THE
DIAMOND
MAKERS

Humans have treasured diamonds for their exquisite beauty and unrivaled hardness for thousands of years. Deep within the earth, diamonds grow. Diamonds the size of footballs, the size of watermelons – billions of tons of diamonds wait for eternity a hundred miles beyond our reach. But how is it possible to create these spectacular gems at the earth's surface?

Spanning centuries of ground-breaking science, bitter rivalry, outright fraud, and self-delusion, *The Diamond Makers* is a compelling narrative centered around the brilliant, often eccentric, and controversial pioneers of high-pressure research. This vivid blend of dramatic personal stories and extraordinary scientific advances – and devastating failures – brings alive the quest to create diamond. Scientists have harnessed crushing pressures and scorching temperatures to transform almost any carbon-rich material, from road tar to peanut butter, into the most prized of gems. The book reveals the human dimensions of research – the competition, bravery, jealousy, teamwork, and greed that ultimately led to today's billion-dollar diamond synthesis industry.

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PREFACE

On a cold winter day in December 1955, Robert Wentorf Jr. walked down to the local food co-op in Niskayuna, New York, and bought a jar of his favorite crunchy peanut butter. This was no ordinary shopping trip, for Wentorf was about to perform an experiment of unsurpassed flamboyance and good humor. Back at his nearby General Electric lab he scooped out a spoonful, subjected it to crushing pressures and searing heat, and accomplished the ultimate culinary *tour de force*: he transformed peanut butter into tiny crystals of diamond.

The triumph of Wentorf and his GE colleagues, who learned to turn just about any carbon-rich material, from road tar to snake oil, into a sparkling treasure, marked the culmination of centuries of scientific study and technological breakthroughs – research driven by a fascination with nature's most romantic gemstone and by our awe at the power of high pressure to transform matter.

Scientific research encompasses much more than the dry data and abstract equations that appear in journals and monographs. Science is a marvelously human endeavor, driven by curiosity and ambition and wonder and greed. *The Diamond Makers* tells the story of scientists who spent their lives enthralled with the transforming power of high pressure. Under pressure, liquid water crystallizes into new kinds of ice, everyday gases condense to metals, and black soot becomes a precious gemstone. The science and technology of diamond making pervades our society, from one-hour eyeglasses to efficient road repair. Synthetic gem diamonds also play a central role in the ongoing adventure of high-pressure research, as researchers squeeze together pairs of diamonds to produce pressures that exceed those at the center of the Earth.

The synthetic diamond story spans more than a century of top-notch science and outright fraud, brilliant insight and self delusion. In spite of the physical risks and economic rewards, most of the high-pressure pioneers were driven ultimately by an overpowering desire to explore the unknown. *The Diamond Makers* is the story of scientists and engineers and the powerful machines they have built to unlock Nature's secrets.

* * *

Every new scientific theory must be considered in the social and intellectual context of its time. Scientists find it tempting to describe the history of science as a series of successes and failures, judged against our modern "correct" theories. Such an approach might seem especially applicable to the diamond story, for there is one simple measure of success: was diamond made in the laboratory? But such a narrow perspective is at best misleading. Science builds on past experience, and discovering what doesn't work is often the key to finding what does. Those dedicated scientists who stumbled and fell short of our perception of truth cannot be viewed as failures, and their story deserves to be told.

Some philosophers criticize scientists who believe in an independent, knowable Nature. Reality, they say, is merely a human construct: There is no absolute truth in nature, only our inadequate perception of that truth. Some scholars even deny the concept of "progress;" for them there is only change. I disagree. Along with most scientists, I am an unabashed believer in a universe with knowable physical laws, and I believe that we can measure scientific progress by our degree of understanding of those laws. To be sure, we have only come the tiniest fraction of the way toward understanding, but each advance marks a triumph for science and technology. The story of the diamond makers represents one such triumph. A few decades ago no one had ever done it; now, anyone with a few hundred thousand dollars and a big basement can make them at home. To me, that's progress.

This book is not a comprehensive account of the history of diamond synthesis. Rather, I want to share some of the lore of science and scientists – the stories that never make it into formal publications. I was drawn into high-pressure research by these remarkable people. I have shared the drama of their discoveries, as well as the frustration of their failures.

Most of this book focuses on the struggles of scientists who first attempted to make diamonds in the laboratory. The history of diamond synthesis cannot be divided neatly into pure versus applied stages of research, as is the case with many of the scientific discoveries that have transformed the twentieth century. With new diamond-making technologies have come both exciting new ways to study matter and extraordinary new uses for synthetic diamonds. As diamond making has become routine, the gems themselves have allowed scientists to achieve higher and higher pressures.

I have tried to present a fair and balanced history of the diamond story, but I cannot escape biases developed during more than 20 years at the Carnegie Institution of Washington's Geophysical Laboratory, home of many central players in the high-pressure game. I am more intimately familiar with work done in the United States than elsewhere, so most of the book focuses on American scientists. Key contributions by researchers in Europe, the former Soviet Union, Japan, and Australia have perhaps received less than their fair share of space; I encourage workers in those regions to recount their own personal histories.

* * *

I wrote this book for three reasons. First, diamond has captivated human imagination for thousands of years, and the fascinating story of the gem's synthesis is not widely known outside of the technical literature. Second, diamond making provides an ideal framework for describing high-pressure science – a field that has profoundly shaped our understanding of the material world and enhanced our ability to alter it. But most important, this book arose as an answer to a rhetorical question posed by my son in the winter of 1990. After a particularly frustrating textbook lesson in his junior high school science course, he asked me "Why would anyone want to be a scientist?"

This book may be a longer answer than Ben expected, but I hope it will help him to see the drama that underlies scientific discovery. I hope it's not too late for him to appreciate how powerful science can be in helping us to understand our world, and, if used wisely, to shape it to our benefit.

* * *

The greatest joy in writing this book has been the opportunity to learn from so many high-pressure pioneers. Sadly, Percy Bridgman died before my years in Cambridge, Massachusetts, but many of his students and younger associates have vivid memories of his unique style and his extraordinary laboratory. Hatten S. Yoder, Jr., Alvin Van Valkenburg, Francis Bundy, Herbert Strong, Robert Wentorf Jr., and Tracy Hall all met Bridgman in his later years, and their recollections have enriched the story. I have also relied heavily on Bridgman's recent biography, *Science and Cultural Crisis* by Maila L. Walter (Stanford University Press, 1990) for biographical details.

Erik G. Lundblad, a member of the Swedish electric firm ASEA's diamond-making team, contributed much information on Baltzar von Platen's personality and inventions, as well as on ASEA's QUINTUS project. Lundblad also provided fascinating historical photographs from the ASEA effort.

Loring Coes, Jr., was remembered by many of his long-time associates at Norton: Neil Ault, George Comstock, Paul Keat, Alan G. King, and Osgood Whittemore all shared their reminiscences. Additional information was provided by Francis Birch, Francis R. Boyd, Eugene C. Robertson, Alvin Van Valkenburg, and Hatten S. Yoder, Jr., who were at the Norton meeting on December 4, 1953, and Edward Chao, who discovered coesite in nature. Samuel Coes graciously provided details on his brother's early years.

All of the original members of the General Electric diamond-making team have contributed significantly to this book. Francis Bundy, Herbert Strong, and Robert Wentorf in Schenectady, New York, spent many hours retelling the story, clarifying details, and showing the site where the "Man-Made Diamond" process originated. Tracy Hall in Provo, Utah, also shared his memories of four decades of diamond making, and patiently explained the nature and origins of the disagreements that have arisen regarding the GE history. Harold Bovenkerk, the last member of the original team to retire from General Electric, provided his unique insight regarding the history of domestic and foreign diamond synthesis. All of these men were generous in sharing historic photographs and documents, as well as unpublished anecdotes. I am also grateful to Mark Sneeringer and Anne Shayeson who hosted a memorable tour of General Electric's Worthington, Ohio, diamond making facility.

Francis R. Boyd, Ivan Getting, Julian Goldsmith, and Alvin Van Valkenburg, along with all the original GE diamond makers, provided stories about George Kennedy's extraordinary life, scientific research, and diamond synthesis endeavors. Armando Giardini contributed much on the unpublished history of diamond making at the Army

Electronics Command, Fort Monmouth, New Jersey. Henry Dyer of De Beers Industrial Diamond Division, and one of the original De Beers diamond synthesis team, shared the history of South African synthetic diamond studies. O. L. Bergmann of Du Pont shared information on Mypolex, an explosively manufactured diamond.

Alvin Van Valkenburg, inventor of the lever-arm diamond anvil cell, had been my friend for almost two decades. Shortly before his death in December 1991, he spent many hours recounting the high-pressure history he knew so well. His son, Eric Van Valkenburg, contributed important photographs and other documents. Bill Bassett, who with his colleague Taro Takahashi learned about the diamond cell from Van and thus became the first earth scientist to use it, shared many memories of his research and his many friends and colleagues in high-pressure research.

Most of all, I am indebted to my many present and former colleagues at the Carnegie Institution of Washington's Geophysical Laboratory. For almost 90 years, the Geophysical Laboratory has played a leading role in high-pressure research, especially in the earth sciences. Hatten S. Yoder Jr., whose work in high-pressure began more than a half century ago, continues to provide inspiration and expertise to the next generation of diamond makers. This book has been shaped by his wealth of first-hand historical knowledge.

Francis R. (Joe) Boyd, who could have been the first diamond maker when he came to the Geophysical Lab in 1953, is still making big presses and squeezing rocks. Joe's decades of research on diamond-bearing rocks from South Africa and elsewhere was critical in telling the story.

I owe a special debt to Peter M. Bell, who advised me in my first years at the Geophysical Lab, and his brilliant colleague Ho-Kwang (David) Mao, who has transformed modern high-pressure research. Peter and David were the first to achieve a million atmospheres pressure in a diamond cell, and David, either directly or through his students, has instructed most of the handful of humans who have learned to duplicate the feat. Now, with Russell J. Hemley and a gifted team of junior colleagues, David Mao continues to make high-pressure history. All of these scientists have contributed immeasurably to my historical research.

I have received thoughtful and constructive reviews of the manuscript from many friends and colleagues. Those who have read and reviewed substantial portions of the manuscript include Allen Bassett, William Bassett, Harold Bovenkerk, Ray Bowers, Francis Boyd, Francis Bundy, James Cheney, Tracy Hall, Russell Hemley, Raymond Jeanloz, David Mao, Charles Meade, Charles Prewitt, Gretchen Prewitt, Herbert Strong, Robert Wentorf, and Hatten Yoder, Jr. Each of these high-pressure experts made important additions and corrections, and to each I am indebted.

Finally I thank Margaret H. Hazen, my greatest supporter and most perceptive critic, whose influence is present on every page of this book.

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PROLOGUE

PRESSURE. TO MOST PEOPLE THE WORD brings to mind the daily stress of our busy lives. Yet to many scientists, pressure means something very different; it is an idea filled with wonder and power – a phenomenon unlike anything else we know. Pressure shapes the stars and planets, forges the continents and oceans, and influences our lives every moment of every day.

Three arenas of high technology drive our economy and propel us toward the twenty-first century. Information technologies link us to the world and its resources as never before, while biotechnologies hold the tantalizing promise of an era of health and plenty for all. But of all the advances that shape this age, none plays a more immediate and dramatic role in our day-to-day lives than the science and technology of new materials, and no technology holds more promise for creating and producing these remarkable new substances than the technology of high pressure. With pressure we can transform liquids into spectacular crystals, ordinary gases into exotic dense metals, and lumps of coal into precious gems.

We experience pressure whenever we push a button, press down with a pen, pump up a tire, or hear the explosive birth of popcorn. Behind such simple actions as inflating a party balloon or squeezing a tube of toothpaste lies a phenomenon that has captivated scientists, driven engineers, and transformed virtually every aspect of our physical world. Pressure occurs whenever a force acts on an area. Your shoe applies pressure to the sidewalk, water exerts pressure on a skin-diver, and the atmosphere weighs down on everyone and everything at the earth's surface with a pressure of about fourteen-and-a-half pounds per square inch. Scientists call normal, everyday pressure – the weight of thirty or forty miles of air pushing down on you – one atmosphere or one bar.

Most of the pressures we experience in everyday life are rather modest. A pressure cooker generates about one-and-a-half atmospheres, while the air in your car's tires is typically pressurized to about two atmospheres. A

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scuba diver 300 feet down experiences almost ten atmospheres of pressure, while a heavy-set woman in stiletto heels could apply a pressure of about fifty atmospheres to the floor on which she walks.

However, when researchers talk about high pressure, they mean vastly greater pressures of thousands or millions of atmospheres – kilobars or megabars. In fact, as pressure records have soared during the past three decades, new superlatives have come into play. “Superhigh pressures” (hundreds of thousands of atmospheres) and “ultrahigh pressures” (millions of atmospheres) are now standard jargon.

Scientists investigate these immense, often dangerous extremes because pressure causes matter to change in remarkable ways – much like the dramatic changes induced by temperature. Humans have known for thousands of years that liquid water freezes to a solid if cooled and boils to a gas if heated. We can now mimic these so-called changes of state at room temperature by using pressure: we can cause water to “freeze” at high pressure and turn it into gas in a vacuum.

Over the centuries humans have learned to use a wide range of temperatures, from a tiny fraction of a degree above absolute zero (the coldest possible temperature) to about 1 000 000°C at the focus of several intense laser beams. Over this temperature range we observe remarkable changes in matter, from superconductivity to nuclear fusion. During the past few decades, scientists have learned to exploit a similar range of pressure, from a high vacuum – less than a billionth of an atmosphere – to pressures of many millions of atmospheres. Matter subjected to these extremes of pressure displays astonishing behavior, rivaling anything seen at exotic temperatures. Researchers have discovered that high pressure can turn ordinary compounds into superhard abrasives and transform everyday rocks and minerals into the dense materials that form the dynamic interior of our planet.

Pressure alters matter by forcing atoms into ever smaller volumes. Every substance displays this phenomenon: as pressure increases, the volume of the compressed material decreases. At high pressures atoms must shift into more efficient, more densely packed arrangements. At high enough pressure any gas will become a solid, and every solid will adopt a new, denser form. To accomplish this volume reduction, the bonds between atoms – the interaction of the atoms’ electrons – must also change. Pressure thus serves as a powerful probe of atoms and their electronic structure, helping us to learn how our physical world holds itself together.