Laboratory – Estimating Dinosaur Speed from Trackways
Part I – Testing the Method of R. McNeill Alexander (1989)

Fossil footprints are of great interest to paleontologists because they record information about what an extinct animal was doing while it was alive and moving around. Careful analysis of fossil tracks has the potential to reveal several aspects of the behavior of the trackmaker, including posture, herding behavior, and walking or running speed. A basic fact of vertebrate motion is that the faster an animal is moving the farther apart its footprints fall along a trackway (Figure 1). By measuring the spacing of fossil footprints it is possible to estimate the speed of the trackmaker, but only after making several assumptions based on footprint size and the behavior of a wide range of living animals. A widely applied method for estimating speed from trackways was developed through the research of R. McNeill Alexander, an expert in biomechanics. This lab is a group exercise designed to lead you step-by-step through the methods and principles involved in estimating speed of movement from trackway data using Alexander's method. First we will test the method on humans to see how accurate it is, and then we will apply it to measurements taken from a variety of dinosaur trackways.

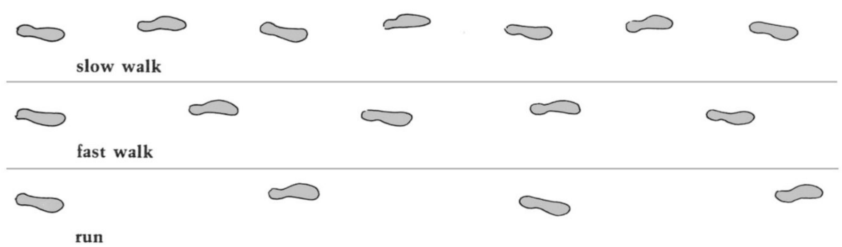


Figure 1 Footprint spacing increases with increasing speed (after Alexander, 1989).

Establishing the Nature of Trackway Data

Footprints / tracks: individual foot impressions. In a continuous line these form a **trackway**. Footprint size is also important because it can be used to estimate leg length, which is an important parameter for estimating speed.

Estimating leg length from footprint size.

How do we arrive at an estimate of how long an extinct animal's leg was from the size of its footprint? We note a basic physiological fact - larger animals have larger feet. This makes sense because the larger you are the more you weigh and the larger your feet need to be to support that weight. The best way to test this idea is to measure foot size and leg length for a wide variety of individuals (and species) and examine the data to see if there is a simple relationship. For dinosaurs, Alexander (1989) notes that most dinosaurs have leg lengths that are about 4 x the length of the foot (based on his own copious measurements of a variety of dinosaur skeletons).

Group Activity: Measure the leg length and foot length for all students in the class. Divide leg length by foot length and compute the average for the class to determine the relationship between leg length and foot length for *Homo sapiens*. How much variation is there among different individuals? Record the average and the smallest and largest ratio observed in the class.

Establishing the relation between speed and stride length.

Stride: The distance between footprints from the same leg / foot.
Have a volunteer walk slowly, then quickly, then run past the class. Measure the distance between footprints of the same foot (right or left). This is the **stride** (see Figure 2).

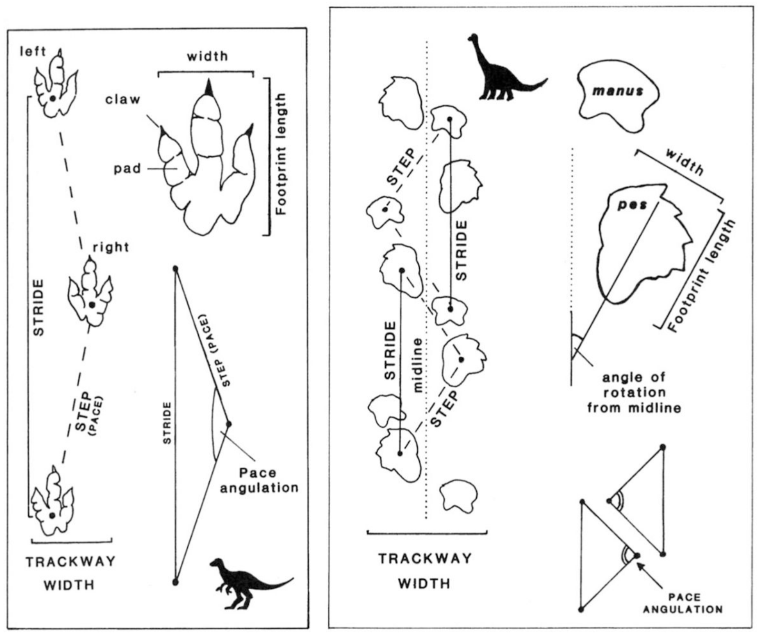


Figure 2 Trackway parameters illustrated for bipedal and quadrupedal dinosaurs. From Lockley and Hunt (1995).

Dynamic Similarity and Dimensionless Speed

Alexander's method is based on the concept of dynamic similarity, which is the idea that structurally similar animals (for example, tetrapods) function equivalently according to the laws of physics. Put simply, the dynamic differences between a Chihuahua and an elephant when they are both walking come from their different sizes. If we can adjust for size, they will show the same dynamic behavior. How do we adjust for size? We need to calculate a quantity called **dimensionless speed**. This is speed that has been adjusted for the size of an organism based on its leg length and the force of gravity. Two animals moving at the same dimensionless speed will be dynamically similar. Alexander (1989) measured speed and stride length for a variety of living animals, including large and small mammals, ostriches, and humans. When he calculated **relative stride** (stride / leg length) and dimensionless speed, he discovered a consistent linear relationship between these two quantities (Figure 4). In other words, regardless of what kind of tetrapod you are, your stride is related to your speed in the same way, once you make adjustments for your size. If we make the reasonable assumption that extinct tetrapods like dinosaurs functioned the same way as the great variety of living tetrapods, then we can apply this same relationship between stride and speed to dinosaurs. Measuring stride from a fossil trackway and estimating leg length from the size of the footprint, we can arrive at an estimate of speed for different types of dinosaurs.

Group Activity: Testing the Dynamic Similarity Method for Estimating Speed from Trackways

Materials
tape measure
chalk
buckets and lots of water
long outdoor walkway, preferably concrete

1. Mark off a length of concrete walkway with chalk (at least 30 feet or so - we'll call this the runway). Wet a wide enough area near the beginning of the runway to produce footprints from at least one foot. One team of students should be in charge of timing how long it takes the test subjects to traverse the runway (direct measurement of speed). Put another team of students in charge of marking footprints with chalk (they will dry quickly) and measuring the stride length. This is best done by measuring the distance across as many strides as can be discerned on the runway and then dividing by the number of strides to get an average value for stride length.

2. Choose a student to be the test subject. Allow them some lead space to start moving by walking or running through the water. Begin timing as they enter the runway and stop timing as they exit the runway. Record their time and runway distance to calculate their actual speed. Measure and record their average stride.

3. Repeat the above experiment with several different students of different size, moving at different speeds (walking and running). Tabulate the data and calculate estimated speeds using leg length estimated from foot size (see Figure 3 for procedure and calculations). Compare estimated speeds to measured speeds.

Worksheet and Questions for Part I

Record all measurements and calculations in the table below.

Data Table for Estimating Speed from Stride Data

	Step 1		Step 2	Step 3	Step 4	Step 5	
Trial Description	**measured** foot size	x4 estimated leg length	**measured** stride length	relative stride length	estimated dimensionless speed	estimated speed	**measured** speed

Answer the following discussion questions.

1. What is the approximate relationship between foot length and leg length in *Homo sapiens* based on the average of measurements from people in this class? What is the maximum and minimum deviation from the average?

2. As speed increases from walking to running, what happens to stride length?

3. Alexander (1988) states that animals are walking at dimensionless speeds below .7 but switch to a running gait at higher dimensionless speeds. Do your results agree or disagree with this? Explain.

1. How do the estimated values compare to the measured values for speed? Calculate a percent error for each pair of values:

$$\text{Percent Error} = \frac{(\text{Estimated Value - True Value})}{\text{True Value}} \times 100$$

5. What are two potential sources of error is this method of estimating speed? Assume that the measurements are made accurately and focus on the assumptions of the method itself.

Computer Analysis Problem: To create a spreadsheet or computer program to analyze trackway data, we need to derive an equation for the relationship between relative stride and dimensionless speed (shown by the straight line fit to the data shown on the graph in Figure 4.)

Hints: Recall from your high-school algebra that the equation for a straight line is:

$$Y = mX + B$$

where m is the slope of the line and B is the Y intercept.

To calculate the slope (m) chose any two X,Y points on the line. Slope = $\Delta Y / \Delta X$

$$m = (Y1 – Y2) / (X1 – X2)$$

Once you have the slope (m), plug any point on the line into the equation Y = mX + B and solve for B.

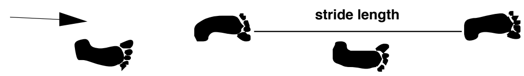
Now you have the equation for the relationship between relative stride and dimensionless speed. However, as derived, the equation calculates relative stride given dimensionless speed. We would like to be able to calculate dimensionless speed by plugging in an estimate of relative stride. This requires that you rearrange the equation Y = mX + B to solve for X.

$$X = (Y-B) / m$$

Estimating Speed from Trackway Measurements

Step 1: Estimate leg length from footprint size - **leg length = 4 x foot length** for dinosaurs

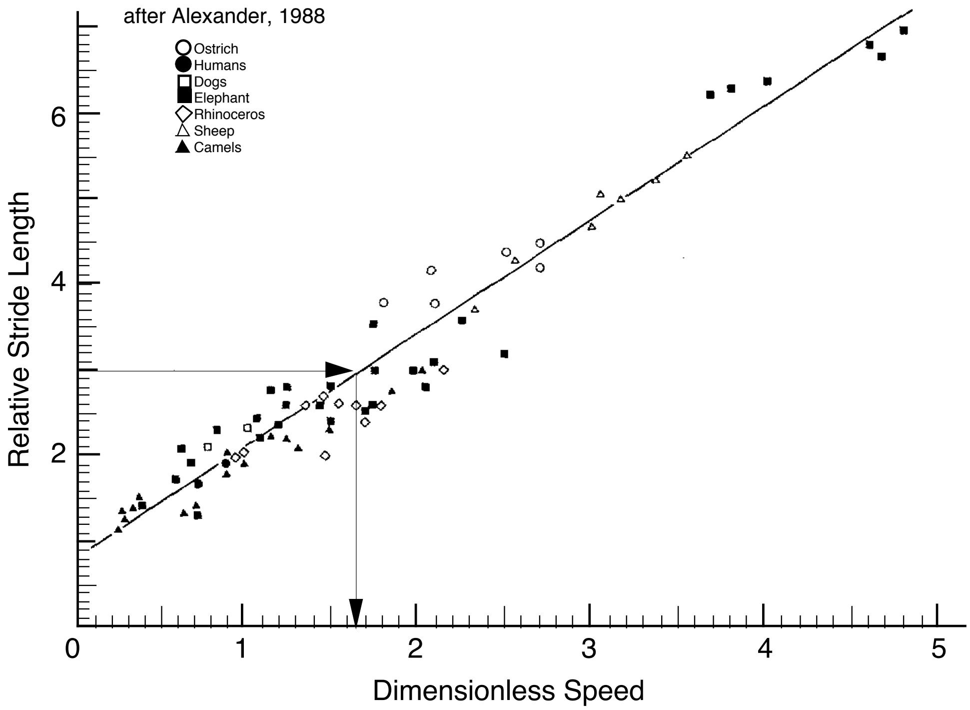
Step 2: Measure stride length from trackway.



Step 3: Calculate relative stride length .

$$\text{Relative Stride Length} = \frac{\text{stride length}}{\text{leg length}}$$

Step 4: Estimate dimensionless speed from relative stride length based on measurements from living tetrapods.



Step 5: Solve the dimensionless speed equation for speed.

<u>Gravitational Acceleration</u>
9.8 meter/sec^2
980 cm/sec^2
32 ft/sec^2

$$\text{speed} = \sqrt{\text{leg length X gravitational acceleration}} \times \text{dimensionless speed}$$

Figure 10.3 Chart outlining procedure for estimating speed from trackway data based on assumption of dynamic similarity.

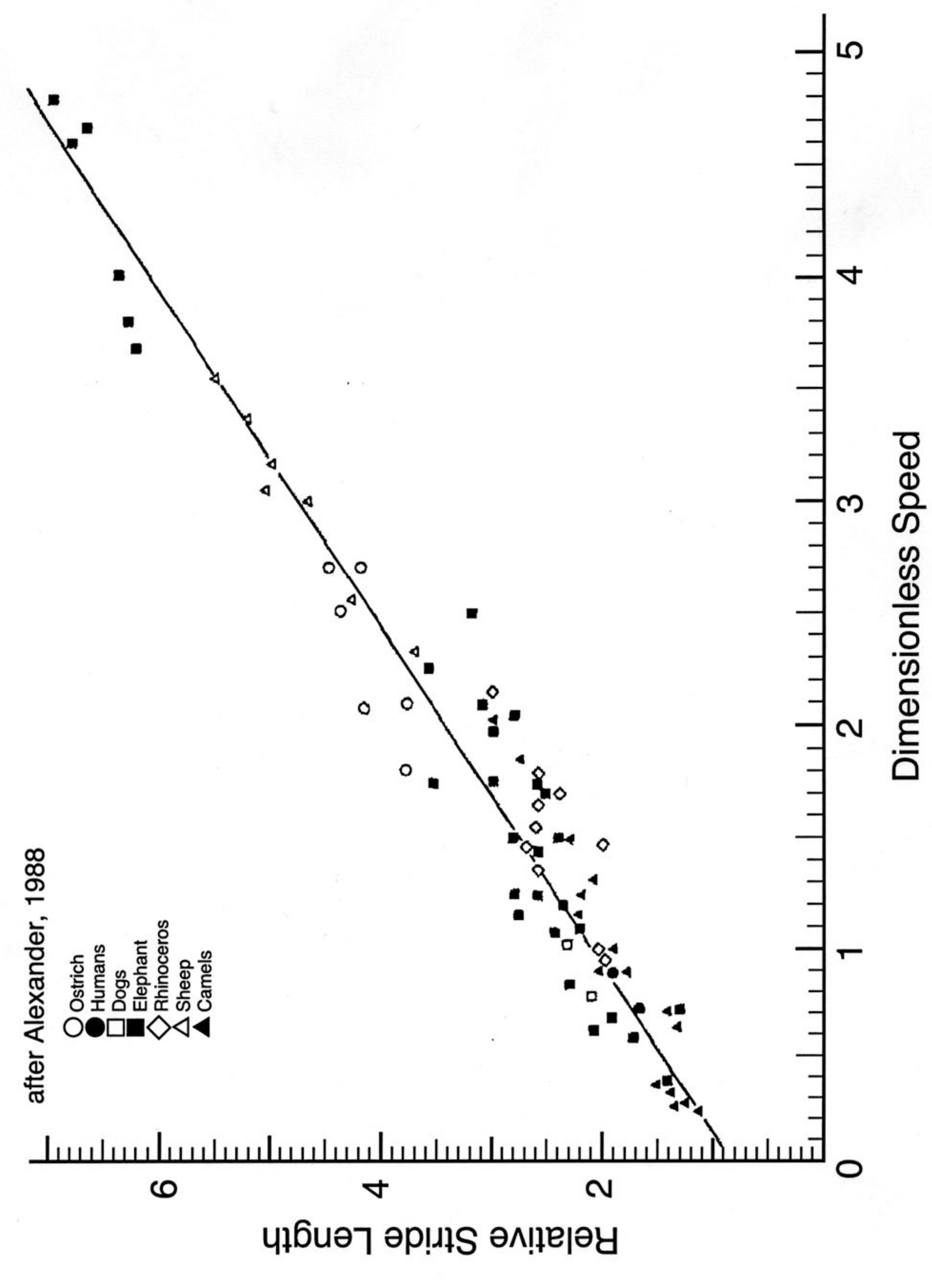


Figure 4 Graph for estimating dimensionless speed from relative stride length.

Laboratory – Estimating Dinosaur Speed from Trackways
Part II – Applying the Method

Having demonstrated that Alexander's method works, we can now apply it to actual fossil trackways to learn something about the behavior of dinosaurs. Figures 5 and 6 show five different dinosaur trackways made by different species of dinosaurs during different periods of the Mesozoic. For each trackway, use the scale bar provided to measure footprint length and stride length. Try to be as accurate as possible, measuring as many strides as possible for each trackway to obtain an average. Note that some trackways only permit measurement of a single stride.

Trackway #5 (Figure 6) is shown in a photograph with a meter stick lying between tracks of the left and right foot. Estimate this distance (the **pace**) and then double it to estimate the stride. Recall that there are 100 centimeters in a meter and that a meter stick is divided into 10 cm segments (these are enhanced with black lines in the photograph). Because of the angle at which the photo was taken the apparent distances are somewhat distorted – for example, the footprint in the foreground is about 30 cm in length, but looks larger relative to the measuring stick. Make your best estimate!

Record your measurements and calculations in the table below.

Estimating Dinosaur Speeds from Trackway Data

Alexander (1976) estimates leg length to be 4x foot size.

	Step 1		Step 2	Step 3	Step 4	Step 5	
Trackway	**measured** foot size	estimated leg length	**measured** stride length	relative stride length	estimated dimensionless speed	estimated speed	MPH
1. Cret. Ornithopod	x 4						
2. Jur. Sauropod	x 4						
3. Trias. Theropod	x 4						
4. Trias. Prosauropod	x 4						
5. L. Cret. Theropod	x 4						

Meters / sec x 2.24 = miles / hour (MPH)

Answer the following discussion questions.

1. Which dinosaurs appear to have been walking and which were running? What do the running dinosaurs have in common and why might they have been habitually moving faster than other dinosaurs?

2. What does it mean when the method for estimating speed from trackways yields a negative number?

3. Do these estimates probably represent the extremes of dinosaur speed? In other words, should we conclude from these trackways that most dinosaurs were incapable of running?

Computer Problem: Make a computer spreadsheet with the measurements and calculations found in the table above.

Repeatedly making the same set of calculations for different measurements is laborious and tedious. By entering data and formulae into a spreadsheet, multiple calculations can be made effortlessly. Furthermore, measurements or estimates can be adjusted and the effect of these adjustments on the computed value can be seen immediately.

1. Recreate the above table of data and calculations for estimating dinosaur speed from trackways in a computer spreadsheet application such as Excel. To estimate speed from stride length (SL) and leg length (LL) use the following equation:

   $v = 0.25 * g^{.05} * SL * LL^{-1.17}$ (from Alexander, 1976)

2. Reexamine trackway #5 – the theropod trackway shown in the photos in Figure 6. Use the spreadsheet to test the effect on estimated speed of adjustments to your measurements of stride length and foot length.

   a. What happens to estimated speed if you decrease or increase your estimate of foot length?

   b. What happens to estimated speed if you decrease or increase your estimate of stride length?

Add four more rows to the spreadsheet showing the above adjustments and calculations.

What to Hand In: Prepare a typed lab report with a short introduction describing the objectives and methods of this laboratory exercise. Include both tables of measurements and calculations, answers to all discussion questions, and a printout of your spreadsheet.

References

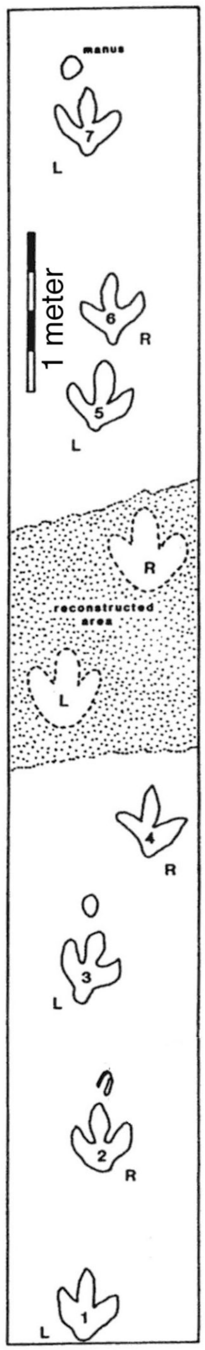
Alexander, R. McNeill, 1976, Estimates of speeds and dinosaurs. *Nature* 261:129-130.

Alexander, R. McNeill, 1989, *Dynamics of Dinosaurs and Other Extinct Giants*, Columbia University Press.

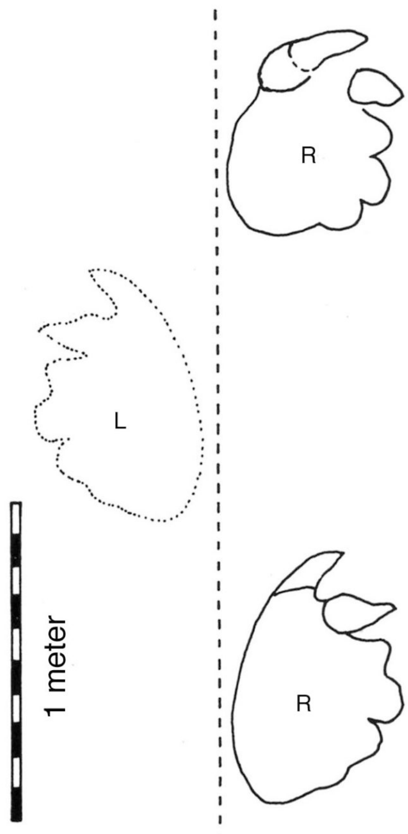
Kuban, G. K., 2004, An Overview of Dinosaur Tracking [online]. Available: http://paleo.cc/paluxy/ovrdino.htm [6-08-2005].

Lockley, M. and Hunt, A.P., 1995, *Dinosaur Tracks and Other Fossil Footprints of the Western United States*, Columbia University Press, 338 p.

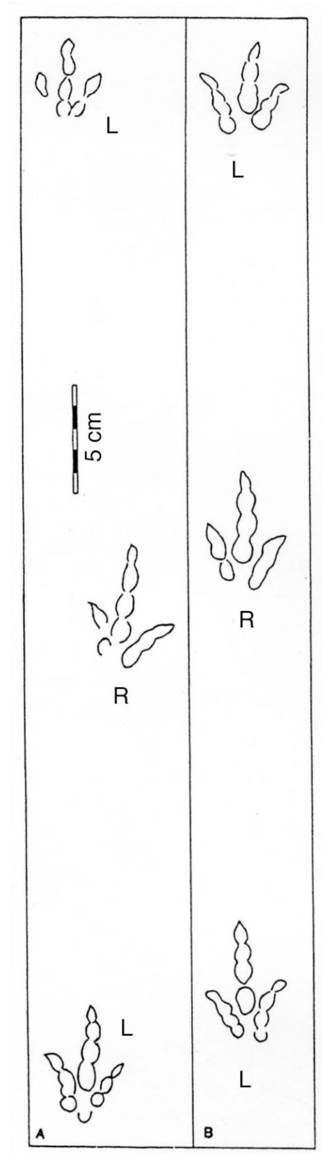
Figure 5 Dinosaur Trackways



1. Cretaceous Ornithopod, Dakota Sandstone, Lamar, Colorado



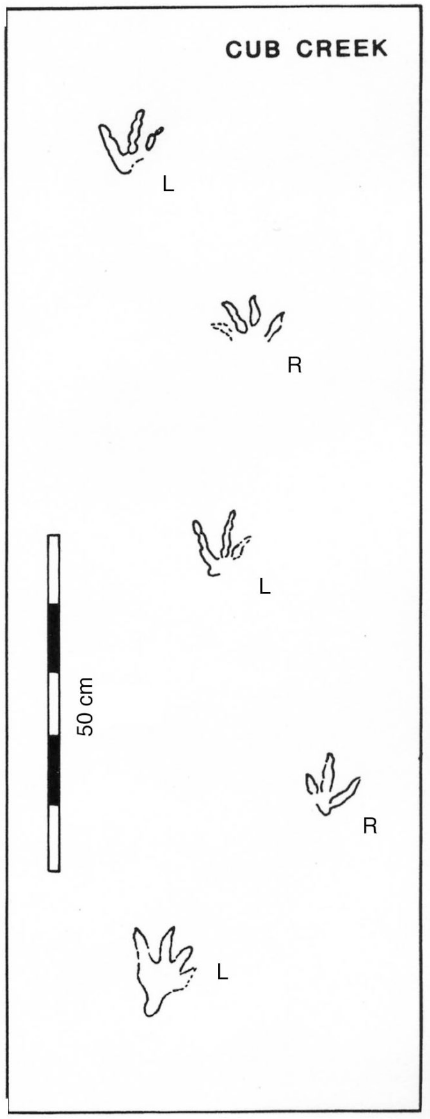
2. Jurassic Sauropod, Morrison Formation, Bullfrog, Utah



3. Triassic Theropod, Sheep Pen Sandstone, New Mexico

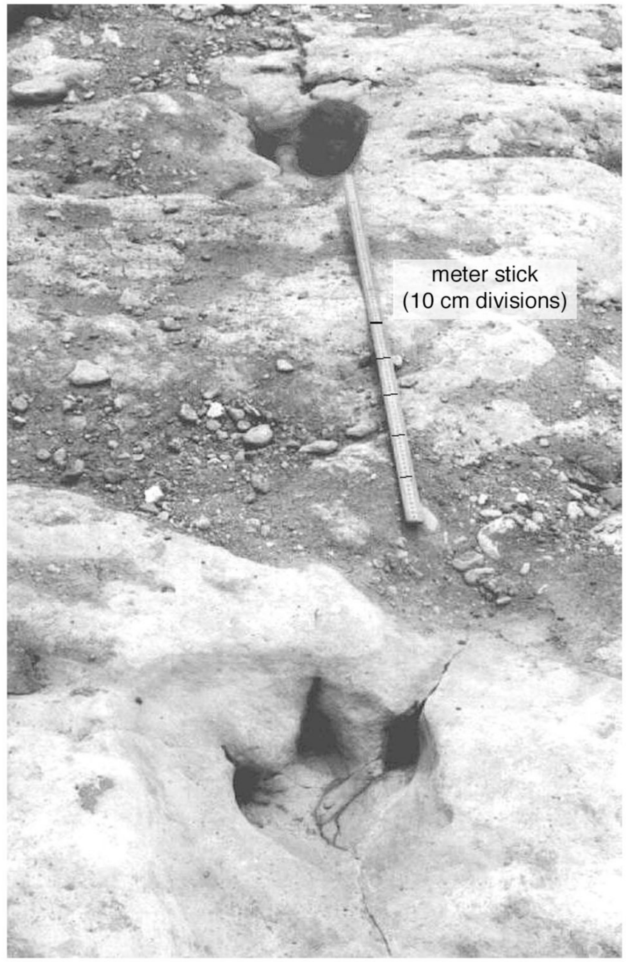
Trackway diagrams taken from Lockley and Hunt, 1995, Dinosaur Tracks, Columbia University Press.

Figure 6 Dinosaur Trackways



4. Triassic Prosauropod
   Utah

Trackway diagrams taken from Lockley and Hunt, 1995, Dinosaur Tracks, Columbia University Press.



5. Lower Cretaceous Theropod
   Dinosaur Valley State Park
   Texas.

Photograph (C) 2002, Glen J. Kuban