complex and variable mixture of water and organic and inorganic materials. Organic constituents include uric acid, urea, ornithuric acid, creatine, and mucoid substances (*3*), while inorganic constituents include Na, K, Mg, Ca, Cl, and phosphate (*3, 4*).

Folk's observations are consistent with this known chemical complexity of avian urine, and he is correct to point out that the white powdery part of the dried excreta may not consist mainly of uric acid and urates. He is not correct to deny, on the basis of the data reported, that the white crystalline material suspended in the watery part of avian excreta consists largely of uric acid and urates. The observation that 20 to 90 percent of the urinary spherules dissolved in weak acid and immediately recrystallized to form crystals resembling uric acid tends to support the idea that a major part of the urinary solids is indeed uric acid.

Folk's data do not contradict the statements in the literature that 50 to 80 percent of urinary nitrogen is excreted in the form of uric acid (*3*), nor do they contradict theories based on this fact.

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References

1. R. L. Folk, *Science* **166**, 1516 (1969).
2. E. Skadhauge and B. Schmidt-Nielsen, *Fed. Proc.* **24**, 643 (1965); E. Skadhauge, *Comp. Biochem. Physiol.* **23**, 483 (1967); ———, *ibid.* **24**, 7 (1968); B. R. Nechay, S. Boyarsky, P. Catacutan-Labay, *ibid.* **26**, 369 (1968).
3. P. D. Sturkie, *Avian Physiology* (Comstock, Ithaca, N.Y., ed. 2, 1965); C. L. Prosser and F. A. Brown, Jr., *Comparative Animal Physiology* (Saunders, Philadelphia, ed. 2, 1962).
4. E. J. Willoughby, *Comp. Biochem. Physiol.*, in press.

17 February 1970

1) The white material I have examined is the solid that forms the bulk of avian urine and is indeed the main form of excreted nitrogen [see many references cited in my original report (*1*)]. To be sure, it is suspended in water and some intestinal fluids, otherwise evacuation would be awkward. I have been very careful not to sample fecal material, which can easily be distinguished. Although bird feces are an interesting petrographic study in themselves, as a geologist I do not feel I can crane my neck out any further into this distinct field.

2) The white material is alleged by biologists to be mainly uric acid. It is not, because the tiny spheres are soluble in dilute acid (uric acid is insoluble in acid); it is not, because the spheres do not give the x-ray diffraction pattern of uric acid. The cardinal virtue of this technique is that it "tells it like it is" without altering the real nature of the material. It is simply ducking the question to repeatedly cite older authoritarian works that have never used x-rays. One should not be gullible or swallow any data coming from wet analysis of this highly reactive material. I suggest that biologists emulate the work of Denning *et al.* (*2*), who verified the presence of uric acid in a saliva stone by both x-ray and petrographic methods. I have never rejected the idea that the spheres may consist of mixed urates—Willoughby to the contrary—and am only arguing against insoluble uric acid per se as an important constituent.

3) I cannot understand the logic of Willoughby's second paragraph.

4) A reprint recently sent to me by Gibbs (*3*) reports very interesting experiments that offer a flicker of hope toward solving the mystery. He found that warming fowl urine caused the contained solids to dissolve, and he also made uric acid gels. Finally, Gibbs found that fowl blood "contains uric acid in a specially soluble form." I believe that Gibbs's "uric acid" was some other acid-soluble nitrogenous compound (perhaps the same one that is actually secreted by the kidney and excreted by the cloaca), and this explains its curious behavior.

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References

1. R. L. Folk, *Science* **166**, 1516 (1969).
2. R. M. Denning, I. M. Blatt, W. M. Mikkelsen, *Ann. Otol. Rhinol. Laryngol.* **67**, 1022 (1958).
3. O. S. Gibbs, *Science* **70**, 241 (1929).

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Fluid Pressure Variations and Prediction of Shallow Earthquakes

Evidence has accumulated recently showing that shallow earthquakes can be triggered by increases in fluid pressure induced by man. An implicit corollary seems to follow: tectonically induced increases in fluid pressure probably constitute an important mechanism for triggering shallow earthquakes, as suggested by Nakamura (*1*). It may be possible to predict where and approximately when some earthquakes are likely to occur in seismically active areas by continuously monitoring variations in fluid pressure in deep wells.

In 1965, Evans (*2*) showed that there was a spatial and temporal relationship between a series of 710 minor earthquakes and the injection of waste water into fractured basement rocks through a deep well located at Rocky Mountain Arsenal, northeast of Denver, Colorado. Evans postulated that the earthquakes were triggered because the fluid pressure at depth was increased sufficiently to reduce the frictional resistance of the basement rocks to faulting. Subsequent investigators confirmed Evans's observations (*3*) and concluded that the release of stored tectonic strain was triggered by the injection of fluid into the basement rocks (*4*). Although this conclusion continues to be questioned (*5*), several other instances have been cited recently in which causal relationships between increases in fluid pressure induced by man and earthquakes seem clear (*6*). In some cases the increases in fluid pressure have been caused by the injection of fluids into deep wells, and in other cases by rising reservoir levels.

Significant tectonically induced variations in fluid pressure are commonly associated with earthquakes and are manifested by increased or decreased flow rates of springs and creeks and by fluctuations in the production rates of oil, gas, and water wells. In general, however, it has not been possible to establish exactly when the fluid pressure variations occur with respect to the time of the earthquakes, except in a few cases in which flow rates or well-casing pressures were measured continuously (*7*).

An interesting example in which tectonically induced increases in fluid pressure may have triggered a major aftershock is suggested by the behavior of oil wells in the Tejon Ranch area, about 7 miles (11.2 km) from the epicenter of the main earthquake in Kern County, California, in 1952 (Richter magnitude = 7.7). Casing pressures increased to as much as ten times the normal pressures from 2 to 4 days after the main shock, declined to about 20 percent below normal in the next 2 weeks, and then increased to pre-earthquake pressures but only after many months (*8*). Two of the larger aftershocks (magnitude = 5.4, 5.2) occurred near Tejon Ranch 2 days after the main shock when the casing pressures were abnormally high.

Measurable variations in fluid pressure may precede large shallow earthquakes soon enough so that some warning may be given. This order of events is suggested by the fact that crude oil seeped through beach sands a few minutes after the foreshock (magnitude = 3.6) which occurred 3 hours before the main earthquake of 29 June 1925 (magnitude = 6.3) at Santa Barbara, California (*9*). The flow of oil amounted to several barrels at each of several points along a mile or so of the beach, and considerable speculation and a few facts suggest that the main shock occurred on a fault whose trace is inferred to be within a few hundred meters of the oil seeps. Natural oil seeps have not been observed along that stretch of beach before or since the earthquake.

Elsewhere in the Santa Barbara Channel manifestations of variations in fluid pressure have been observed recently by Allen who obtained quantitative measurements on one of the largest submarine oil seeps near Coal Oil Point during October 1969 (*10*). The greatest increases and decreases in the seepage rates were observed during December 1969 (*11*) before two minor earthquakes occurred in the central part of the Santa Barbara Channel approximately 20 km from Coal Oil Point on 29 December 1969 and on 2 January 1970. These two shocks are the only felt earthquakes that occurred in the channel region during the previous year (*12*). Unfortunately, Allen's observations were made only at weekly intervals, so it is not possible to establish with confidence temporal or causal relationships between the two earthquakes and the seepage variations.

These examples strongly suggest that it might be possible to predict shallow earthquakes, at least in the Santa Barbara Channel area, if fluid pressures could be measured continuously in a number of deep wells. Recent theoretical and experimental studies of pore pressure and confining pressure in rock deformation (*13*) provide qualitative indications of the kind of response that might be expected in the fluid pressure in a well before an earthquake. These studies show that as a rock specimen is stressed and strain accumulates, the pore pressure gradually increases to some maximum value at which point microfracturing begins to occur. This results in an increase in the volume and a relatively rapid decrease in the pore pressure before the specimen ultimately fails by brittle fracture. The microfracturing marking the initial failure of the specimen would correspond to foreshock activity and ultimate failure of the specimen to the main shock. The rates at which the changes in pore pressure occur and the elapsed time between the maximum pore pressure and ultimate failure are governed by numerous variables such as initial confining pressure, strain rate, strain history, and lithology. In nature, these parameters may vary not only from one fault system to another, but also along a single fault. In practice, therefore, the relationships will not be as idealized as they seem to be experimentally. Nonetheless, additional experimental data on rock deformation are needed to obtain a more quantitative understanding of the relationships among induced variations in fluid pressure and the variables mentioned above.

In the meantime, the hypothesis can be tested empirically in the seismically active Santa Barbara Channel where numerous wells and core holes penetrate nearly to focal depths of some of the shallower local earthquakes. Unfortunately, nearly all the abandoned wells and core holes are plugged and capped, and static fluid pressures are measured too infrequently in most producing oil wells to show the relatively abrupt variations that might be expected before an earthquake. It should be possible, however, to utilize wells and core holes as they become depleted and abandoned by placing continuously recording pressure gauges in them.

Although the proposed system involves several formidable technological and legal problems, it offers several advantages over other systems that are presently conceived to obtain premonitory information on earthquakes. Information would be obtained continuously and in offshore areas where periodic geodetic or laser strain-gauge measuring methods are difficult. Even in onshore wells it would be possible to measure a parameter of rock deformation nearer depths where strain effects may be noticed before they are on the surface where most measurements of other parameters must be obtained.

If the hypothesis is confirmed by the successful prediction of an earthquake in the Santa Barbara Channel area or another seismically active area, wells may be eventually drilled along many of the major faults situated near densely populated areas. Some wells might be used simply as barometers of tectonically induced variations in fluid pressure to predict earthquakes as described here. In other wells it might be possible to prevent large destructive earthquakes by the injection of fluids that would cause a series of minor earthquakes through variations in fluid pressure, as other writers have proposed (*6*).

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References and Notes

1. K. Nakamura, *Trans. Amer. Geophys. Union* **50**, 389 (1969).
2. D. Evans, *Mountain Geol.* **3**, No. 1, 22 (1966).
3. J. H. Healy, W. H. Jackson, J. R. Van Schaack, *U.S. Geol. Surv. Open File Rep.* (1966), part 5; F. C. Ball and G. R. Downs, *U.S. Army Corps of Eng. Omaha Dist. Rep.* (1966); J. C. Hollister and R. J. Weimer, *Quart. Colo. Sch. Mines* **63**, 1 (1968), part A.
4. J. H. Healy, W. W. Rubey, D. T. Griggs, C. B. Raleigh, *Science* **161**, 1301 (1968).
5. R. B. Simon, *ibid.* **165**, 897 (1969); *ibid.* **167**, 1519 (1970).
6. D. Evans, *Trans. Amer. Geophys. Union* **50**, 387 (1969); L. C. Pakiser, J. P. Eaton, J. H. Healy, C. B. Raleigh, *Science* **166**, 1467 (1969).
7. F. Greve and F. Bravo, *Univ. Chile Contrib. Cient. Technol. Ser. F Sismol. Publ. 1* (1956).
8. R. L. Johnston, *Calif. Div. Mines Geol. Bull.* **171**, 221 (1955).
9. H. Nunn, *Bull. Seismol. Soc. Amer.* **15**, 308 (1925).
10. A. A. Allen and R. S. Schlueter, *Tech. Mem. 1230* (General Research Corporation, Santa Barbara, Calif., Nov. 1969).
11. A. A. Allen, personal communication.
12. Numerous earthquakes (maximum magnitude = 5.9) occurred in November and early December 1969, in the Pacific Ocean, 80 km west of Point Arguello and more than 120 km west of the fluctuating seeps near Santa Barbara. Preliminary epicentral determinations by the U.S. Coast and Geodetic Survey show that the faults may be associated with the Santa Lucia escarpment and the Santa Lucia bank, which are northwest-trending structures that contrast with the generally easterly trends of the western Transverse Range province of which the Santa Barbara Channel is merely a submarine extension.
13. W. F. Brace, B. W. Paulding, Jr., C. Scholz, *J. Geophys. Res.* **71**, 3939 (1966); Z. T. Bieniawski, *Int. J. Rock Mech. Mining, Sci.* **4**, 395 (1967); J. D. Byerlee and W. F. Brace, *J. Geophys. Res.* **73**, 6031 (1968); M. J. Aldrich, *Geol. Soc. Amer. Bull.* **80**, 1577 (1969); K. S. Lane, *ibid.*, p. 1587.
14. Some of the ideas expressed in this paper were realized independently by R. O. Burford using much of the same data. Discussions with Burford and other colleagues have clarified and broadened my own ideas. Supported by funds received from the National Science Foundation under the National Sea Grant Program, grant No. GH 43. Marine Science Institute contribution No. 2.

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