	36	37	-	45
Femur	36	36	36	-	51	-	68	36	36	36	-	9
Patella	36	0	0	0	-	15	-	25	0	0	23	-
Tibia	36	36	36	-	24	-	36	36	36	36	-	6
Calcaneus	36	0	0	2	-	6	-	24	0	0	9	-
Astragalus	36	0	0	0	-	0	-	8	0	0	30	-
Metatarsal	36	36	36	-	5	-	60	39	42	26	-	30
Phalanges	36	0	0	0	-	17	-	40	0	0	12	-

* The casts used in this trial were removed from EFSR Trial #1, so the recipe used to make them is unknown.

** The casts used in this trial were extras from other casting runs, so the recipe used to make them is unknown.

*** The casts used in this trial were removed from Levelock Creek having not moved, so the recipe used to make them is unknown.

Table 5. Timeline of trial initiation, observation, number of casts recovered at each observation, and percent recovery per trial.

Location	Trial #	Year Initiated	# of Casts Seeded	Years Observed and Number of Casts Recovered 2010	2011	2012	2013	Total % Recovery
EFSR	1	2010	1149	Trial Initiated	130	22	16	15
	2	2010	291	Trial Initiated	34	4	15	18
	3	2012	606			Trial Initiated	182	30
LC	1	2010	1272	Trial Initiated	112	Not Observed	Not Observed	9
BBC	1	2011	368		Trial Initiated	5	0	1

Table 6. Reported observations of floating bones. From Evans (2013a, figure 6.1)

Citation and Page Number	Floating Bones	Taxa	Duration of Floatation	Observation Made In
Alley 2007:39, 40, 42	Ribs, thoracic vertebrae, and articulated vertebrae	Pig (*Sus scrofa*)	1-2 weeks	Standing Water
Ayers 2010:37, table 3, p. 27, table 5, p. 35, appendix C, p. 82, 83, 92	Vertebra, phalanx, other bones	Pig (*Sus scrofa*)	1-2 days	Standing Water
Behrensmeyer 1973:31	Foot bones and vertebrae	Not reported	Hours	Standing Water
Behrensmyer 1975:485	Foot bones and vertebrae	Not reported	Hours	Standing Water
Boaz and Behrensmeyer 1976:57, figure 2	Cranium	Human (*Homo sapiens*)	Not reported	Flume
Coard 1999:1371	Thoracic and lumbar vertebrae, ribs, and sacrum	Mouflon sheep (*Ovis musimon*), Pig-tailed macaque (*Macaca nemestrina*), Alsatian dog (*Canis familiaris*)	7-30 meters	Flume
Coard and Dennell 1995:447	Cranium	Pig-tailed macaque (*Macaca nemestrina*)	Not reported	Flume
Dodson 1973:18	Nearly every bone in the body	Mouse (*Mus*) and Frog (*Rana*)	Few days (mouse), month (frog)	Standing Water
Evans 2010:28	Not reported	Not reported	Month and a half	River, standing water
Frison and Todd 1986:67	Smaller elements'	Indian elephant (*Elaphas maximus*)	Minutes	River
Gnidovec 1978:18, 20, table 3, p. 19, figure 8, p. 21	Not reported	Mammals, birds, and herps	3 hours	Standing Water

Table 6 Continued

Gutierrez and Kaufmann 2007:155, figure 2, p. 158	Lateral tuberosity, head, distal epiphysis of humerus, femur, caudal vertebrae, sacral vertebrae, and others	Guanaco (*Lama guanicoe)*	Several hours	Standing Water
Kaufmann et al. 2011	Many, see Tables 1-3	Guanaco (*Lama guanicoe)*	Minutes	Flume
Morden 1991:77	Cervical vertebra, thoracic vertebra, ribs, calcaneus, and metacarpal	Human (*Homo sapiens*)	5 days	Standing Water
Trapani 1996:116, 148	Cranium, most bird bones	Pigeon (*Columbia livia*)	Not reported	Flume
Trapani 1998:481, and table 1, p. 480	Cranium	Pigeon (*Columbia livia*)	Not reported	Flume
Voorhies 1969:67, text and footnote	Sacrum and sternum	Sheep, coyote (species not reported)	Not reported	Flume
Personal Observations	Nearly every bone in the body	Mammals, birds, frogs, salamanders, snakes, lizards	Seconds to 2.5 months	Buckets, rivers, settling columns, etc.

Table 7. Observed bone hydration rates. From Evans (2013a, figure 6.2)

Citation	Time to Saturation or Sinking
Behrensmeyer 1973:31-32, figure 2	Hours, 70+ hours (time to saturation)
Behrensmyer 1975:485, figure 2, p. 486	Hours, 70+ hours (time to saturation)
Coard and Dennell 1995:442	5 to 7 days (time to saturation)
Dodson 1973:18	Few days to a month (time to sinking)
Gnidovec 1978:18, 20, table 3, p. 19, figure 8, p. 21	8 to 83 hours (time to sinking)
Gutierrez and Kaufmann 2007:155, figure 2, p. 158	Hours (time to saturation)
Trapani 1996:82-83, table 6.1, p. 84	2-13 days (time to saturation)
Young 1989:12,49	Bones released gas for over half an hour
Personal Observation	2.5 months (time to sinking)

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CHAPTER FIVE

CONCLUSIONS

The literature review in chapter two showed that, as a scientific community, we have very little understanding of how decay occurs in fluvial systems, or how bodies and body parts are transported in rivers. While there is considerably more information about the transport of bones in rivers, many studies conflict in their conclusions. The unavoidable conclusion is that the decay and transport of vertebrate tissues downstream is poorly understood. Much more research is needed in each of these subjects before we have a solid grasp of the taphonomic processes occurring in fluvial systems.

What became abundantly clear by comparing predictions from flume research to observations in natural rivers is that the research performed in flumes is not representative of what occurs in nature. The homogenous environments of flumes produce results that are not reliable analogs for natural heterogenous systems. Future research should be performed in rivers so that the results encorporate realistic variability. While scientific reductionism (reducing the number of variables in a research study) is a powerful technique in understanding the world, fluvial systems are complicated enough that removing variables during research produces unrealistic results. As such, the copious observations of bone transport and deposition in modern rivers presented here highlights how much we presently do not understand about taphonomy in natural river systems.

Chapter three presented the results of observing bone orientations in rivers, which demonstrated that our prediction of what orientations bones should adopt was not

observed in the field. Elongate bones showed no preferred orientation relative to flow direction, and no polarity was evident either. Concave bones tended to orient concave down (~70% of the time) however it is unclear how consistent this ratio is. Consequently, readers are cautioned in using this figure analytically because this is but one measurement of what could be a highly variable ratio in natural systems. Flat bones were observed laying flat on the bed, though this orientation provides no useful paleoenvironmental information because flat bones lay flat on nearly every surface. The net result is that bones observed in natural river systems were not oriented as expected; suggesting our understanding of bone orientation during deposition is incomplete.

Chapter four similarly highlighted what we do not understand related to bone density, shape, and transport. There was no association between bone shape and transport, demonstrating that shape is not a controlling variable in bone transport. While shape is important during transport of some bones some of the time, it is not a controlling variable for most bones most of the time, so the variable of shape is not generally predictive of the relative transport potential of different bones. Dense bone casts transported shorter distances than less dense bone casts, however there was considerable overlap in the transportabilities of bone casts of the same shape but with different densities. There does apper to be a relationship between bone cast density and transport, suggesting that density is important in determining transport potential. However, the variable of density could not predict the transportability of a given sample, so it is not the only important variable governing bone transport. Consequently, it is important to

identify what other variables also control bone transport and deposition in fluvial systems.

The literature suggests that bones are constantly changing density during weathering, transport, and deposition through hydration/dehydration and the removal of organic material (e.g., marrow, fats, etc.). This change of density radically alters bone transport potential from floating, to neutrual buoyancy, to bedload transport. The radical change in transport potential between floating and bedload transport suggests that changes in bone density is the single most important variable determining bone transport potential, but the density of a bone at any given time does not predict a bones relative transportability. So while the variable of density change is the most important in determining bone transport, bone density itself does not correlate well with transport potential.

In addition, the persistant observation that bones are interacting with the bed via short or long term burial, or being deposited in association with bed obstructions, suggests that interactions with the bed are critically important in determining bone transport and deposition. The net result is that changes in bone density is the most important variable in determining bone transport (but density alone is not predictive of relative transportability), while interactions with the bed largely control bone deposition (also a component of relative transportability). These results suggest a more complicated model of bone transport and deposition, where bone densities are constantly changing, and interactions with the bed constanly alter bone orientations, deposition, and movement. This model is much more realistic than the more simplictic models presented

in previous literature. Consequently, as a scientific community we need to embrace the observed complexity between bones and rivers during transport.

Realizing the greater complexity of fluvial systems and their interactions with bones has implications for interpreting skeletal assemblages derived from fluvial systems. The analytical techniques based on a simplistic understanding of bone transport are either wrong entirely, or highly suspect. As a community we should discontinue using these methods until we know if they ever work, and if they do work, under what conditions. In the mean time, what methods will replace them? New analytical methods must be based on massive amounts of data incorporating changes in bone density under different conditions. Gathering these data will be incredibly difficult and time consuming. More importantly, if a complex bone transport and deposition model is developed, it may be too unweildly to use to interpret skeletal assemblages of any age (e.g., forensic, archaeological, or paleontological).

This means we should perform more fluvial bone transport research in rivers, but be realistic in understanding that, even with perfect data, it may not be possible to generate a useful or meaningful skeletal assemblage analysis tool to interpret skeletal assemblages derived from fluvial systems. While a herculean and sobering task, we should pursue this course rather than continuing to use methods that have never been shown to work under any natural fluvial conditions, and contain an unknown quantity of error in their interpretations.

Ultimately this is a wake up call for the scientific community reaffirming that we should test our analytical methods before they are used for decades. Similarly we should

ensure the methods we use to investigate taphonomic processes (e.g., flumes) produce data applicable to natural systems before we use them for decades. Being this conservative in the methods we use will prevent the loss of research time, money, and reduce the risk of building understanding on suspect results and interpretations. Moreover, in other disciplines it is standard practice to test research methods and analytical techniques before widespread adoption. The historical sciences should adopt this policy both to improve the quality and quantity of the science performed, but also to produce information more efficiently.

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