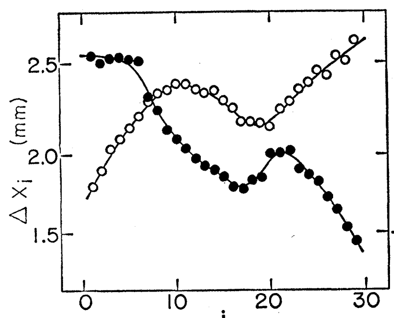

Fig. 3. Coordinate differences Δx_i and Δy_i versus image number i for a representative trajectory near the inner boundary.

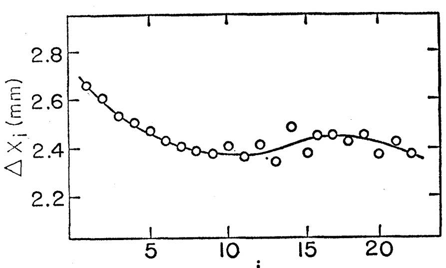

Fig. 4. Δx_i versus image number i for a trajectory whose images become less distinct from left to right; there is a corresponding increase in the scatter.

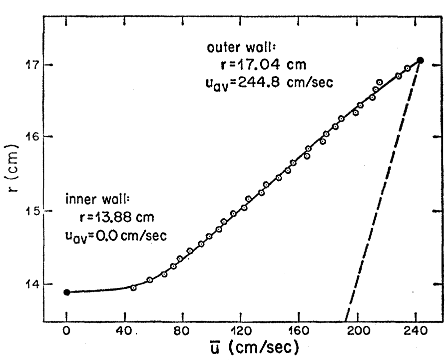

Fig. 5. Average tangential velocity versus radius. The open circles represent the known velocities of the inner and outer boundaries. The dashed line shows rigid-body velocities of the end plates.

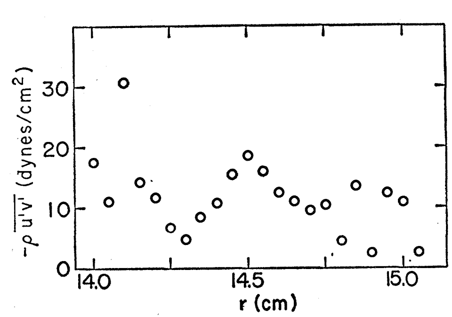

Fig. 6. Computed momentum flux versus radius.

age of the momentum flux values (12 to 13 dyne/cm^2) representing the entire zone should be close to momentum flux values based on a much larger number of trajectories.

Ideally, the computed momentum flux should be checked by adding the shear stress due to mean motion, to obtain the total shear stress, and then evaluating the total shear stress independently by measuring torque on the inner cylinder. There is no straightforward way of doing this, because secondary flow due to end friction causes the distribution of total shear stress across the annulus to vary with distance from the ends. A satisfactory check can nonetheless be made by determining the total shear stress at the inner boundary from the slope of the mean velocity curve there and assuming that the total shear stress does not decrease greatly from the inner wall to the zone where the momentum flux was computed.

The shear stress due to mean motion in the zone where momentum flux was computed was found by measuring the velocity gradient, about 100 cm sec^{-1} sec^{-1}, from Fig. 5 in the range 14.00 to 14.50 cm and using the relation $\tau = \mu(d\bar{u}/dr)$. The result, 1 dyne/cm^2, is so small that the measured momentum flux represents quite closely the total shear stress. Very near the inner boundary, where the turbulent momentum flux decreases to zero and the shear stress is due entirely to laminar flow, the mean velocity gradient increases very sharply. The slope of the $\bar{u}$ versus r curve at the inner wall can be estimated reliably, because the position of the inner wall was measured at the same time as the coordinates of the images. The total shear stress in the immediate vicinity of the inner wall determined in this way is 25 ± 5 dyne/cm^2. The total shear stress in the zone where momentum flux was computed is thus smaller than the total shear stress at the inner wall by no more than a factor of 2, so that the computed momentum flux should be less than the true momentum flux by no more than a factor of 2. Actually, the agreement may be much closer, depending upon how rapidly the true total shear stress decreases away from the inner wall.

Thus, the foregoing method of measuring momentum flux should suffice to obtain a value for the momentum transport ratio that is in error by considerably less than a factor of 2, because the momentum transport ratio defined above involves the quotient of two values of momentum flux which, owing to the experimental method, should differ from the respective true values by about the same factor. The method is thus certainly sensitive enough to provide a test of Bagnold's grain-collision theory.

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7. Supported by NSF graduate fellowship funds and by the Committee on Experimental Geology and Geophysics at Harvard University. I thank A. V. Jopling and R. Siever for their advice and encouragement.

17 April 1967

Seed from the Upper Devonian

Abstract. *We present evidence proving the existence of seeds in the Upper Devonian and extending the known age of seed plants from the Lower Carboniferous (Mississippian) into the Upper Devonian.*

The origin of seed plants is one of the most interesting problems in the fossil history of the vascular plants. In the Lower Devonian, vascular plants were entirely homosporous. The late Devonian saw attainment of heterospory in some lycopsids and some macrophyllous plants, and hitherto it is from the Lower Carboniferous (Mississippian) that fossils that are unquestionably seeds are first recorded.

Recent discovery (*1*) of megaspore tetrads (*Cystosporites devonicus*) in the Upper Devonian, in which a single, large, presumably functional megaspore was developed at the expense of the other three members of the tetrad, demonstrates that by the late Devonian one group of plants had attained a markedly high level of heterospory. More recently (*2*) it has been shown that this type of tetrad organization occurs in some authenticated Lower Carboniferous gymnosperm seeds; in these the megasporangium (nucellus) encloses a tetrad of spores, one of which is axially elongated to almost fill the megasporangium; the other three spores of the tetrad, smaller and abortive, are arranged at the apex of the functional spore. The occurrence of a triradiate suture at the apex of the large spore indicates that meiosis resulted in a tetrahedral tetrad precisely as in *C. devonicus*.

We now report the discovery of some Upper Devonian fossils showing, we believe, the essential features of a primitive gymnospermous seed and proving, therefore, the existence of seed plants in pre-Carboniferous times.

In 1935 Arnold described some fossils from the Upper Devonian of McKean County, Pennsylvania, as resembling detached seed cupules (*3*); they were among a collection of vegetative and fertile remains of *Archaeopteris*. The association of the seed cupules with the *Archaeopteris* was considered significant by Arnold, who suggested that the cupules may have contained the seeds of this plant. Later, however, after discovering that the *Archaeopteris* was free-sporing he modified his view (*4*). Although we now know that at least two species of *Archaeopteris* were free-sporing heterosporous plants (*5*), the possibility that Arnold's cupules represent another, more advanced level of reproductive organization in the genus cannot necessarily be dismissed. It has been shown (*6*) that *Archaeopteris* has a gymnospermous type of anatomy, and it is at least possible that gymnospermous reproductive structures had also evolved in some "species" of the plant.

Fig. 1A shows one of Arnold's cupule-like fossils, which has been transferred to a glass slide by the balsam transfer method, a technique that enables examination of the parts of a specimen that are enclosed within the rock matrix. The transfer clearly shows that the specimen consists of a short stalk or pedicel bearing an assemblage of about seven flattened appendages at one end. Each appendage bifurcates some distance above its origin on the pedicel, and the apices are extended into two long, tapering, attenuate tips, many of which are broken in this specimen (Fig. 1A). There appears to be no concrescence between the individual appendages.

One particularly instructive transfer reveals that the cupule-like structures were probably borne in groups of four on a common stalk, a double dichotomy of the stalk (the second dichotomy being in a plane at right angles to the plane of the first) producing four pedicels, each of which terminated in one of the structures.

During oxidative maceration of one of the cupule-like fossils removed from a transfer, we observed the release of a single, large, thick-walled megaspore (Fig. 1B) some 4.8 mm long and 2 mm in maximum width. The megaspore membrane, which almost filled the cupule, is thinner at the apical end (the end beneath the open end of the cupule) than in the middle of the spore. Situated at the apex are two or possibly three small, more or less spherical bodies which are probably the remains of the abortive spores of the tetrad. As we have mentioned, abortive spores have been found at the apices of the functional megaspores in some Lower Carboniferous seed compressions (*2*).

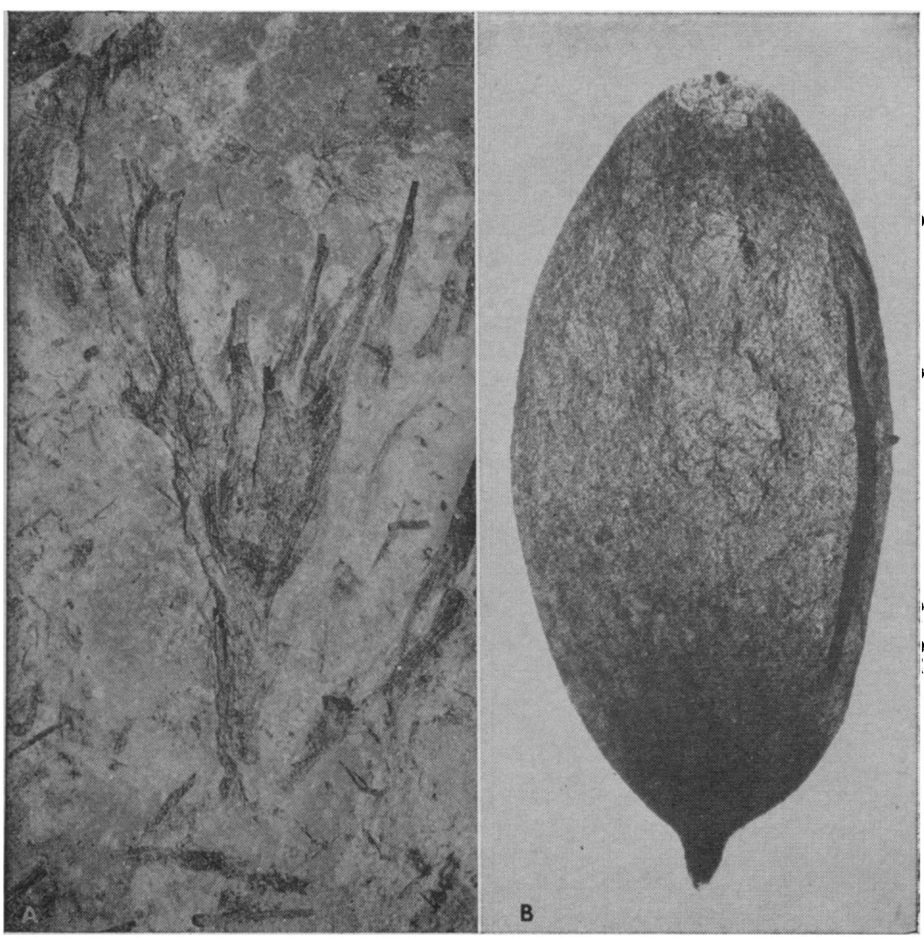

Fig. 1. (A) Devonian seed. The cupule-like structure is formed from an aggregation of bifurcate appendages. Balsam transfer photographed by reflected light; about × 8. (B) Megaspore released from a specimen similar to that shown in (A); the apical end is at the top; × 25.

Covering the megaspore exine is a thin tapetal membrane, a feature frequently found in close connection with the megaspores of Paleozoic seeds (*2*). At the basal end of the megaspore the tapetal membrane is extended to form a short stalk-like process, another structure common to the seeds of some Lower Carboniferous gymnosperms (*2*).

The occurrence of a single, large megaspore within our Devonian fossil is, we believe, most significant; it demonstrates that the plant that bore the cupule-like structures had attained the level of heterospory that is considered a characteristic of the seed habit.

Some morphological details of the Devonian seeds are still rather conjectural. The aggregation of bifurcate appendages could indeed be a true cupule; in this case it would be expected to enclose an integumented megasporangium. Alternatively, the appendages could be an integumentary covering of unfused elements. Evidence from one of our specimens seems to favor the first suggestion, but at the moment we cannot give a conclusive interpretation.

Limited comparison of our fossils can be made with the cupules of the Lower Carboniferous seed petrifactions *Stamnostoma huttonense* and *Eurystoma angulare* described by Long (*7*). In the first of these the cupule is formed by the repeated dichotomy of simple cylindrical axes, and in the second the branched structure (a primitive cupule) bearing the seed shows some suggestion of dorsiventrality. Differences exist, however, and in the Devonian seeds the appendages forming the cupule-like structures are distinctly dorsiventral. The specimens also bear a certain resemblance to *Moresnetia zalesskyi* and *Xenotheca bertrandi* of Stockmans (*8*), but our knowledge of these particular fossils is limited to their external appearance.

This discovery not only demonstrates the existence of seed plants in the Devonian, but also further supports the proposal of the origin of gymnosperms in the Upper Devonian progymnosperm (*6, 9*). More detailed discussion and a formal description of the specimens will be published elsewhere.

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Venus: Volcanic Eruptions May Cause Atmospheric Obscuration

Abstract. *High rates of volcanic and tectonic activities are inferred from Venus's high surface temperature. The effects of volcanic effluents, gas and dust, on obscuration in the atmosphere are considered. The optical extinction due to particulate matter is estimated from assumed distributions as to particle size and altitude. As few as ten explosive eruptions per annum would cause significant absorption and scattering of visible light.*

The reports of high surface temperatures on Venus, derived from Mariner II (*1*) and earlier data, have raised much speculation about atmospheric processes, but little effort has yet been expended toward reconciliation of the observations with the theory of planetary interiors. One immediate inference from the observations is that the lower part of the crust may be very warm. The subsurface heat conductivity (0.006 cal/°C cm sec) and surface heat flow (1.1×10^{-6} cal/cm^2 sec) measured on Earth (*2*) would lead to temperature gradients around 19°C/km. A high surface temperature would imply that the surface heat flow on Venus is considerably greater than on Earth, so temperature gradients would be correspondingly increased. A surface temperature of 500°K and a thermal gradient (say) twice that of Earth would result in temperatures of 1300°K at depths less than 25 km, which would be adequate to melt silicate rocks (*3*). Therefore the crust is probably quite thin; it may even float on a layer of molten rock (*4*).

An important result of intense volcanic activity is very high atmospheric concentrations of volcanic gases and suspended particles. Water vapor may be present; if it is, the concentration depends on whether large amounts of steam are generated during volcanic eruptions; sulfur compounds may be present in detectable quantities. Meinel and Meinel (*5*) recently noted that the terrestrial high-atmospheric haze following important volcanic eruptions may be due to a sulfate aerosol resulting from reactions involving SO_2; much of the atmospheric obscuration of Venus may be caused by such a high "smog" layer. Volcanoes may be considered a likely source of the HCl recently discovered in the atmosphere of Venus (*6*).

Particles from terrestrial volcanoes are carried upward by the momentum acquired on ejection and by convective currents (*7*). The most important unknown factor is the height to which particles can rise. A violent volcanic eruption can create a strong thermal column that carries micron-size particles to great heights. Certainly some material ejected by terrestrial volcanoes can go as high as the tropopause. The tropopause on Venus may be at a much greater altitude, but its atmosphere also appears to be subject to stronger convection. Small particles at high altitudes may take years to drift down to the surface. We shall make some estimates of light absorption and scattering by small particles and show that complete blanketing of Venus could result from a modest rate of volcanic activity.

In computations of particle density and optical depth we have assumed that all particles from an eruption rise in the atmosphere of Venus to the tropopause altitude, where they are completely dispersed in latitude and longitude. If $N(r)$ represents the distribution of particle radii and if there are S eruptions per second, the steady-state particle distribution at any altitude (below the tropopause) is

$$n(r,h) = S\ N(r)/Av(r,h)$$

where A is the surface area of the planet and $v(r, h)$ is the terminal descent velocity of a particle of radius r at altitude h.

An empirical distribution of particle sizes

$$N(r) \approx C/r^{1.56}\ (1 + 4.38 \times 10^5 r^2 + 9.33 \times 10^9 r^4 + 1.57 \times 10^{19} r^8)$$

(r in centimeters) was derived from investigations by Miller and Lee (*8*) of fallout from a volcanic eruption. The total amount of material was normalized to 1 km^3, which is consistent with Humphrey's (*9*) estimate of the amount of micron-sized material injected into Earth's atmosphere by the 1912 Katmai explosion. It follows that the total (vertical) optical depth of volcanic dust in a planetary atmosphere is

$$\tau = \int dr \int dr\ n(r,h)\ \sigma(r) \approx$$

$$\frac{SC}{A} \int_0^{h_T} dh \int_0^{\infty} dr\ (2\pi \mathrm{X}\ r^2)/$$

$$[v(r,h) r^{1.56} \times (1 + 4.38 \times 10^5 r^2 + 9.33 \times 10^9 r^4 + 1.57 \times 10^{19} r^8)]$$