# Giant Corporations from Tiny Chips Grow

*It now takes a big company to make miniaturized microcircuits, and this new development is changing the nature of the industry*

The world market for electronics—including computers, telecommunications devices, consumer products like pocket calculators, industrial process control equipment, scientific instruments, and defense systems—is growing so fast that electronics could be a $400 billion industry by the late 1980's, a figure that puts electronics in the same league with oil, automobiles, and other giants of the business world.

At the heart of most electronics products are ultraminiaturized circuits emblazoned on chips of silicon a few millimeters on a side. These microelectronic circuits will soon account for about 10 percent of the value of all electrical equipment sold, or $40 billion. Microelectronics is the basis for everything electronic, and that is quite a lot considering that industrialized society is hooked on information processing and transmission as fully as it is on energy consumption.

These forecasts about the growth of the electronics industry depend on the next generation of microcircuitry, which goes by the name of VLSI, for very large scale integration. VLSI is expected to continue the tradition of lowering the expense of computation by further miniaturization, thereby enlarging tremendously the variety of uses for which intelligent electronics is cost-effective. And, as in the past, the uses will far exceed in ingenuity and vision what had been predicted. But there are numerous barriers, both technological and institutional, to be overcome before VLSI "happens":

- Techniques for fabricating microcircuits having features with dimensions of 1 micrometer or smaller need to be perfected. Some of these are extensions of current technologies, but others are not. Moreover, demands on the control of the properties of the silicon itself are much more stringent than in the past.
- Miniaturization means more than just making something that was big tiny. In the case of electronic devices such as transistors, new phenomena appear as sizes shrink, and these need to be understood and accounted for.
- As more and more devices get packed onto a single silicon chip, the resulting circuits become enormously complex. The task of designing such circuits is becoming unmanageable, and new methods for doing the job have to be devised.
- Microfabrication equipment becomes more sophisticated and more expensive with decreasing circuit feature sizes. Microelectronics companies are changing in character from small technology-dominated ventures to large marketing-oriented corporations as they search for ways to raise the capital needed to continue in the VLSI race.
- Japan and the western European countries, recognizing the importance of microelectronics to the world economy in the coming years, are rushing to establish their own homegrown industries. The Japanese have already succeeded and are threatening to pull even with the United States in the battle for dominance in world markets.

With this story on changes within the microelectronics industry being wrought by VLSI, the Research News section of *Science* begins a series of articles examining some of these hurdles and the means for getting over them.

Microelectronics companies are changing in character from small, high-technology ventures of the 1950's and 1960's to large, mature corporations as they struggle to compete in the upcoming VLSI era. The companies are now finding that the traditional determinants of competitive advantage in the business world, capital and labor, are becoming major problems, whereas advancing technology at a rapid rate has been a major preoccupation of the past. Because the cost of equipment for fabricating VLSI microcircuits is rising even faster than the rate of inflation, companies face huge new demands for capital. One source of funds is through the acquisition of—or at least substantial investment in—microelectronics firms by large conglomerates, both foreign and domestic. The cost of designing complex VLSI circuits is climbing even more steeply than the price of new equipment because of labor-intensive design procedures. To pay off development costs, microelectronics companies must sell tremendous quantities of microcircuit chips. Finally, continuing a trend begun in the heyday of pocket calculators, microelectronics companies are expanding from simple makers of microcircuit chips to manufacturers of electronic equipment built around the chips—from computers to electronic toys. All in all, VLSI means more than just making tiny circuits even tinier; it is making small companies large.

The microelectronics story started at Bell Laboratories. The basic element of solid-state electronics, the transistor, was invented there by John Bardeen, Walter Brattain, and William Shockley more than 30 years ago. But perhaps just as significant were the two remarkable Bell Labs-Western Electric "Transistor Seminars" of 1952 and 1956 in which information about transistor technology was made available to other companies, thereby launching a semiconductor electronics industry. A third important event occurred in the mid-1950's when Shockley left Bell Labs and moved to the San Francisco Peninsula. There, Shockley set up his own company near


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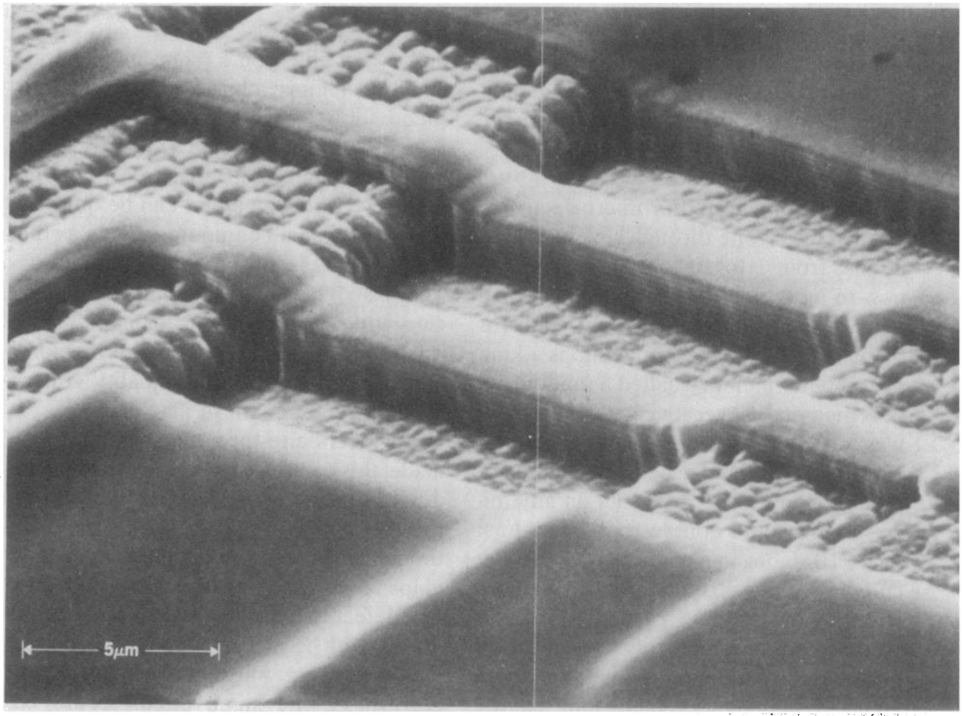
Stanford University, the Shockley Semiconductor Laboratory.

At first, Shockely was successful in attracting some exceptional technical talent, but within 2 years he lost much of it, when eight engineers left to form a new company in nearby Mountain View with the backing of an East Coast firm, the Fairchild Camera and Instrument Corporation. While Shockley eventually retreated to a faculty position at Stanford, where he pursued other interests, Fairchild's Semiconductor Division became the victim of the same phenomenon that gave it its start, the entrepreneurial urge to start one's own company and reap the rewards.

The 1960's were the heyday of the small, high-technology company founded with the then plentiful supply of venture capital, and microelectronics was leading the way. By just over a decade from its founding, when changes in tax laws made money for new businesses hard to get and the rate at which new companies started therefore slowed considerably, defectors from Fairchild had had a hand in more than a dozen new starts, and the original eight engineers from Shockley Semiconductor were themselves responsible for at least five of them.

Among the brightest stars were Robert Noyce and Gordon Moore of the Intel Corporation in Santa Clara. Noyce and Moore began at Shockley Semiconductor, were in on the founding of Fairchild, and left in 1968 to start Intel with $500,000 of their own money and $2.5 million of venture capital. Intel is now the largest microelectronics company in the area, just ahead of National Semiconductor (National, also in Santa Clara, was itself revitalized in 1967 by an infusion of personnel from Fairchild) and far in front of Fairchild, the perhaps not so proud father of this remarkable proliferation. (Since National and Fairchild make other electronic products in addition to microcircuits, their total sales exceed Intel's.) All of this took place in what was once an endless prune orchard in the Santa Clara Valley, between Palo Alto and San Jose. Now, in recognition of the concentration of microelectronics companies there, it is dubbed Silicon Valley.

Not all the microelectronics action is in Silicon Valley, nor are all the successful companies new ventures. The biggest maker of the tiny circuits is, fittingly, Texas Instruments, in Dallas. Starting life in 1930 as a geophysical exploration company, TI got into semiconductors with its 1954 commercialization of the silicon transistor. (Previously, transistors were made from germanium.) Similarly, the second leading microelectronics company, Motorola, which is in Phoenix, also began life in the 1930's. Only about one-third of these companies' sales are in microcircuits. Overseas, there are large corporations in Europe, including Philips in the Netherlands and Siemens in West Germany, and in Japan, such as the Nippon Electric Company, the largest semiconductor producer, and Fujitsu, the biggest computer maker there.

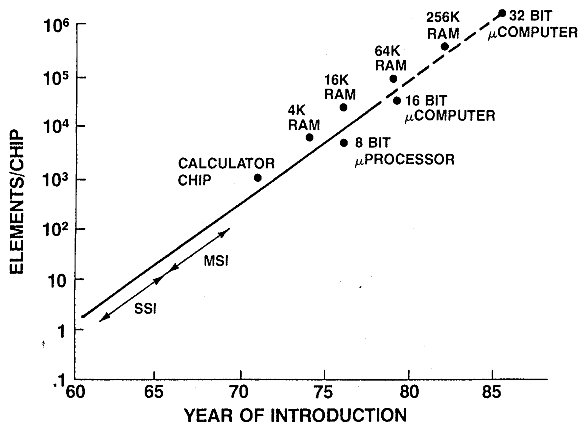



*In photolithography, ultraviolet light shines through a mask containing a circuit pattern and exposes a layer of photosensitive polymer that coats the silicon wafer. Machines that can produce patterns with features as small as those shown on this partially completed microcircuit can cost over $600,000. Several such instruments would be needed in a production line. [Source: GCA Corporation, Burlington Division]*

The fortunes of the microelectronics companies have paralleled the dizzying growth in the pervasiveness of electronics and computers in our lives. Electronic funds transfer and electronic mail are widely predicted to revolutionize businesses of the 1980's. Most 1981 General Motors cars will be equipped with two microcomputers to control fuel economy and emission of pollutants. And computerized appliances are already commonplace.

Alfred Stein of Motorola explained this pervasiveness at a seminar given in New Orleans last May by the investment banking firm Morgan Stanley and Company. In the late 1800's, industrial factories typically had one large electric motor to drive all the machines in a building. Now, by contrast, Stein counts 68 small motors in his home alone to power everything from large appliances to the electric toothbrush. Similarly, in the early 1960's, a company typically had one large central computer, but the trend is to find more uses for the machines as they become smaller and less expensive.

The reason for all this is miniaturization. Some can still recall the days when portable radios were bulky affairs that one operated as often as possible from a wall socket in order to save the batteries. The transistor changed all that because the solid-state device performed the same functions as a vacuum tube but was smaller, cheaper, more reliable, and consumed less power. But transistors still had to be manufacturered individually. Next, engineers invented a batch process in which hundreds of transistors were made on a thin wafer of silicon that was later broken into individual chips or dice, each containing a single device. It was not long after that the logical next step of connecting the transistors on a wafer into a complete computer logic circuit was taken, thereby eliminating the need to solder each device individually into a circuit board. This advance, called an integrated circuit, was made independently in 1959 by Jack Kilby of TI and Noyce (still at Fairchild). All the components of a circuit (transistors, diodes, resistors, capacitors, and connecting wires) were formed from silicon or thin films of other materials deposited on the silicon, further reducing size,




*The number of electronic components on a microcircuit chip has been increasing exponentially. SSI refers to "small scale integrated" circuits with less than 10 components per chip, and MSI refers to "medium scale integrated" circuits with less than 100 components per chip. The number of bits storable in random access memory (RAM) chips and the number of bits in the word length of microcomputers generally scale with the number of components on a chip. [Source: Morgan Stanley* Electronics Letter]

cost, and power consumption and increasing performance. In this way, applications of "intelligent" electronics once far too expensive to even consider are becoming routine.

By now, integrated or microelectronic circuits have gone through several generations, from 1 to 10 to 100 to 1000 and now to more than 10,000 transistors on a chip. The standard measuring stick for the density of devices on a chip is a kind of computer memory called a random access memory. Several years ago when he was director of research at Fairchild, Gordon Moore suggested that the maximum number of components on any microcircuit would double each year. Last year, IBM began producing (and other companies began circulating in demonstration quantities) a random access memory chip capable of storing 65,536 bits of information and containing about 70,000 components. With 1962 as the starting point, this is somewhat behind the 131,072 components projected. Moore says that a nearly 20-year-long exponential growth in chip density is at last "slowing down" to a doubling every $1^1/_2$ years. (The industry jargon measures memory size in kilobits, where 1 kilobit equals $2^{10}$ or 1024 bits. Thus, the 65,536-bit chip is called a 64K random access memory.) We are now in the last moments of the large-scale integration or LSI generation. VLSI begins with the 64K random access memory or perhaps the next chip after, which because generations of random access memory chips increase in density by factors of four would be a 256K.

The astounding fact is that, once enough circuits are sold to pay off the design and development costs, manufacturers can sell chips from each succeeding generation for about the same price as from the preceding ones. One old saying among engineers is that eventually every microcircuit will sell for $5 or less. This is where the cost reductions in computation that microelectronics makes possible come from, as exemplified by memory chip prices. Benjamin Jacoby of RCA was already able to write 3 years ago that a jelly bean was more expensive than one transistor on a large memory chip. The effect can be quite as dramatic in small computers, such as the small business or personal computers. Thomas Whitney of Apple Computer, Cupertino, California, for example, says it is the ever decreasing cost of memory chips that has made high-quality graphics affordable for these machines.

Engineers cite three factors that have made this nearly exponential growth in device density possible. The first is simply the ability to make chips larger. Although it sounds trivial, making bigger chips is not easy because the probability of a defect that renders the chip unusable grows with its dimensions. The second factor is what might be called circuit cleverness; the same circuit could be made from fewer transistors, for example. Finally, the size of each transistor could be decreased. Although there is some disagreement on the matter, most observers think that it is the third factor that will be most important in the transition from LSI to VLSI.

Today's LSI microcircuits are complex mazes of patterns that TI's George Heilmeier has likened in intricacy to the network of streets in the Dallas-Fort Worth metropolitan area. In the early days of microelectronics, the basic instrument for laying out the patterns, a process called photolithography, was a contact printer. A mask containing an array of identical patterns (one for each chip) was put in direct contact with the wafer, in precise alignment with the pattern emplaced by the previous masking step. Today's microcircuits may require a dozen or more masks to be used in succession in order to build up the finished circuit pattern. As the minimum size of features, such as the width of a metal strip connecting transistors, dropped below 5 micrometers to the now common 3 micrometers, a new type of instrument, the projection printer, in which a lens focuses an image of the mask onto the wafer, became popular. Advantages of the mask not touching the wafer include longer mask life and fewer defects in the chips. A crucial parameter of microcircuit production lines is the fraction of chips produced that are usable; that is, the yield. New products have been stalled for months while companies tried to improve their yields. But these advantages came at a cost. Whereas a contact printer could be bought for $15,000, a projection printer first went for $120,000, more recently for $240,000.

The latest arrival on the scene is called a direct step-on wafer, with which a single chip is exposed at a time. As feature sizes decrease to 2 micrometers or less, optical systems that can maintain high-resolution patterns across an entire wafer no longer exist, and the slower direct step process is necessary. These machines, just now being phased in at many plants, cost more than $600,000. Eventually, as feature sizes decrease even further to less than 1 micrometer, no conventional optical system will work, and some alternative such as the use of x-rays or a computer-controlled electron beam to directly write a pattern without a mask will be required. Some electron beam systems are in operation now at IBM and cost about $1.5 million. A similar cost escalation is taking place in other types of processing equipment.

Microelectronics was never something to be done in a garage, but the increased cost of the necessary equipment to stay abreast of advancing technology is changing the character of companies from small high-technology ventures to big businesses. Although venture capital has recently become more plentiful again, no one is rushing to invest in new microelectronics companies because the amount of money needed is too great. To put things in perspective, consider figures cited by Pierre Lamond of National Semiconductor, who says that in the 1960's, $5 million was adequate to start a state-of-the-art microelectronics company; now the figure is at least $50 million. Moreover, he adds, it is important to have a large volume of business, at least $100 million a year in sales, in order to pay off the large overhead. Intel's Noyce told attendees at the New Orleans seminar that the volume of microelectronics business worldwide could grow to $100 billion annually by the turn of the century. To increase production capacity enough to meet this volume would require a capital investment of some $50 billion over the same period which would be a major challenge. Capital spending by the industry in 1979 was just over $1 billion.

Thus, one of the signs of the times is that there are few microelectronics companies that have not been swallowed up by larger corporations. This is one way to generate the capital needed to continue in the business. Despite their success, microelectronics companies are extremely poor generators of capital. A fact of life in the electronics jungle is a concept originated by the Boston Consulting Group called the experience curve, which asserts that manufacturing costs decrease a fixed amount (25 percent or more in microelectronics) every time cumulative production doubles because engineers learn how to make their products more efficiently (high yields in the case of microcircuits) as they make more of them. TI has championed, and others followed, the concept that, to maintain market share, prices must follow costs, even in times when demand exceeds supply. The process is self-reinforcing. A larger market share means that the time to double cumulative production is less, so prices can be lowered faster, which leads to increasing market share. But even for those companies that have succeeded in establishing a new chip early and therefore have established a larger share of the market, profits are not large. Some observers, including Dan Klesken of Dataquest, a Cupertino market research organization, say that in order to generate adequate profits for R & D as well as capital expansion, microelectronics companies are going to have to start pricing their wares more closely according to their value rather than slavishly adhering to the learning curve. TI, in fact, has already begun such a policy by actually raising some prices on mature products in the second half of 1979.

In the meantime, microelectronics companies are rapidly disappearing as independent entities. Even the grandfather of Silicon Valley, Fairchild, was acquired by the French conglomerate Schlumberger, Ltd., last May, and Mostek, a 1969 spin-off from TI that has grown into the leading maker of state-of-the-art random access memory chips, became part of the United Technologies empire last October. Analyst Benjamin Rosen (formerly with Morgan Stanley but now president of his own firm, Rosen Research, Inc.) has counted 28 cases in the last few years in which domestic or foreign corporations either substantially invested in or acquired American microelectronics companies. And Richard Petritz (another entrepreneur who once was with TI, helped found Mostek, and now with the $100 million help of Britain's National Enterprise Board is starting a new microelectronics company called INMOS) told engineers at the International Electron Devices Meeting in Washington last December that in the 1980's there may be only about ten firms worldwide that remain as major suppliers of microcircuits.

Apart from capital costs, there is another force guiding microelectronics into the fold of traditional large corporate life: the problem of designing complex VLSI chips.

Zilog in Cupertino is one of the few microelectronics firms to start up in the 1970's. As one of the Exxon Information Systems companies, money for capital equipment was not the barrier it might have been for less well-parented ventures. President of Zilog is Federico Faggin, a defector from Intel. Faggin was on the team at Intel that designed the first microprocessor. A microprocessor performs the functions of the central processor unit of a computer, and it is on a single integrated circuit chip. It is this device that has made the blossoming of consumer electronics possible this past decade.

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Says Faggin, "The first microprocessor at Intel had about 2300 transistors and took 4 man-years to develop. In contrast, Zilog's most sophisticated device has some 20,000 transistors on it and required 30 man-years of development effort." Intel's Moore has compiled a graph showing the exponential growth in the average man-hours per month required to define and design new microelectronic circuits since 1960. The data point for 1980 is off-scale at the top of the graph and is indicated by an arrow pointing to the moon. James McGroddy of IBM cites as a yardstick a price tag of $100 per gate on an integrated circuit (a gate is a logic circuit formed from a few transistors). As the number of gates climbs to 10,000 or more, the design costs skyrocket to over $1 million. Just as the technology for submicrometer lithography and processing is under intensive development and will come in due course, so too are computer-aided design tools and new ways to organize the components of a microcircuit being extensively studied. But, says Moore, design costs are rising so much faster that they, rather than production costs, will soon dominate the total spent on developing new products (except for memory chips, where the transistors are in regular arrays.)

But design costs were already a problem as the LSI era began. In order to amortize the large amounts spent in designing a new product, huge numbers of chips had to be sold, although as chips got more complex, and therefore more specialized (again, with the exception of memories), the market for each design shrank. The microprocessor was a partial answer to this dilemma, because it was programmable. A single general-purpose chip could be manufactured in large numbers and then customized to perform specific applications by means of its programming instructions. The strategy worked, and talking-computer chess games, computerized supermarket checkout counters, and automated scientific instrumentation were some of the results. Now, on the threshold of the VLSI era, the programmable chip seems to be only part of a solution.

In the days of discrete transistors, components manufacturers made transistors, while someone else designed circuits for specific uses. As integrated circuits became more complex, components manufacturers became circuit designers as well as parts makers. Even with microprocessors, it was mainly left to the end user to devise the programs to run them. But today's most sophisticated microprocessors are as powerful as minicomputers, and chips yet more powerful are on the drawing boards. Andrew Grove, president of Intel, told a January meeting of New York security analysts that components manufacturers are now makers of computer systems and must provide the same kind of software support long characteristic of large computer companies. Otherwise, he said, the cost to the user of writing his own software is too large, and the next generation microcircuits would find no markets. More than half of the development time for the newest microprocessors is spent on software, a certain sign that it is no longer enough just to be a microcircuit producer.

Moreover, there is a blurring of the line between chip makers and equipment manufacturers, in part because of the consumer electronics boom. Companies that made microcircuits for calculators, for example, soon realized that it could be more profitable to make the entire instrument. National and TI, more than other companies, have exemplified this trend, whereas Intel, except for an ill-fated digital watch venture, has stayed aloof from it.

A further blurring of the line comes from those companies making products that use microcircuits, such as defense systems manufacturers who wanted chips so specialized that microelectronics firms would not agree to fashion them. They have developed their own in-house microcircuit fabrication capability. Western Electric and IBM have always made integrated circuits for internal use. (IBM makes about the same number of microcircuits as TI.) Now most major manufacturers of large and minicomputers have the ability to make some of their own components. Among instrument manufacturers, Hewlett-Packard is an outstanding example of a company making its own proprietary chips.

One of the hot topics of debate at recent electronics conferences has been whether the VLSI era of microelectronics will belong to components manufacturers newly become equipment makers or to systems houses that now make their own microcircuits. At the International Electron Devices Meeting, Petritz took the middle road, declaring that there would continue to be a place for both types of businesses, because it is too hard for most companies to be successful in both activities. Some chip companies might survive as independent divisions of larger corporations, however.

It is remarkable that, almost to a man, those in the microelectronics industry do not regard themselves as being in revolutionary times. Ralph Gomory, a vice president at IBM in charge of its Research Division, thinks it may all be a matter of perspective. In his view, technology inches ahead continuously. But new applications can seem to be revolutionary because they appear only when a succession of technical advances suddenly makes possible an application that was previously not feasible. Whatever the case, the changes being worked within the microelectronics industry itself as the VLSI era approaches certainly seem as dramatic as the effects previous generations of microelectronics have already had on society.

One question that has been asked (*Business Week* titled a story last December, "Can Semiconductors Survive Big Business?") is whether the creativity and entrepreneurial drive that characterized the early days of microelectronics can be continued in the new era of giant corporations. It is important that the answer be "yes" because competition from overseas and Japan in particular is becoming formidable. The next article will be on international competition in microelectronics.

—ARTHUR L. ROBINSON

# A New Kind of Storm Beneath the Sea

***Marine geologists and physical oceanographers are each sorting out their own types of evidence for surprisingly swift currents across the bottom of the deep sea***

The bottle of water hauled onto the ship's deck from near the sea floor 5000 meters below was strange indeed. Instead of being as crystal clear as bottled springwater, the way most open ocean water is, this sample was muddy—it looked more like river water than seawater. Although researchers had come to this spot south of Nova Scotia last year to study how currents lift clouds of mud off the sea floor, the heavy cloudiness that they found astounded them. Measurements showed that water near the bottom had been muddied with 100 times as much sediment as is found in most parts of the ocean and several times more than had ever been seen before.

All the mud was being kicked up by intermittent currents that were twice as swift as physical oceanographers expected, among the strongest currents ever measured across the deep sea floor. Geological oceanographers, who have been studying ripples in the bottom mud caused by currents, expected high-speed currents because they could not imagine any other cause for the kinds of ripples seen in the bottom sediments. The new observations lend some credence to the geologists' claims of a broad, fast current along the western edge of the deep Atlantic, but detailed observations have covered too short a period to permit firm conclusions. Many researchers would agree at this point with the oceanographer who noted that "we just don't know what's going on down there."

Circumstances are inevitably pushing geological and physical oceanographers toward closer cooperation in the study of the boundary between the sea and the sea floor, but such studies have been some time in coming. As early as 1936, the late Georg Wüst of the Institute of Oceanography at Kiel measured variations in the deep-sea temperature, pressure, and salinity, variations that drive the major ocean currents, and concluded that deep-sea currents were not as sluggish as had been supposed. They probably could, he said, alter the shape of the sea floor and carry sediment great distances. "Geologists were slow to grasp the importance" of Wüst's calculations, according to Charles Hollister, a marine geologist at the Woods Hole Oceanographic Institution on Cape Cod. Further papers by Wüst in the 1950's and personal appeals to individual geologists, such as Hollister and the late Bruce Heezen of Lamont-Doherty Geological Observatory, eventually led to the first studies of the effects of currents on the deep-sea bottom.

But then it was the geologists' turn to goad the physical oceanographers. The latter began to directly measure deep current speeds of 10 to 15 centimeters per second (or about 0.5 kilometer per hour), speeds that had been predicted by Wüst. But the geologists started to suggest, on the basis of photographs of bottom features, that even faster flows must occur over many parts of the ocean. By looking at the types of ripples, the way sediment collects behind obstacles, the shapes of scour marks in the mud, or the smoothness of the bottom, geologists eventually assigned speeds of 40 centimeters per second or more to currents


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