did the neutron-stripping measurement in reverse, with the ^{132}Sn nucleus 'picking up' a neutron as it passed by a deuterium nucleus. The experiment's success depended not only on the quality of the ^{132}Sn beam produced by the HRIBF, but also on the advanced detection system ORRUBA, the Oak Ridge Rutgers University Barrel Array, named after the institutions that constructed it.

The experiment determined quantities called spectroscopic factors — essentially, measurements of the purity of quantum states — for four orbitals of the nuclear-shell model. In a rigidly spherical doubly magic nucleus, the spectroscopic factors should each be close to 1.0, which indicates a perfectly pure orbital quantum state. All four spectroscopic factors measured by Jones and collaborators[2] were consistent with the value 1.0, given the experiment's statistical uncertainties.

ORRUBA demonstrates the technological advances that will be necessary to study isotopes that have even greater neutron excesses. These will be produced at the Facility for Rare Isotope Beams (FRIB) at Michigan State University, which will begin experimental operations in around 2019. FRIB will join the facilities already operating at the German laboratory GSI and at RIKEN in Japan in performing experiments with nuclei that have the greatest neutron excesses ever produced. Together, these laboratories should illuminate the cosmological origins of the heavy elements. ■

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BIOGEOGRAPHY

Horned dinosaurs venture abroad

Xing Xu

The discovery in Europe of fossils of a small horned dinosaur, a member of a group previously known only from Asia and North America, will prompt a rethink of biogeography at that time in the past.

Reconstructing the historical distribution of Earth's fauna and flora is a challenging task, not least because of the incomplete, often poorly dated, nature of the fossil record. Such problems are particularly severe with respect to European biogeography in the Late Cretaceous period (about 100 million to 65 million years ago), when Europe was an archipelago. A ceratopsian (horned dinosaur) from Hungary, described by Ősi and colleagues on page 466 of this issue[1], now enters the picture. It represents the first horned dinosaur to be named from Europe, and provides information that will require re-evaluation of our biogeographical understanding of the Late Cretaceous fauna of Europe.

Prevailing biogeographical hypotheses suggest that this fauna was different from its counterparts in Asia and North America, because of Europe's isolation from other northern landmasses and relative proximity to Africa[2–4]. Although some European Late Cretaceous animals show affinities with relatives on other northern landmasses, these links do not support a continuing close biogeographical relationship because the European taxa involved are thought to be surviving relict lineages from earlier spans of geological time[2]. However, the discovery of an advanced horned dinosaur demonstrates that Europe had biogeographical connections with Asia and/or North America during the Late Cretaceous, because all previously known unquestionable horned dinosaur species are from these continents.

Asian and North American horned dinosaur fossils are often well preserved, and this group is among the best represented in the dinosaur fossil record. Although some fossils from other continents, including Europe, have been identified as horned dinosaurs, these specimens are so fragmentary that their real affinities are questionable, with only partial exception[5]. Even the specimens of the new European horned dinosaur (named *Ajkaceratops* by Ősi *et al.*[1]) are limited to three skull bones, but these bones display clear diagnostic features of horned dinosaurs. More precisely, *Ajkaceratops* belongs to the coronosaurians (Fig. 1), a group of advanced horned dinosaurs that is known only from the Late Cretaceous and includes members such as the famous *Triceratops*.

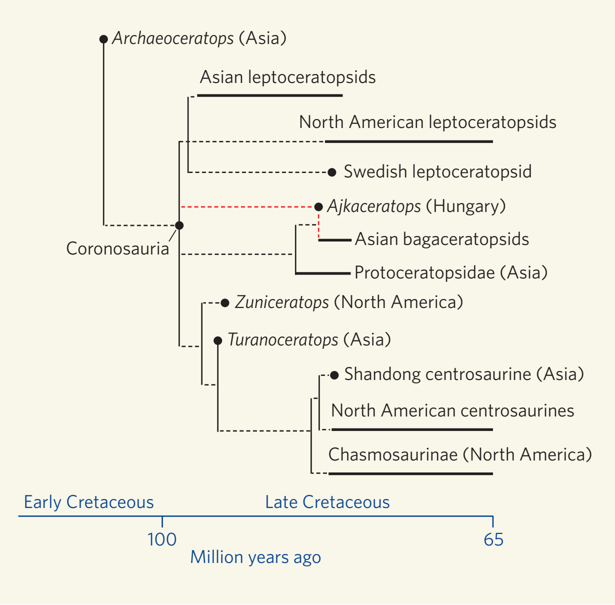

Figure 1 | Coronosaurian horned dinosaurs in time and space. This evolutionary tree has been compiled and simplified from several phylogenetic analyses, and includes *Ajkaceratops*, newly described by Ősi and colleagues[1]. Solid bars and circles refer to known temporal durations, and dashed lines to inferred ranges. The authors favour the view that the presence of fossils of *Ajkaceratops* in modern-day Hungary, and of a leptoceratopsid horned dinosaur in Sweden, resulted from two separate dispersal events from Asia to Europe during the Late Cretaceous. But because of uncertainties in the relationships of these taxa to other coronosaurian horned dinosaurs, the possibility of dispersal from North America to Europe cannot be excluded.

One feature of *Ajkaceratops* is its small size. The largest known individual of *Ajkaceratops*, inferred to be nearly mature by Ősi *et al.*[1], is estimated to be about 1 metre in total body length. If this individual was an adult, *Ajkaceratops* probably represents a dwarfed animal because other, nearly contemporary, horned dinosaurs were much larger. An inference of dwarfing would not be surprising, given that several other dinosaurs from the Late Cretaceous European archipelago are also much smaller than their respective close relatives[1]. This characteristic has been interpreted as an instance of the 'island rule' in animal biogeography, according to which animals tend to become small when isolated on islands with limited resources.

The biogeographical implications of this new find[1] are clear. Accepted hypotheses about the evolutionary relationships of horned dinosaurs, in combination with the previously known fossil record of this group, led researchers to infer that coronosaurian horned dinosaurs originated in Asia and diversified in both Asia and North America in the Late Cretaceous. But the discovery of a coronosaur in Europe shows that this group was not restricted to Asia and North America, and suggests that the European fauna was not fully isolated relative to the other northern continents during the Late Cretaceous.

Accordingly, prevailing biogeographical hypotheses of European isolation[2–4] seem to be at least partly a product of incomplete fossil sampling, a factor that has bedevilled biogeographical investigations of many dinosaur groups[6]. For example, several recently discovered Asian dinosaurs — brachiosaurid[7] and diplodocid[8] sauropods, a ceratosaurian theropod[9], and a centrosaurine ceratopsian[10] — have altered the accepted biogeography of the groups to which they belong.

Ősi *et al.*[1] go even further. Because *Ajkaceratops* is very similar in some features to the bagaceratopsids (Fig. 1), a small group of horned dinosaurs previously known only from the Late Cretaceous of Asia, they suggest that *Ajkaceratops* or its immediate ancestors reached Europe during the early Late Cretaceous by 'island-hopping' across the Tethys Ocean, a prehistoric ocean lying between the southern and northern continents. Taking into account the previous discovery of some teeth from a leptoceratopsid (another type of Late Cretaceous coronosaurian) from the Late Cretaceous of Sweden, the authors propose that there were two independent dispersal events from Asia to Europe during the Late Cretaceous.

This might well be true. But biogeographical hypotheses are strongly influenced by phylogenetic hypotheses: when the evolutionary relationships of a group are not well understood, the associated biogeographical conclusions are not entirely reliable. For now, this reservation applies to the hypothesis of a double Asia-to-Europe dispersal proposed by the authors[1].

The affinity of *Ajkaceratops* with Asian bagaceratopsids is supported by some minor features from a limited anatomical region of the animal. However, if complete specimens of *Ajkaceratops* exhibit a combination of anatomical features seen in different groups, which is not unusual among dinosaurs, the systematic position of *Ajkaceratops* might have to be reconsidered. Furthermore, the position of the Swedish coronosaur among the North-American-dominated Leptoceratopsidae is even more ambiguous. Ősi and colleagues' Asia-to-Europe hypothesis is thus supported by the available data, but cannot be described as a firm conclusion. More complete specimens of *Ajkaceratops* and the Swedish leptoceratopsid are needed to securely reconstruct their systematic positions, and to evaluate the Asia-to-Europe dispersal hypothesis.

Because Europe is considered to be a biogeographical buffer between the Southern and Northern Hemispheres[11], it plays an essential part in reconstructing global biogeographical patterns during the Late Cretaceous. The discovery of *Ajkaceratops* may mark the beginning of a better understanding of the Late Cretaceous fauna of Europe, and ultimately of the Late Cretaceous biogeography of the planet as a whole. ■

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EARTH SCIENCE

Our planet's internal weakness

James A. Van Orman

The influence of the region where the lower mantle meets the core extends to Earth's surface. A computational study of mineral properties shows one way forward in understanding this enigmatic zone.

Earth's mantle is composed of solid rock, but on geological timescales it behaves as a sticky liquid. Just as in ordinary liquids, hotter material tends to rise and colder material to sink. The bottom of the mantle is hotter than the top, and the resulting convective flow leads to plate tectonics, earthquakes and volcanism. But unlike ordinary liquids, the mantle's resistance to flow varies with depth owing to changes in temperature, pressure and mineralogy. How these flow properties vary is largely unknown, because it is difficult to carry out the appropriate laboratory experiments at the extreme conditions of the deep mantle. Ammann *et al.* (page 462 of this issue[1]) have used first-principles physics at the atomic level to suggest that a change in mineral structure in the region just above the core will cause it to flow much more easily — be weaker — than the materials above.

The bottom layer of the mantle, known to geophysicists as D′′ (D double-prime), has a key role in mantle convection, as it is the region where heat is transferred up from the core. This layer is also the probable birthplace of mantle plumes, thin zones of upwelling rock that underlie volcanic centres such as Hawaii. Plumes are notoriously difficult to track by geophysical means, and much of our understanding of their behaviour relies on geodynamic simulations. The strongly enhanced flow in D′′ suggested by Ammann and colleagues will undoubtedly change our picture of plume development. It may also help to explain the complicated and enigmatic structures of the D′′ region that have been revealed by seismology[2].

Mantle convection occurs through the gradual deformation of minerals at the microscopic scale. The most direct pathway to information on the flow properties of mantle minerals is to apply a well-defined stress to a sample and to measure the resulting rate of plastic deformation. This experimental approach is not yet viable under conditions relevant to the deepest parts of Earth's mantle, although significant progress towards this goal has been made recently[3].

A second approach is to investigate the fundamental rate-limiting step in plastic deformation — the hopping of atoms from site to site through diffusion within the mineral. If the diffusion rates of the constituent atoms are known, the flow properties of the material can be estimated on the basis of established theoretical relations. Diffusion rates in the deep-mantle minerals magnesium silicate perovskite (MgSiO$_3$ perovskite) and periclase (magnesium oxide) have been determined experimentally at the pressures and temperatures reached in the middle of the mantle, but such experiments are beyond present capabilities under deeper mantle conditions. Thus, no experimental data exist on the plastic rheology of the recently discovered post-perovskite[4] phase of MgSiO$_3$, the high-pressure mineral that probably predominates in the D′′ region.

Ammann and co-authors[1] used methods based on a quantum-mechanical approach known as density functional theory to estimate atomic diffusion rates in all of the major deep-mantle minerals, including post-perovskite. The calculations necessarily involve some important approximations. But similar methods accurately predict a wide range of mineral properties under deep-mantle conditions[5], and the results of Ammann *et al.* are in reasonable agreement with diffusion data for MgSiO$_3$ perovskite and periclase. Ammann *et al.* found that the diffusion properties of post-perovskite are highly dependent on direction, with Mg and Si diffusion rates in one crystallographic orientation, <100>, being several orders of magnitude faster than in orthogonal directions.