statistical studies [J. A. Jacobs (6); ——— and K. Sinno, *J. Geophys. Res.* **65**, 107 (1960)] and may be of extreme importance in an ultimate understanding of the plasma wave source mechanism.
11. W. D. Parkinson, *Geophys. J. Roy. Astron. Soc.* **2**, 1 (1959); *ibid.* **6**, 441 (1962).
12. Y. Inoue and D. L. Shaeffer, Report AFCRL-70-0531, University of Pittsburgh, Pittsburgh, Pennsylvania (September 1970) (unpublished); Y. Inoue, personal communication.
13. W. B. Hanson, in *Satellite Environment Handbook*, F. S. Johnson, Ed. (Stanford Univ. Press, Stanford, California, ed. 2, 1965). The average conductivity changes are due predominantly to changes in density; the temperature remains fairly independent of LT.
14. Little theoretical work has been done on the transmission of these frequency waves. In contrast to the finite-layered ionosphere models sufficient for studying the transmission of waves with frequencies > 1 hertz [C. Greifinger and P. Greifinger, *J. Geophys. Res.* **70**, 2217 (1965); E. C. Field and C. Greifinger, *ibid.*, p. 4885; *ibid.* **71**, 3228 (1966)] a full-wave solution is needed for the plasma waves considered here, whose wavelengths are of the order of several earth radii. Recently, significant progress has been made in the direction of a full-wave solution with the use of a daytime ionosphere model (12).
15. H. C. Stenbaek-Nielson, paper 3-8-3 presented at the spring meeting of U.S. National Committee of the International Scientific Radio Union, 15 April 1972, Washington, D.C.
16. J. A. Gledhill, D. G. Torr, M. R. Torr, *J. Geophys. Res.* **72**, 208 (1967); D. G. Torr and M. R. Torr, *Nature* **216**, 1193 (1967).
17. We thank A. Hasegawa, Y. Inoue, W. L. Brown, M. H. Rees, J. W. Wright, J. A. Gledhill, D. G. Torr, and L. A. Jaeckel for profitable discussions and C. G. Maclennan and M. F. Robbins for much computational assistance. The work in the Antarctic was made possible by an arrangement with the National Science Foundation. The measurements at the station in Quebec were made possible through the cooperation of the Bell Telephone Company of Canada, Ltd.
* Present address: Department of Physics, University of Calgary, Calgary 44, Alberta, Canada.

16 June 1972; revised 16 August 1972

Sandstone: Secular Trends in Lithology in Southwestern Montana

Abstract. *Long-term secular trends in the composition and texture of sandstones in southwestern Montana reflect changing provenance and depositional environment, which in turn reflect changing tectonic patterns in the Cordilleran mobile belt just to the west.*

The stratigraphic column at the northern end of the Tobacco Root Mountains in southwestern Montana is a diverse sequence of detrital, chemical, and volcanic rocks deposited on the eastern flank of the Cordilleran mobile belt during Paleozoic, Mesozoic, and Cenozoic eras of geologic time. Its total thickness of 4200 m is divided about equally among the three eras. Several large gaps appear in the stratigraphic record, notably, Ordovician through Middle Devonian and Middle Triassic through Middle Jurassic. Rock units corresponding to these time intervals either were never deposited in this area, or were eroded prior to deposition of the overlying units. The column is not uniform from bottom to top; rather, each erathem (*1*) is broadly characterized by a distinct assemblage of lithologic types. The strongest secular contrasts occur in the sandstones. This report describes long-term trends, both compositional and textural, in sandstone lithology in the column, and relates these trends to tectonic evolution of the Cordilleran mobile belt.

In general, the composition of sandstones is controlled by provenance, that is, the character of the source area, where detritus is generated. The texture is controlled largely by the environment in which deposition of the detritus takes place, but is not totally independent of provenance. Provenance and depositional environment are in turn controlled by the character and intensity of tectonism, that is, deformation of the earth's crust, both in the source area and at the depositional site.

Composition and texture are frequently described in terms of maturity. A sandstone having a high content of well-rounded, well-sorted quartz, and a correspondingly low content of unstable materials, such as feldspars and lithic fragments, is mature. Besides quartz, other relatively indestructible minerals, such as zircon, tourmaline, and rutile, may be present in small quantities. (These and other so-called heavy minerals, although of diminutive

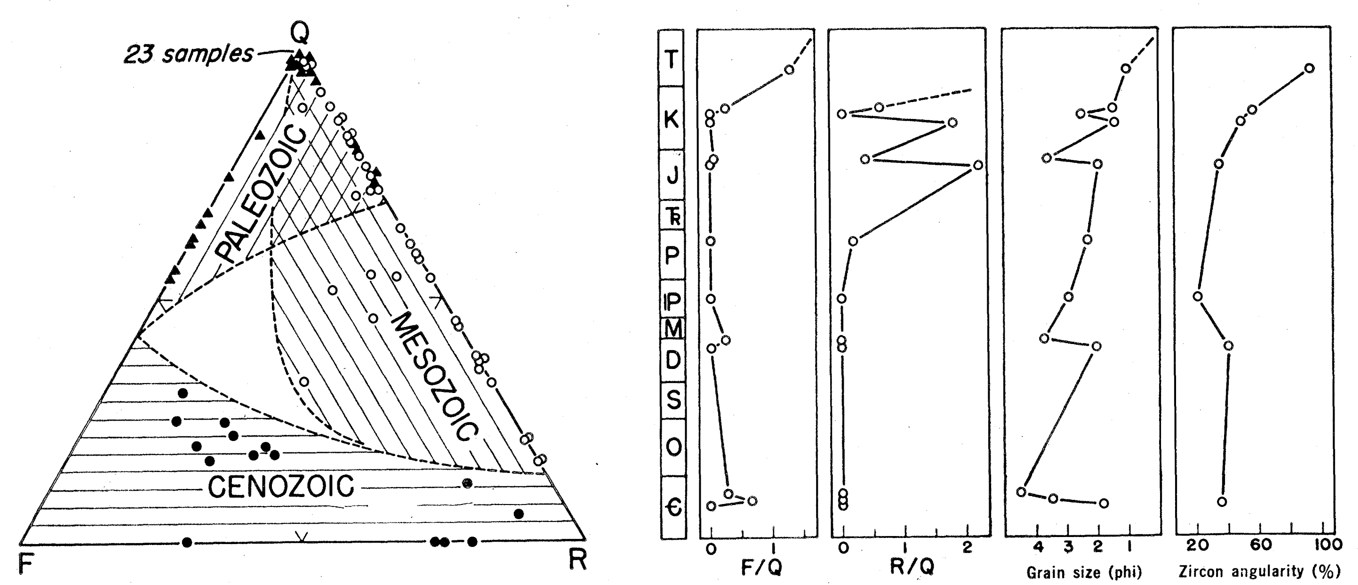

Fig. 1. Composition of 105 sandstones from the study area according to Folk's ternary classification (*2*). The poles of the ternary diagram are quartz (*Q*); feldspars and feldspathic rock fragments (*F*); and all other rock fragments, including chert (*R*). Paleozoic samples (triangles) are concentrated near the *Q* pole, Mesozoic samples (open circles) along the *Q-R* edge, and Cenozoic samples (black circles) along the *R-F* edge of the triangle. Note that one point at the *Q* pole of the ternary diagram represents 23 Paleozoic samples. The Paleozoic and Mesozoic fields overlap because of a gradual transition in sandstone composition from late Paleozoic to Mesozoic time. (All the Permian samples and most of the Jurassic samples are contained within this overlap.) At the right, certain compositional and textural properties of the sandstones are averaged over major rock units and plotted against time, on a scale ranging from Cambrian through Tertiary. The feldspar/quartz ratio, rock fragment/quartz ratio, mean grain size, and zircon angularity increase in younger sandstones.

concentrations in most sandstones, are very important in sandstone interpretation.) Immature sandstones, on the other hand, have a higher content of unstable materials, including such heavy minerals as apatite and amphiboles, and lower roundness and sorting values. In addition, a fine-grained matrix, usually composed of clay, is often present.

Conditions favoring the formation of mature sands obtain most frequently during long periods of tectonic quiescence, when production of weathered material, and its subsequent transport and deposition, are slow. Active tectonism increases the relief of the source area, makes new and varied source rocks available, and accelerates the production, transport, and deposition of detritus. Immature sandstones are the result.

In southwestern Montana, sandstones of the Paleozoic Erathem are generally well-sorted, fine-grained quartzarenite (*2*) containing ultrastable, well-rounded heavy mineral grains (mostly zircon and tourmaline). A large proportion of the grains appears to be multicyclic, having undergone several cycles of erosion and deposition.

Deposition of the Paleozoic Erathem was little affected by events in the Cordilleran mobile belt to the west. The detritus was derived mainly from distant source areas of low topographic relief, lying to the east of the depositional site, on the craton. The parent rocks in these source areas consisted of Precambrian metamorphics and, more importantly, quartz-rich sandstones overlying the metamorphic basement. The final deposition of Paleozoic sands in southwestern Montana occurred in shallow marine environments. The sedimentation rate was low, so that the sands were subjected to abrasive wave action in the marine environment for long periods of time before their burial. The depositional site was tectonically quite stable, subjected only to very gentle vertical movements. Periodic mild uplift caused local reworking of the deposits.

The Mesozoic Erathem, which is gradational with the underlying Paleozoic sequence, is dominated by moderately sorted, medium- and coarse-grained litharenites and lithic wackes (*3*) in which most of the lithic clasts are sedimentary and volcanic. Typically, the fine-grained matrix in the wackes is composed of a mixture of clay minerals. Well-rounded zircon and tourmaline grains, similar to those of the Paleozoic sandstones, are present, but angular and idiomorphic grains of zircon and apatite, showing only minor abrasion, also appear.

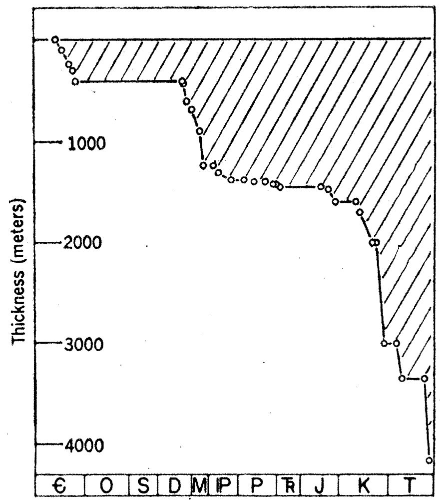

Fig. 2. Present distribution of sediment thickness as a function of age, on a time scale ranging from Cambrian through Tertiary. The vertical distance above the curve shows the total thickness of sediment older than a particular age. The slope of the curve is a measure of the sedimentation rate.

Mesozoic sedimentation was greatly affected by tectonism in the Cordilleran mobile belt. Eastern detrital sources active during Paleozoic time continued to supply mature sands to the depositional site during the Mesozoic Era, but at a diminished rate. The great bulk of Mesozoic detritus was derived from sources to the west, which had begun to emerge near the close of the Paleozoic. Western sources consisted of Paleozoic and Mesozoic sedimentary and volcanic rocks of the Cordilleran mobile belt. These sources supplied increasing quantities of immature detritus as strong deformation and intense volcanism continued in the mobile belt throughout Mesozoic time. Deposition of this material occurred in marine, nonmarine, and transitional environments. Subsidence was rapid and the sedimentation rate was high. At the close of Mesozoic time, volcanics and associated epiclastics accumulated at the depositional site.

The Cenozoic Erathem contains poorly sorted, coarse-grained to conglomeratic lithic arkoses in which the lithic clasts are of plutonic, volcanic, sedimentary, and metamorphic origin. Many of these Cenozoic rocks contain a matrix, although not always composed of clay. More frequently, the matrix is a mixture of volcanic ash and fine-grained terrigenous carbonate. Heavy minerals are abundant and very diverse, and are mostly angular or idiomorphic.

In Cenozoic time, the depositional site itself was involved in the strong tectonism which had earlier affected the region to the west. Cenozoic detritus was derived from a very heterogeneous array of active local sources of high relief surrounding the depositional site. The major detrital sources were nearby granitic batholiths and andesitic lava flows, all of late Mesozoic age, rhyolitic volcaniclastics of Cenozoic age, and uplifted sedimentary rocks of all ages. Smaller contributions were made by metamorphic terrains where erosion had exposed the Precambrian basement. Deposition took place in a totally nonmarine, intermontane setting, in fluvial, alluvial, and lacustrine environments. Sedimentation was very rapid.

A secular trend toward decreasing compositional and textural maturity in the sandstones is apparent (Fig. 1). The quartz content gradually decreases in progressively younger sandstones, as the quantity and variety of lithic fragments and feldspars increases. Heavy minerals also become more abundant and varied. When all kinds of matrix, including clay, volcanic ash, and terrigenous carbonate, are considered, the quantity of matrix relative to that of grains in the sandstones increases upward in the column. Mean grain size increases and sorting decreases upward. Grain roundness, as determined for zircon and tourmaline grains, decreases. These secular trends in sandstone characteristics reflect gradual changes in provenance and depositional environment. Through time, source areas came ever closer to the depositional site, assumed increased relief, and became more heterogeneous. As source areas supplied detritus in ever increasing quantities, the rate of sedimentation gradually surpassed the rate of subsidence at the depositional site (Fig. 2), and the depositional environment changed from typically uniform marine to rather varied nonmarine. These gradual changes in provenance and depositional environment in turn reflect the evolving tectonic pattern within the Cordilleran mobile belt, where tectonic quiescence gave way to moderate deformation, thence to volcanism, plutonism, and violent deformation.

MICHAEL MCLANE
University of Wisconsin,
Marathon County Campus,
Wasau 54401

References and Notes

1. The rocks formed during an era are called an erathem [J. Gilluly, A. C. Waters, A. O. Woodford, *Principles of Geology* (Freeman, San Francisco, ed. 3, 1968), p. 107].
2. The sandstone classification is according to R. L. Folk, *Petrology of Sedimentary Rocks* (Hemphill's, Austin, Texas, 1968), p. 124.
3. Wacke is a sandstone containing more than 10 percent clay matrix; arenite is a sandstone containing less than 10 percent clay matrix [C. M. Gilbert, in *Petrography*, H. Williams, F. J. Turner, C. M. Gilbert, Eds. (Freeman, San Francisco, 1954), p. 290].
4. I thank Paul Edwin Potter for his guidance.

3 August 1972

Artificial Cloud Formation in the Atmosphere

Abstract. *An artificial cloud in the cloudless atmosphere at a temperature below 0°C was formed by introducing pellets of Dry Ice into air containing more water vapor than would be present at the saturation point with respect to ice. Such clouds could be utilized to establish radiative equilibrium between ground and air so as to inhibit the cooling of selective arctic surface regions under clear skies.*

The formation of a cloud in the atmosphere at a temperature below 0°C can be accomplished by the introduction into the air of ice crystals containing more water vapor than would be present at the saturation point with respect to ice. Seeding with Dry Ice powder or liquid propane, which produces temperatures of approximately −80°C (*1*), results in the condensation of water vapor from the air followed by the spontaneous freezing of the water droplets thus formed. In ice-supersaturated air, such ice crystals grow to larger sizes and the cloud is formed. In order to find out whether the air is ice-saturated or not, it is useful to employ a radiosonde in addition to another small balloon onto which is attached a small piece of Dry Ice in a thin cloth bag. When the Dry Ice penetrates the ice-saturated air, it forms a condensation trail which produces a small-scale seeding of the atmosphere. If the trail persists or grows, this indicates that the air is ice-supersaturated. This is a usable technique to compensate for the relatively unreliable measurement of humidity by radiosonde hygristor sensors (humidity sensors) at lower temperatures.

The preliminary experiment was carried out on 18 January 1972 in the Fairbanks area. At 13:00 A.S.T. a rawinsonde balloon onto which was attached about 200 g of Dry Ice detected ice-saturated air in a layer between 1000 and 2000 feet (300 and 600 m) from the ground. The radiosonde reported an isothermal temperature of −26°C in this layer.

Using a light aircraft, we seeded about 5 kg of Dry Ice powder in the clear sky at a height of 2000 feet (temperature, −20°C) above the ground level (ground temperature, −32°C) at 13:40 A.S.T. Just after seeding, we observed the formation of cloud cells which grew and merged into a larger, uniform thin cloud. The size of the cloud at 20 minutes after seeding was approximately 1 km in diameter with a thickness of a few hundred feet (Fig. 1). There was no other cloud in the sky, and there was a slight wind from the east-southeast. The cloud grew into a thicker depth (apparently 500 feet or more) and drifted out of sight 1½ hours later.

Fig. 1. The artificial cloud at 20 minutes after seeding.

In the subarctic winter months (late November to early February) the maximum solar elevation is only a few degrees, for example, 2 deg in Fairbanks, Alaska. Because of the low sun angle and the short duration of daylight, the incoming solar radiation is negligible and therefore the warming effect of the solar radiation is small. On the other hand, under clear skies the ground loses infrared radiation steadily, and the amount lost is sufficient to produce radiative cooling at the rate of 1.5°C per hour (*2*). This radiative cooling leads to the establishment of strong surface inversions and ground temperatures as low as −40°C. In cities, such as Fairbanks, Alaska, where human activity produces large quantities of water vapor, such low temperatures and strong inversions lead to the formation of ice fog (*3*). Episodes of ice fog have been found to persist for several days to a few weeks and to produce severe visibility problems at airports and along roadways. This ice fog consists of ice crystals without liquid water droplets (*3*); no successful ice fog dissipation technique has yet been reported.

If an artificial cloud can be formed when the skies are clear, then the radiative cooling can be inhibited, thereby preventing the possibilities of an ice fog episode. The cloud should be optically thick and should last until the weather systems bring in sufficient extra moisture for natural cloud formation. An artificial cloud may also be used to dissipate already existing ice fog. Because of the strong temperature inversion characteristics under ice fog conditions, the artificial cloud will be considerably warmer than the ground. If the cloud is optically thick, it will establish radiative equilibrium in the space between the cloud and ground, and eventually there may be a warming of the ground surface of several degrees. This temperature rise should be sufficient to remove most of the ice fog, since a temperature rise of 10°C will more than double the capacity of air for water vapor.

K. O. L. F. Jayaweera
Takeshi Ohtake

Geophysical Institute,
University of Alaska,
College 99701