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# THE RECAPITATION OF A LATE JURASSIC THEROPOD DINOSAUR: A SUCCESSFUL APPLICATION OF RADIOLOGICAL SURVEYING FOR LOCATING SUBSURFACE FOSSILIZED BONE

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ABSTRACT: **A modified, shielded gamma scintillator has proven useful in locating subsurface fossil bone in a variety of matrices, as evidenced by the recovery of a buried dinosaur skull in an abandoned quarry. The equipment, and the method of data gathering and analysis is described, and limitations of the technique are discussed. While this technique is not a universal solution, it has many applications in vertebrate paleontology and is the best method devised to date to locate buried fossil bone.**

RESÚMEN: **La utilidad de un "shielded gamma scintillator" modificado para localizar huesos fósiles incluídos en diferentes materiales bajo la superficie, es probada con el hallazgo de un cráneo de dinosaurio en una cantera abandonada. Se describe el equipo utilizado, los métodos de recogida de datos y análisis y se discuten las limitaciones de la técnica. Aunque esta técnica no es una solución universal, tiene muchas aplicaciones en paleontología de vertebrados y es el mejor método disenado hasta el momento para localizar huesos fósiles enterrados.**

## INTRODUCTION

Dinosaur paleontology is often cursed with "headless wonders"; good skeletons missing only one major part - the skull. Cranial morphology is such an important component in phylogenetic analysis that most dinosaur paleontologists would rather have a good skull with no postcranium than a good postcranium without a skull. We here report the use of a radiological survey instrument to locate the skull of one of these headless wonders, describe the technique of radiological surveying, and discuss its implications for vertebrate paleontological studies.

In 1990, while inventorying paleontological sites in Dinosaur National Monument, Dr. George Englemann discovered pedal phalanges and caudal vertebrae of a theropod dinosaur weathering out of the Salt Wash Member of the Upper Jurassic Morrison Formation. The exposed bones were difficult to reach, they were 7 m off the ground in a sandstone layer dipping about 70°. These conditions made excavation difficult and time consuming, and three-and-a-half field seasons were required to complete excavated and helicopter the skeleton out.

The specimen was well worth the effort. It is one of the most complete theropod skeletons ever found in Upper Jurassic rocks. The skeleton lay on its left side and is in nearly perfect condition, including a furcula in contact with both scapulocoracoids (CHURE & MADSEN, 1996) and a complete gastral basket. The neck was hyperdorsoflexed and complete except for the atlas. The greatest disappointment was the lack of the skull, especially as that was the last part of the skeleton to be reached and for the three years of excavation, the specimen had shown little postburial disturbance.

The taphonomy of the site has been described by HUBERT & CHURE (1992). The skeleton (Fig. 1) was in a sequence of sandstone, pebbly sandstone, and

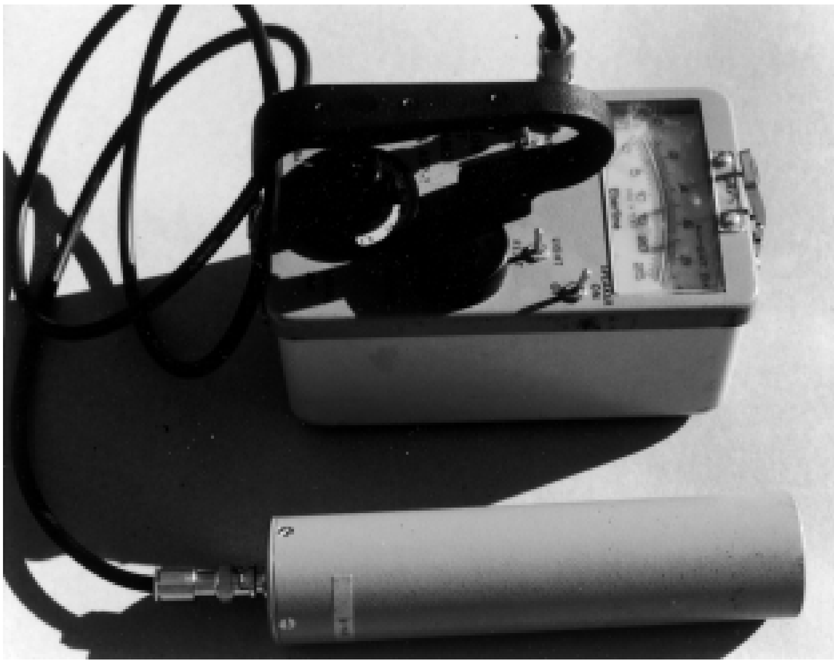

Fig. 1 - Eberline Analog Smart Portable Micro-Roentgen survey meter with a model SPA-8 sodium iodone detector.

conglomerate about 5 m thick. It was buried in a 60 cm thick conglomerate layer at the bottom of a channel about 1.4 m deep. The river was braided, wide, and shallow, with multiple channels which shifted positions during flood stage. The skeleton lay at the top of the conglomerate and the conglomerate is overlain by trough cross bedded and plane bedded sandstones. There is no scour at the top of the conglomerate, suggesting that the water level did not fall low enough to expose the skeleton.

The flow that deposited the skeleton and the conglomerate was substantial, with chert pebbles up to 5 cm in length were found wedged between the transverse process of some anterior caudal vertebrae and clay rip up clasts of similar size were found under the ilium and many of the ribs on the up side of the specimen. This, coupled with the lack of isolated teeth or skull fragments in the area of the neck, led us to suspect that if the skull had been attached to the skeleton when is entered the river it had probably been washed away. Additional excavation was done after the skeleton was removed in the hope that the skull had been only slightly displaced, as in magnificent *Albertosaurus libratus* described by LAMBE (1917). However, this additional work turned up nothing. At this point additional blind excavation was out of the question because the dip of the sandstone plus the fact that the quarry face was perpendicular to strike which meant that additional digging would require tunneling. The project finally reached the point where we had to give up and go home. We had a great specimen, but it was still a disappointment that after so much time and hard work the gods had chosen to cheat us out of the skull.

Unbeknownst to the crew at Dinosaur National Monument, one of us (RJ), was experimenting elsewhere with radiological survey instruments to locating subsurface bones. The method had been successful in locating two new dinosaurs with skulls in the Cedar Mountain Formation in central Utah. When the current authors got in contact with one another we decided that even though the situation seemed hopeless, we would try the equipment at the Dinosaur National Monument theropod quarry. After all, things could get no worse than they already were and maybe, just maybe, we would cheat the gods.

## RADIOLOGICAL SURVEYING EQUIPMENT AND METHODS

Radiological surveying utilizes instruments designed to detect and measure the gamma radiation that is emitted by uranium and/or vanadium concentrated in the bone during fossilization.

The radiation survey instrument used to locate the theropod skull at Dinosaur National Monument is an Eberline Analog Smart Portable Micro-Roentgen ( R) model ASP-1 with a model SPA-8 sodium-iodine radiation detector (Fig. 1). The detector is mounted inside a thick lead shield (Fig. 2). The lead shield completely encloses the detector except for a 1.25 cm opening at the top for a electronic cable and

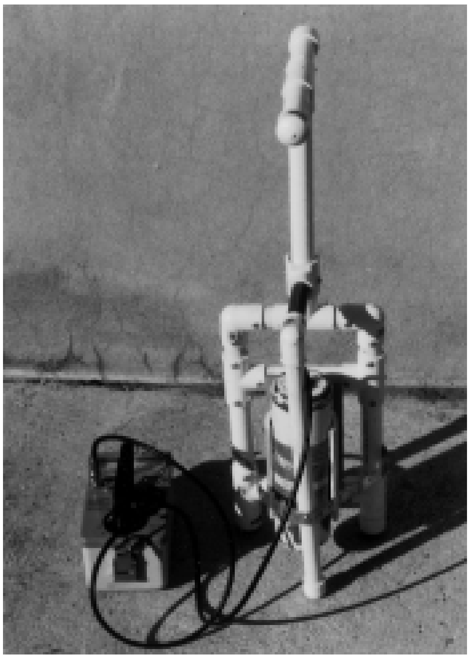

Fig. 2 - Radiological survey instrument with detector in lead shield, mounted in a PVC plastic frame.

2.5 cm diameter window at the bottom for the detector (Fig. 3). By enclosing the detector in a lead shield, the detector is shielded from most of the normal site background radiation (7-8 R.hr$^{-1}$) and the instrument background reading is reduce to 1 to 2 R.hr$^{-1}$, allowing the instrument to detected the low level (<6.5 R.hr$^{-1}$) gamma radiation emitted by the fossil bone. Without the shielding the very low level radiation emitted from the bone would be masked or over shadowed by the normal background radiation of the matrix.

The lead shield is mounted in a holder which is designed to position the detector at a 90° angle to the ground surface, to facilitate the handling of the shield, and to keep the detector window at a constant distance (10 cm) from the ground surface each time a reading is taken. The 2.5 cm diameter window collimates the gamma radiation emitted by the bone. This provides directional capability and greater transitional definition as the detector passes over the buried bone because the detector sees only the gamma radiation that is emitted at a 0° angle from the bone with respect to the face of the detector window.

The area to be surveyed is marked with a grid, then a radiological survey is conducted using the radiation measuring instrument described above. Each reading is recorded on the data sheet with respect to its location on the grid. At each grid location, the survey instrument will always read either background radiation or elevated radiation from fossilized bone or something else that has concentrated the uranium. In horizontal or beds with low angle dip the radiological survey equipment can be operated by one person, with another person recording the data. However, at the Dinosaur National Monument theropod quarry the quarry face was near vertical and this required a second person to hold the detector perpendicular to the quarry face while another person handled the Eberline ASP-1 meter, and a third recorded the data.

After the survey is completed, the data is entered into a computer spread sheet (Fig. 4). The next step is to delete the radiation background readings. This leaves only those readings that are higher than the background. The only object that will trigger a reading on the radiation survey instrument is gamma radiation from some radioactive source and thus each of these elevated readings indicates the location of something that has concentrated the uranium.

## THE THEROPOD QUARRY RADIOLOGICAL SURVEY

Radiological measurements of the prepared theropod skeleton in the lab at Dinosaur National Monument gave readings of 6.5 R.hr$^{-1}$. This is 4.5 R.hr$^{-1}$ higher than the theropod quarry background radiation readings of 1 to 2 R.hr$^{-1}$. The 6.5 R.hr$^{-1}$ reading indicates that uranium was deposited during the fossilization process and that the bone had concentrated enough uranium to make a radiological survey feasible with a reasonable chance of success.

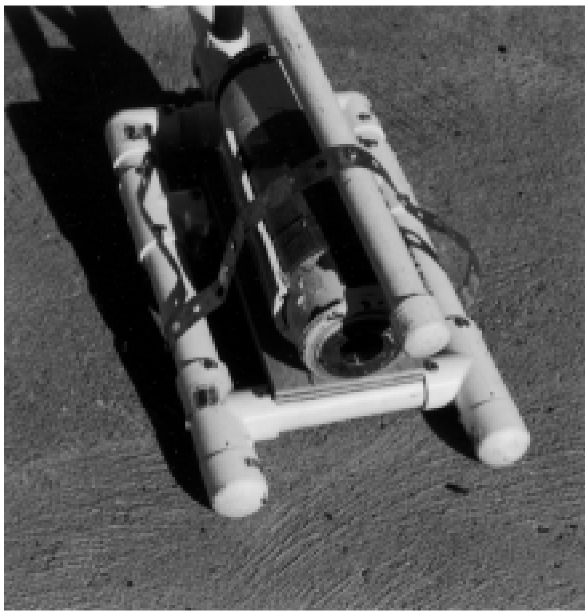

Fig. 3 - Underside of the lead shield and the 2.5 cm window for the sodium-iodine detector.

| Meters | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.8 | 1.8 | 2.0 | 1.8 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 1.6 | 1.5 | 2 | | |
| 0.1 | 1.8 | 2.0 | 2.0 | 2.2 | 2.0 | 2.0 | 2.0 | 2.3 | 2.0 | 2.0 | 2.0 | 2.0 | 2.2 | 2.2 | 2.2 | 2.0 | 2.0 | 1.9 | 1.8 | 2.0 | |
| 0.2 | 1.8 | 1.8 | 1.8 | 2.0 | 2.0 | 1.9 | 1.9 | 1.9 | 1.8 | 2.3 | 2.0 | 2.2 | 2.3 | 1.9 | 1.3 | 1.2 | 2.0 | 2.0 | 2.0 | | |
| 0.3 | 1.8 | 1.7 | 1.5 | 1.8 | 2.0 | 2.0 | 2.3 | 2.0 | 2.3 | 2.3 | 2.3 | 2.0 | 2.0 | 2.2 | 2.0 | 2.0 | 1.7 | 1.8 | 2.5 | 2.0 | |
| 0.4 | 1.8 | 1.6 | 1.8 | 2.0 | 1.8 | 1.7 | 2.2 | 2.1 | 1.8 | 2.0 | 2.0 | 2.1 | 2.2 | 2.2 | 1.9 | 2.1 | 2.2 | 2.0 | 2.8 | 2.0 | 1.8 |
| 0.5 | 2.2 | 2.0 | 2.2 | 1.6 | 1.8 | 1.5 | 1.8 | 2.2 | 2.2 | 2.3 | 2.3 | 2.2 | 2.6 | 2.3 | 2.7 | 3.2 | 4.2 | 6.4 | 4.8 | 2.7 | 2.0 |
| 0.6 | 2.0 | 1.8 | 2.0 | 1.8 | 1.6 | 1.8 | 1.8 | 2.2 | 2.3 | 2.3 | 2.0 | 2.2 | 2.2 | 2.4 | 2.7 | 3.3 | 4.2 | 4.7 | 3.5 | 2.6 | 2.1 |
| 0.7 | 1.8 | 1.5 | 1.8 | 1.8 | 1.8 | 1.8 | 2.0 | 2.0 | 2.0 | 2.2 | 2.2 | 1.9 | 2.2 | 2.0 | 2.0 | 3.0 | 3.4 | 3.0 | 2.5 | 2.5 | 2.0 |
| 0.8 | 1.8 | 1.6 | 1.8 | 2.0 | 1.9 | 1.8 | 1.8 | 2.4 | 2.2 | 2.7 | 2.6 | 1.8 | 1.8 | 1.8 | 2.0 | 2.4 | 2.8 | 2.6 | 1.5 | 1.5 | 1.8 |
| 0.9 | 2.0 | 2.0 | 2.0 | 1.6 | 1.5 | 1.6 | 1.0 | 2.6 | 2.0 | 2.6 | 2.5 | 2.0 | 1.8 | 1.8 | 2.4 | 2.8 | 3.0 | 2.6 | 2.2 | 1.8 | 1.8 |
| 1.0 | 2.0 | 2.0 | 2.3 | 2.0 | 1.8 | 1.8 | 1.8 | 2.2 | 2.0 | 2.5 | 2.4 | 2.4 | 2.2 | 1.8 | 2.0 | 2.4 | 2.7 | 2.6 | 2.0 | | |
| 1.1 | 2.2 | 2.2 | 2.2 | 2.3 | 2.0 | 2.0 | 2.2 | 2.2 | 2.4 | 1.9 | 2.3 | 2.0 | 2.2 | 2.3 | 2.3 | 1.9 | 2.3 | 2.0 | 2.1 | 1.8 | 2.3 |
| 1.2 | 1.8 | 1.9 | 1.9 | 1.9 | 2.3 | 2.3 | 2.4 | 2.3 | 2.1 | 2.1 | 1.6 | 1.8 | 2.0 | 2.0 | 2.2 | 2.0 | 2.5 | 2.0 | 2.0 | 1.9 | 1.6 |
| 1.3 | | 2.0 | 2.0 | 1.9 | 2.0 | 2.8 | 3.3b | 3b | 2.6 | 1.9 | 1.8 | 1.8 | 1.6 | 1.9 | 1.9 | 2.2 | 2.3 | 2.1 | 1.9 | 1.6 | 1.6 |
| 1.4 | | | 2.0 | 1.8 | 1.9 | 2.4 | 2.6 | 2.8b | 2.4 | 2.2 | 1.8 | 1.9 | 2.0 | 2.0 | 2.0 | 1.8 | 1.8 | 1.8 | 2.0 | 2.0 | 1.8 |
| 1.5 | | | 1.6 | 2.0 | 2.0 | 2.2 | 2.3 | 2.6 | 2.7 | 1.9 | 2.1 | 1.9 | 1.8 | 1.8 | 1.7 | 1.4 | 1.5 | 1.9 | 1.8 | 1.6 | 1.6 |
| 1.6 | | | | | | 1.7 | 2.4 | 2.9 | 3.5b | 3.0 | 2.7 | 2.7 | 2.0 | 2.0 | 1.4 | 1.5 | 1.9 | 1.8 | 1.7 | | |
| 1.7 | | | | | | | 1.8 | 2.3 | 2.5 | 2.3 | 2.1 | 2.0 | 2.2 | 1.8 | 2.0 | 1.9 | 1.9 | 1.8 | 1.8 | | |
| 1.8 | | | | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | | | | |
| 2.0 | | | | | | | | | | | | | | | | | | | | | |

Fig. 4 - Total data set from radiological survey of theropod site at Dinosaur National Monument, June 24, 1995. Survey was done with the instrument shown in Figures 1-3. Readings are in R.hr$^{-1}$. **b** = sauropod bone exposed in quarry.

A radiological survey of the theropod quarry was conducted in June of 1995. The area surveyed measured 2 x 2 m, encompassing the area where the theropod skeleton was found. A grid was established using string to mark the outside boundary of the grid (Fig. 5). The grid was divided into 10 x 10 cm squares. A tape measure was used to locate the boundaries of the 10 cm squares inside the grid. A reading was taken inside each 10 cm square and recorded on a data sheet. After the survey was competed, the data was entered in a computer spread sheet for analysis. Figure 4 shows all the radiological survey readings and their location with respect to the survey grid. For analysis the radiation background readings must be deleted, as shown in Figure 6.

A fragment of a sauropod rib was still imbedded and exposed in the quarry sandstone. This bone is inside the survey grid in the lower left hand quarter and marked with the letter "b" in Figures 4, 6. Readings on this bone were 2.6 R.hr$^{-1}$ to 3.6 R.hr$^{-1}$, which indicated that the equipment was able to detect bone on this site.

The first step in analyzing the survey data is to establish the background readings. Background readings will indicate areas where uranium has a normal distribution and where it is concentrated in the rock. When the bones are widely space apart there is sudden change in readings as the detector passes over a bone. The readings will suddenly elevate and then drop off as the detector moves past the bone. By taking the mean of the readings and applying a plus and minus number to all the readings the background can be established.

The radiological background reading with a shielded detector for the theropod quarry is a mean of 2.0 +/- 0.5 R.hr$^{-1}$. Figure 4 shows all the radiological survey data on a computer spread sheet. Figure 6 shows the radiological survey data with the background readings plus all readings less than 2.5 R.hr$^{-1}$ deleted. The radiological readings that are greater than 2.5 R.hr$^{-1}$, indicate that there is a ra-

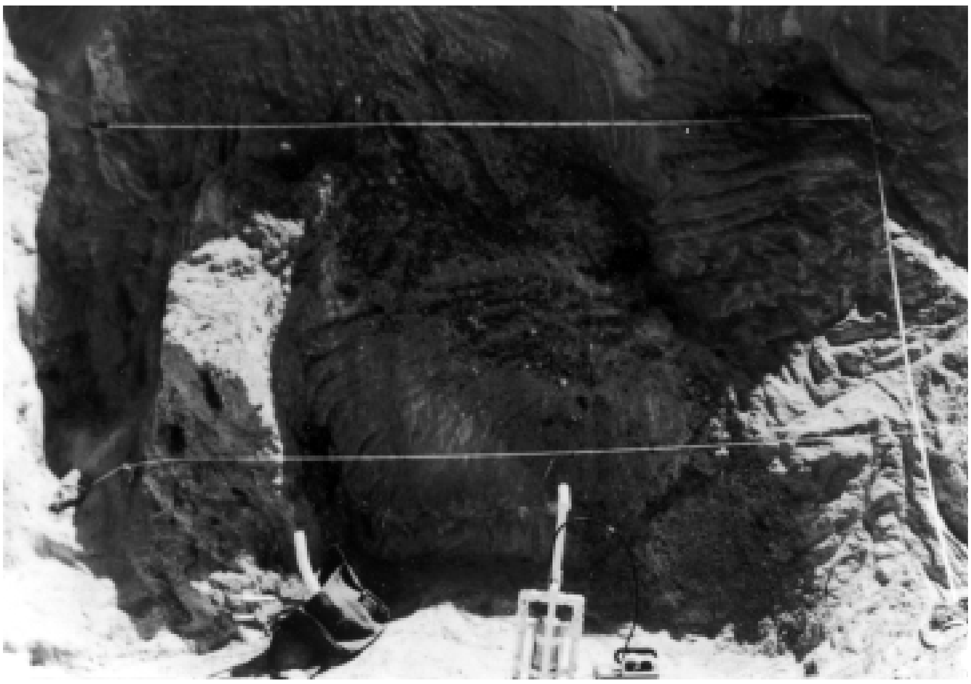

Fig. 5 - Theropod quarry, Dinosaur National Monument, showing grid boundaries laid out for radiological survey.

| Meters | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | | | | | | | | | | | | | | | | | | | | | |
| 0.1 | | | | | | | | | | | | | | | | | | | | | |
| 0.2 | | | | | | | | | | | | | | | | | | | | | |
| 0.3 | | | | | | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | | | | | | | 2.8 | | |
| 0.5 | | | | | | | | | | | | | 2.6 | | 2.7 | 3.2 | 4.2 | 6.4 | 4.8 | 2.7 | |
| 0.6 | | | | | | | | | | | | | | | 2.7 | 3.3 | 4.2 | 4.7 | 3.5 | 2.6 | |
| 0.7 | | | | | | | | | | | | | | | | 3.0 | 3.4 | 3.0 | 2.5 | 2.5 | |
| 0.8 | | | | | | | | | | 2.7 | 2.6 | | | | | | 2.8 | 2.6 | | | |
| 0.9 | | | | | | | | 2.6 | | 2.6 | 2.5 | | | | | 2.8 | 3 | 2.6 | | | |
| 1.0 | | | | | | | | | | 2.5 | | | | | | | 2.7 | 2.6 | | | |
| 1.1 | | | | | | | | | | | | | | | | | | | | | |
| 1.2 | | | | | | | | | | | | | | | | | 2.5 | | | | |
| 1.3 | | | | | | 2.8 | 3.3b | | 3b | 2.6 | | | | | | | | | | | |
| 1.4 | | | | | | | 2.6 | 2.8b | | | | | | | | | | | | | |
| 1.5 | | | | | | | | 2.6 | 2.7 | | | | | | | | | | | | |
| 1.6 | | | | | | | | 2.9 | 3.5b | | 3.0 | 2.7 | 2.7 | | | | | | | | |
| 1.7 | | | | | | | | | 2.5 | | | | | | | | | | | | |
| 1.8 | | | | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | | | | |
| 2.0 | | | | | | | | | | | | | | | | | | | | | |

Fig. 6 - Data set from radiological survey of theropod site at Dinosaur National Monument June 24, 1995, with the background readings of 1.0 to 2.4 R.hr$^{-1}$ deleted. Readings are in R.hr$^{-1}$. The upper right cluster, with high readings of 4.2 - 6.4, was the site of the missing skull. b = sauropod bone exposed in the quarry.

dioactive source at these locations. The readings associated with the letter "b" on the survey, are exposed sauropod rib and each of this bone gave readings above the background readings.

Fossilized wood in the Morrison Formation is know to concentrate uranium. There is a section of fossilized wood exposed in the sandstone just outside the upper right corner of the survey grid. This wood is carbonized rather than permineralized and gave radiological readings equivalent to the background readings.

With the sauropod bone giving elevated readings and the fossilized wood producing only background readings, we interpreted the other elevated readings shown in Figure 6 to be from buried fossil bone. This is the condition that was encountered at the Carol/RJ Quarry in Emery County Utah (JONES & BURGE, 1995), where radiological survey instruments have been used very successfully in locating buried fossilized bone.

The radiological data (Fig. 6) shows that to the upper right of the readings associated with exposed bone, there is an area of elevated readings. This didn't appear to be the logical location for the skull, but the elevated readings showed that there was bone buried there and the size of the area indicate the bone is about the size expected for the missing skull. This data warranted an excavation, but because of other priorities was postponed until the following year.

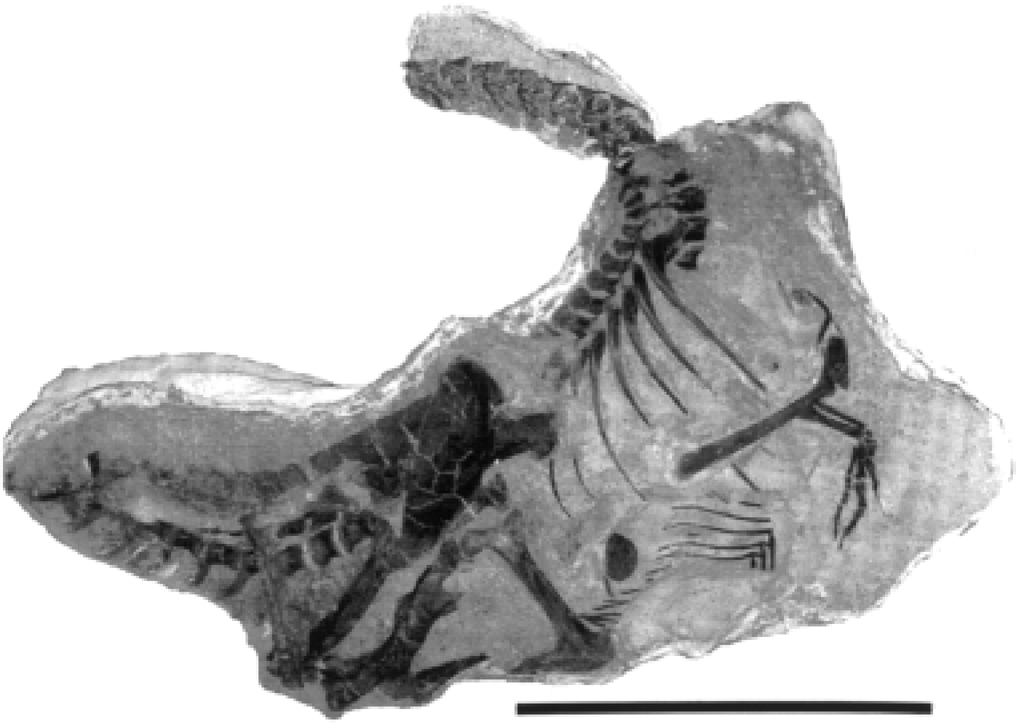

Fig. 7 - The two main blocks for DINO 11541, showing the completeness of the postcranium. Scale = 1 m.

Fig. 8 - Ray Jones (left) and Dan Chure (right) examining the theropod skull after preparation. Even the skull appears to be smiling.

In July 1996 we returned to the site and quickly relocated the area of elevated readings. Because the readings were close to those obtained from the specimen in the lab, we suspected that the bone was close to the surface. The second hammer blow uncovered a thin edge of bone, and within two hours the occipital surface of the missing theropod skull was visible. The skull, which was laying at the conglomerate-sandstone contact was missing the palate, the right (up) mandible, and right (up) side of the skull. Miraculously, the braincase, the left side of the skull, the left mandible (still occluded) and the dentition were perfectly preserved. The skull had moved approximately 2 m from the end of the neck (Fig. 7-9).

## DISCUSSION

For years paleontologists have sought a means to locate subsurface bone, but up to now no promising technology has been developed. Probably the most concentrated effort was at the *Seismosaurus* (GILLETTE, 1994) quarry. Gillette called on the scientists from Los Alamos National Laboratory, Sandia National Laboratory, in New Mexico and Oak Ridge National Laboratory in Tennessee to apply their expertise and equipment to look for still buried bones of the type and only known specimen of *Seismosaurus halli* (GILLETTE, 1994). A variety of ground penetrating techniques were tried, including ground penetrating radar, proton free-precession magnetometry, radiological long-period scintillation counters, acoustic diffraction tomography, and even "bone dowsing" using a coat hanger, but results were inconclusive (GILLETTE, 1994). This lack of success may well be due to the thickness (3.5 m) of sandstone overburden that needed to be penetrated and /or the configuration of the detectors and shielding which were unable to overcome the problem of the sites natural radiation background masking the very low level gamma radiation coming from the bone. The configuration of the detector and shield for the radiological surveying instrument used to locate the theropod skull was designed to overcome this problem of shadowing by the sites natural background radiation.

For a fossilized bone site to be receptive to the use of radiological survey instruments there must be uranium present and it must be concentrated in the bone. The actual source of uranium that is mineralizing the bone in the Morrison Formation is not yet known with certainty, but is believed to come from igneous rock located in highlands to the west of the Dinosaur National Monument and is dependent on the geochemical cycle of uranium (TRIMBLE & DOELLING, 1978). The geochemical cycle of uranium occurs at low temperatures and pressures, uranium in igneous rocks undergoing weathering and leaching is oxidized from $U^{+4}$ to $U^{+6}$ and becomes soluble in ground water as $(UO_2)^{+2}$ ion, as one of the uranyl carbonate complex ions. As long as the ground waters remain oxidizing, uranium ions remain mobile. When the uranium ions encounter a reducing environment like decaying organic material, such as vegetation or animal remains, they will bond with $O_2$ to form the uranium-oxide mineral $UO_2$ uraninite.

There appear to be two mechanisms involved in concentrating the uranium in the bone. The first is that the fossil-bone mineral in dinosaur bone of the Morrison Formation is well-crystallized, stoichiometric francolite (a variety of hydroxyapatite enriched with fluorine). After burial the francolite crystals grow on pre-existing crystallite seeds and fill the space formerly occupied by collagen. As the francolite crystals grow, they incorporate other ions including uranium ions into their crystal structure and these ions become part of the bone mineralization (HUBERT *et al.*, 1996).

The second mechanism is the precipitation of crystalline uraninite and other minerals from ground water into the cracks and voids of the bone (GUILBERT & PARK, 1986: 911). The concentration of uranium in the bone does not result in a homogenous disposition. The disposition is more a result of opportunity or chance and is dependent on the size of the cracks and voids and their locations in the bone. For this reason the radiation level can be variable between different bones in the same site.

The amount of uranium contained in the bone is dependent on the number of uranium ions that are in solution in the ground water. If there is a higher number of uranium ions present in solution, then there are more uranium ions available for concentration in the bone. The more uranium concentrated in the bone the higher the radiation readings emitted by the bone. This is why the radiation level may vary in fossilized bone from different sites.

The relative depth of the bone can be determined if the radiation level can be determined for a bone previously excavated from the site or for bone exposed on the surface at the site is known. This is due to the physics of the gamma radiation coming from uranium. The gamma radiation is electromagnetic radiation similar to light or x-rays. As a gamma ray travels though some shielding medium, such as rock soil, water, etc., it collides and interacts with atoms of the medium. Each collision interaction results in the loss of energy. Thus, the gamma ray intensity is attenuated exponentially until it ceases to be detectable. The distance a gamma ray will travel is related to the original energy of the gamma ray, and the density and atomic number of the medium or shielding material. The higher the density and atomic number of the medium the shorter the distance the radiation travels. The inverse square law also applies to gamma rays traveling through air, i.e. as the distance traveled from the source doubles the radiation intensity drops to 1/4 the amount before.

Therefore, the highest radiation readings are found at the surface of the fossilized bone, then as the distance from the radiation detector to the bone surface is increased the readings rapidly drop off. Since the Dinosaur National Monument theropod bone in the lab read 6.5 R.hr$^{-1}$, it could be assumed that the bone in the quarry was close to the surface because the readings were similar.

There are limiting factors in the use of radiation measuring instruments on fossilized bone sites. These are: **1**) The amount of uranium concentrated in the bone; **2**) The depth of the bone below the ground surface; **3**) The sensitivity of the radiation measuring instrument; **4**) The size of the bone.

The first three limiting factors are interdependent. If the content of uranium in the bone is increased, it can be detected at greater depth or with a less sensitivity instrument. The reverse is true if the uranium content of the bone is lower. If the depth of the bone is shallow, then the content of uranium and the sensitivity of the instrument can be less. If the sensitivity of the instrument is increased then it will detect bone at greater depths with a lower content of uranium. The size of the bone can be a limiting factor due to the small diameter of hole in the shielding for the detector. It is easy to miss very small bone because of this small field of view for the detector.

Regardless of the above limitations, this new equipment clearly has many applications in vertebrate paleontology. This technique works in a variety of sediments, from mudstone to conglomeratic sandstone and has been successfully used in rocks ranging from the Jurassic (the oldest yet sampled) to the Pleistocene. Both the surveying and the data analysis is relatively quick and simple. Radiological surveying can be especially useful when field time is limited and/or the location is remote. A radiological survey can quickly give information on the extent of the deposit and help evaluate whether or not to return to the site in the future. During the excavations at the Carol/RJ site (JONES & BURGE, 1995) the in-


Fig. 9 - DINO 11541, the Mona Lisa of the Morrison Formation, the theropod skull recovered through radiological surveying. Scale in cm.

struments located both single and groups of bone, and were used in defining bone boundaries when trenching around bone thus minimizing bone damage, and minimizing unproductive digging in barren ground.

## ACKNOWLEDGMENTS

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