Our Changing Planet
The View From Space

For over forty years now, satellites have been orbiting above the Earth, quietly monitoring the state of our planet. Unseen by most of us, they are providing information on the many changes taking place on Earth, from natural processes such as land movements, volcanic eruptions, and the ebb and flow of the seasons, to human-caused changes such as the growth of cities, deforestation, the spread of pollutants in the atmosphere and oceans, and the depletion of the ozone layer over the poles.

Led by four editors with support from a production team at NASA Goddard Space Flight Center, many of the world's top remote sensing scientists showcase spectacular and beautiful satellite imagery and provide informed essays on the science behind the images and the implications of what is shown. The images and text highlight numerous examples, on local, regional, and global scales, of both natural changes and the many effects that human activity is having on the Earth.

Our Changing Planet: The View from Space is a stunningly attractive and informative book for anyone interested in environmental issues and the beauty of our home planet. It portrays the astounding range and scientific utility of information that can be derived from satellites and demonstrates the great benefit that satellites provide for monitoring both natural and human-caused changes occurring throughout the world. It will provide inspiration for students, teachers, environmentalists, the general public, and scientists alike.

Pre-publication praise for *Our Changing Planet: The View from Space:*

'I've had the good fortune to visit some of the most beautiful parts of our home planet, and witness first hand the effect human activity is having on our world. This book allows you to explore some of these effects through an awe-inspiring collection of images of the Earth from space. This wonderful volume provides a masterful association of imagery and explanation. You will have difficulty closing it once opened. I give it my highest recommendation.'

Sir Ranulph Fiennes, internationally renowned explorer and adventurer

'Our understanding of the world radically changed when we first saw it from space. It became at once precious yet vulnerable, romantic yet realistic, and above all unified as the physical and living environments came indissolubly together. The pictures in this remarkable book could almost tell the story by themselves; but they are supported by a well written collection of essays which together explain the underlying science and how the system actually works. As tiny ephemeral creatures on the surface, we can also see the alarming effects our activities are having, whether on the land, in the seas or in the atmosphere, so that this epoch in the Earth's long history can be appropriately named the Anthropocene. We still have to reckon with the consequences. This is an excellent guide to greater understanding of the fundamental issues of our time.'

Sir Crispin Tickell, Director of the Policy Foresight Programme at the James Martin Institute for Science and Civilization at Oxford University, former British Ambassador to the United Nations, former President of the Royal Geographical Society

'Great, readable book with spectacular space views of how our home planet is changing – the land, atmosphere, oceans and ice.'

James Hansen, Director of the NASA Goddard Institute for Space Studies

'We have been advised for years to act locally and think globally and nothing helps us think more about the globe than the wonder of viewing the whole and all its changeable parts from space. This book tells us what is happening to our world in graphic detail and it is truly an eye opener.'

'William Ruckelshaus, First Administrator of the U.S. Environmental Protection Agency'

'This collection of stunning images of our planet from space serves as a focus for a discussion of geologic, atmospheric and oceanic processes. The emphasis is on change, and here the images of shrinking glaciers are particularly impressive. Much of scientific progress has been associated with increased magnification of ever smaller subjects, down to the molecular and atomic dimensions. This volume illustrates rather the opposite: of how much can be learned from integrated views of large areas, up to the planetary dimension.'

Walter Munk, Professor Emeritus Scripps Institution of Oceanography

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The View From Space

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Cover image: View of Earth's horizon as the Sun sets over the Pacific Ocean. This image was taken by a crewmember onboard the International Space Station (ISS), July 21, 2003. Anvil tops of thunderclouds are visible. Image courtesy of the Image Science and Analysis Laboratory, NASA Johnson Space Center, photograph number ISS007-10808

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Foreword

Astronaut Piers Sellers on a spacewalk during the STS-112 mission, October 2002. (Image courtesy the Image Science & Analysis Laboratory, NASA Johnson Space Center.)

There are six and a half billion people on Earth right now, and this number will likely grow to about nine and a half billion by 2050. All of us inhabitants grow up with our own perception of the world around us, how it works and our place in it. Gandhi said that when a person dies, a whole Universe dies with him, and somehow we all know this to be true—every one of us has a unique view of the environment outside of ourselves; its form, its meaning, and its purpose. And this view changes for each one of us as we grow, as it has changed for mankind as a whole as humans have evolved and understood more about the Universe around them.

For small children, the world is a small and exciting place consisting of a few rooms, a garden, and perhaps a street or fields, all inhabited by gigantic people. This little Universe is simply there to be explored and enjoyed. As we grow up, our horizons expand, through direct experience and from learning, to encompass the whole Earth and, dimly, the Universe beyond that. But still, places, scales and people that we have seen or met for ourselves seem

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more real and tangible, which is why Gandhi was demonstrably correct: the Universe in Einstein's head was surely different than the Universes inside the heads of a rock star, a desert nomad, or an astronaut. In general, more knowledge and experience tend to nudge us towards common alignments in our thinking, so that, as Science progresses, we tend to share more similar, and hopefully more realistic, perceptions of the world. This can only be for the good, as generally shared views based on science usually lead to better discussions and better decisions. This book makes a solid contribution towards this common alignment, as it brings to us realistic views of our world which modify the sometimes abstract and vague pictures we have in our heads. For example, a school kid once asked me if the countries of the world all had different colors, like on the atlas in the classroom—this book should help him out.

The book has a compilation of stunning images, but there are dozens of beautiful coffee table books out there full of Earth images. I should know; I have a stack of them at home. These images appeal to the human and the aesthetic in each of us, as the world is a staggeringly beautiful place at almost every scale we choose to observe. But this book is more than just a succession of attractive images; it penetrates deeply into the science of what is being observed: not just the what, but also the how, the why, the where and when. For example, the images of global temperature (pages 54 and 55), when analyzed, combined and replotted as trends against time, clearly show the stratospheric cooling and tropospheric warming that are the signatures of global warming. So, beauty and aesthetics—certainly; knowledge, insight, and understanding—emphatically.

Satellites have revolutionized the way we see our home planet. The first interplanetary spacecraft sent back fuzzy but intriguing images that changed the way we saw these far-off places forever: Venus turned out to be a high-pressure, boiling hell—no princesses or dinosaurs to be seen anywhere. And Mars turned out to be airless, arid, and very cold—no canals, no princesses and, disappointingly, no signs of current life either. The point is that whatever ideas any of us had about these places prior to the arrival of the early spacecraft were irrevocably changed—generally in the direction of objective reality—by the first bits of data received back. It should have been no surprise then that Earth-viewing satellites would change the way we see our planet and likewise correct and converge the many and varied ideas people had about its form and functioning. But it was a surprise—in fact there was a continuous succession of surprises—to both the public and scientists alike. Most people expected that satellites would mainly confirm what we have already learned from 500 years of scientific investigation, but the impact of the satellite viewpoint went far beyond that. The orbital view combines an incredible enlargement of scale—the term "God's-eye view" is not far off the mark—while still providing detail that relates back to our everyday experience. For example, we have all seen pictures of hurricanes from space (page 36). From orbit, we can see them in their entirety; huge, cloudy cartwheels sliding across the oceans. Prior to the satellite age, people knew very well what hurricanes were, and how they formed, behaved and their size and shape, but nonetheless, the first actual pictures mesmerized scientists and laymen. People could take in everything about the scale and structure of these immense phenomena, but at the same time could see the constituent clouds that provide yardsticks back to the scale of our everyday lives. (Another school kid I met, eight years old, was looking at a picture of a hurricane and pointed at a little cloud at the edge of one spiral arm. She immediately understood everything about the size of the hurricane from that one cloud and even pointed out that she would be a little dot down here, under this cloud, near that island. She also, without prompting, understood that she was seeing the clouds from above, able in her mind to turn her ground-based idea of a cloud upside down and see it from the other side, with the Earth below it.) So images from satellites enlarge our view, literally, of the greater world. All of us, from kids to scientists, can thereby gain a deeper understanding and appreciation of the scale and beauty of Earth, how it works, how it is changing, and what its future state might be.

Satellites and their instruments are extraordinary, almost miraculous, devices, among the most intricate and complex things that man has devised, incredibly expensive and unbelievably powerful and useful. Consider that a satellite instrument is a combination of precision optics, propulsion and navigation units, and delicate electronics but must nevertheless withstand the rigors of launch—vibration and acceleration to the unthinkable velocity of 8 kilometers per second—and then survive a lifetime of coasting through an airless void with extremes of heat and cold, flashing into day and night every 50 minutes or so. It is surprising that they work at all, let alone that they can be lofted into orbit in the first place. But once there, the satellite provides an extraordinary perch from which to view the world. In a matter of a few hours, it can map the whole planet, using the same well-calibrated instrument, and send the stream of pointillist data back to our laboratories almost as soon as they are collected. We can drive the point home with a concrete example: biologists and scientists working on the global carbon budget want to know how much green material there is on the Earth at any given time, which translates to knowing roughly how many green leaves there are. Not only that, they want to know how this pattern of greenness changes over time; with the seasons, with different weather conditions, and as a result of human activities—deforestation, logging, fire, cultivation. Now we can envisage sending out a million biologists every day to do leaf density surveys, bringing back their results every night, and transmitting their reports to NASA's Goddard Space Flight Center where an army of researchers would process and reduce the data to a time series of vegetation density maps. Once the problems of ensuring that the data collectors all use the exact same measurement technique, are equally conscientious, and can maintain their enthusiasm over several decades are ironed out, it may be possible to finally produce a time series of maps. (Funding would be a challenge, organization a nightmare, and quality control a fantasy, but we will skip over these management problems for the purposes of this thought experiment.) Instead, all of this is avoided by having the data collected by a couple of satellites which provide us with wall-to-wall global estimates of vegetation density at intervals of a few days (pages 134–135), using a consistent, vandal-proof pair of instruments and a single measurement methodology. These data are being quietly collected somewhere above you right now and are being sent to laboratories to be studied and analyzed at leisure. Thus it is the synoptic quality of satellite instruments that is so unique and so powerful, and which make them such cheap tools when compared to other methods of global observation, like our million diligent biologists.

The book starts with images of the atmosphere. The static pictures tell us much about the structure of the atmosphere but time-series data reveal the dynamics of the atmosphere as well as information about its interactions with other parts of the Earth system. The transport of heat from the equator to the poles is done by the large-scale circulation, some by the stately and steady flow of ocean currents and some by the violent and episodic hurricanes. Both are key to maintaining the current climate; both are thought to be sensitive to global warming. The large-scale transport of dust particles in the atmosphere—almost completely ignored before being revealed by satellite observations—can exert a direct influence on the climate by absorbing sunlight and warming the air, or by reflecting sunlight and thereby contributing to reduced warming. Satellites have shown us how much of the atmospheric dust burden is directly due to cultivation. The concentration of carbon monoxide (CO), a by-product of incomplete combustion, is now routinely measured from orbit—we can see the traces of industrial output and field burning all over the world.

Images of ship tracks and aircraft contrails again bring us to the junction of a new larger scale with the familiar scales of our own experience. We can see a recognizable picture of the United States (page 73), busily crisscrossed by aircraft contrails. Each tiny contrail leads back to an invisible aircraft containing a couple of hundred souls flitting from somewhere to somewhere else. Were you flying on a commercial aircraft on January 29, 2004? Look at page 73—you might be able to see yourself. (Once, while spacewalking outside the International Space Station, I looked down to see a brilliant sunlit Atlantic Ocean dotted with tiny clouds hovering above the water, each one slant-tethered to its own perfect, slightly displaced cloud shadow. Then I saw a minute jet contrail slowly and bravely pushing its way across the huge ocean towards me. I could not see the aircraft at the apex of that long, white streak, but I wondered what the people on board were thinking and doing. After another few seconds, the scene with its clouds and contrail slipped below the horizon behind me, into my past and into their future.)

The ozone hole has been cited, convincingly, as the first global environmental crisis that was recognized, discussed, and dealt with by the global community. Satellites played a key role in understanding and monitoring the problem, but perhaps more importantly, in convincing people everywhere that a problem existed and needed to be addressed. Most of the public and politicians did not understand the chemistry and dynamics of the Antarctic ozone hole, but everyone could grasp the size and the growth of the problem just by looking at the images (see page 78). The sequence of images allowed non-scientists to leapfrog over a bewildering tonnage of scientific discussion and analysis to see, to really see, what was happening. And no truths were lost in the process.

When I watch people looking at images of the land surface for the first time, I almost always see the same thing. First, they turn the pages quickly, but after a while they slow down, as their minds synchronize with the things they are seeing, aligning the images with almost-forgotten geography lessons, or with familiar places seen from a different vantage point. ("Hey—that's where I used to live.") A favorite is the Nile valley (page 92)—the river snakes its way through the desert, flanked by green banks of cultivated land, ultimately fanning out into an emerald delta as it reaches the sea. Desert, mountains, lakes, greenery, seas are shown as they really are, not conceptualized abstractly like on a map. The image of the great deserts of North Africa and the Middle East (page 130) shows us striking patterns and structures—great swirls of sand washing up against mountain ranges and rock plains.

Satellites have allowed us to study the oceans in a completely new way. Satellite-based radar altimeters detect the bumps and dips in the ocean's surface caused by currents, tides, and flows over subsurface structures. These data, combined with satellite-derived sea surface temperature and wind data, allow us to map the great currents. What have we learned? Again, we have achieved a short cut to our understanding of how the oceans work. El Niño can be explained with words and graphs, but a couple of images (pages 160–161) do a better job in getting across the size, scope, and pattern of this dynamic phenomenon. Likewise, a graph of sea level rise (page 163), distilled from billions of bits of data into a single line, speaks volumes: it's tough to argue with hard data that even a fourth-grader can understand. "Dad, it's going up, isn't it." (Note the lack of a question mark.)

If our million biologists would have to be a hardy and motivated bunch to complete their weekly leaf surveys, the army of glaciologists required to map the cryosphere would need to be of very stern stuff indeed. Instead, satellites have allowed us to assay the global ice volume without unnecessary heroics and to determine how it changes seasonally and over the decades. It is now clear that many of the great Greenland glaciers have accelerated towards the sea, almost in unison, lubricated by increases in meltwater flowing between the rocks and the glacier bottoms. Likewise, the Arctic Ocean ice cap is unevenly but decidedly shrinking, with ramifications throughout the Arctic climate and ecosystem.

Satellites show us directly the evidence of Man's hand at work on the planet. When we look at a multiyear trace of CO_2 concentration, we see a clear annual cycle—the dips in the trace correspond to the Northern Hemisphere spring and summer, when continental vegetation pulls CO_2 down from the atmosphere for photosynthesis (plant growth), and the peaks represent the release of CO_2 back to the atmosphere by dying and decomposing vegetation in the fall and winter. This cycle is closely matched by the time series of images of vegetation greenness over the land. Each spring, we can see the "green wave" creep northwards over North America and Eurasia, reach a high tide mark in the late summer, and then slowly flow back towards the equator during the fall. The combination of atmospheric CO_2 data, with their precise inferences about the amounts of CO_2 being exchanged, with the spatial patterns provided by the satellite data, has given us a powerful new way to understand the global biosphere. This much we know: the growing season in the Northern Hemisphere has stretched out by 12 to 18 days over the period 1982–1999 (page 283). In addition, we now think that the land biosphere has acted as a net sink for CO_2 over the same period, burying more carbon than it has returned to the atmosphere.

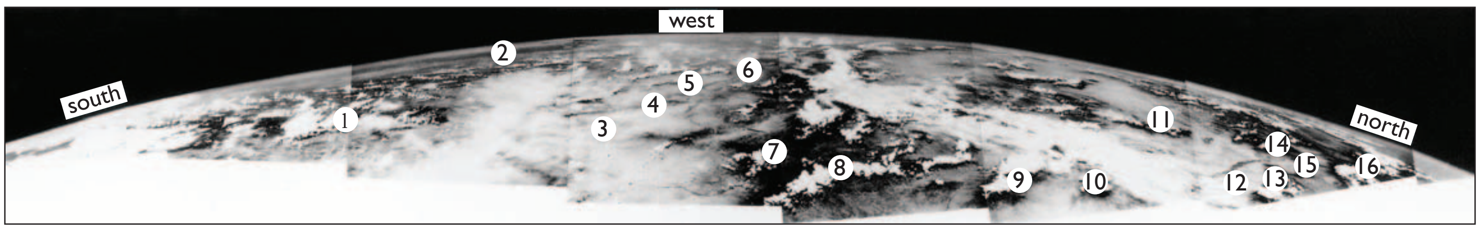
Finally, satellites can tell us a lot about the inhabitants of this planet. Pages 292–293 show a synthetic night time view of the Earth. The city lights outline the continents and dot the interiors, and to a great extent tell us who is consuming how much energy and where. North America, Europe, and Japan are all brightly lit—the southern half of the densely populated United Kingdom is almost a continuous wash of light, much to the annoyance of amateur astronomers there. Most of Africa is dark—just a few widely spaced cities can be seen. The patterns of industrialization in India and China show up unambiguously. All the people of Earth, snapshotted onto a pair of pages.

Sometimes it's good to stand back and take in the "big picture." This book will allow you to see the world as visualized by billions of dollars worth of satellite hardware, and analyzed by several hundred dedicated scientists over several years of painstaking work. You can read it in the time it takes you to fly across the country, followed by your own tiny contrail which will probably be observed through a satellite lens or a spacewalker's visor several hundred kilometers above you.

Piers J. Sellers
Over the Atlantic between Scotland and Greenland
Continental Flight CO5 (London Gatwick to Houston)

Artist's rendition of the Upper Atmosphere Research Satellite (UARS) superimposed on a sunrise view of the Atlantic Ocean off the coast of Jacksonville, Florida on February 23, 2003. NASA's UARS satellite is one of 48 different international Earth-observing satellites used throughout this book. It was deployed from Space Shuttle Discovery on September 14, 1991 and raised to an orbital altitude of 600 km, where it provided observations of the Earth's atmospheric chemical composition until the end of 2005, circling the globe for over 5000 days. (Photograph from the International Space Station, NASA image number ISS006-E-32544.)

Preface



Panorama of the Earth taken from a V-2 rocket fired from White Sands, New Mexico, on July 26, 1948. The area shown is approximately 2 million km^2, photographed from an altitude of 100 km. The V-2 rockets were the world's first ballistic missiles. Parts of almost 100 rockets were captured from Germany at the end of World War II and transported to the United States, where they were instrumental in initiating the post-war 'space race.' (Image courtesy Johns Hopkins University Applied Physics Laboratory.)

The numbers on the photograph correspond to the following locations: 1-Mexico, 2-Gulf of California, 3-Lordsburg, New Mexico, 4-Peloncillo Mountains, 5-Gila River, 6-San Carlos Reservoir, 7-Mogollon Mountains, 8-Black Range, 9-San Mateo Mountains, 10-Magadalena Mountains, 11-Mt. Taylor, 12-Albuquerque, New Mexico, 13-Sandia Mountains, 14-Valle Grande Mountains, 15-Rio Grande, 16-Sangre de Cristo Range.

Just over 60 years ago, in 1946, an unmanned V-2 rocket was launched into space from White Sands, New Mexico, and recorded the first picture of Earth from space, demonstrating the feasibility of observing our planet from beyond. By the early 1960s, Earth-orbiting satellites were providing black and white photographs of clouds and other major phenomena in the Earth's atmosphere. The famous photographs of the Earth taken by Apollo astronauts on their way to the moon provided iconic images of the 1960s and early 1970s in which our planet appears small and isolated, helping to spur the environmental movement of the late 20th century, epitomized with the creation of Earth Day on April 22, 1970. Since then, the public has experienced an increasingly sophisticated and ever-present exposure to images of the Earth from space. The capabilities of satellites and their Earth-imaging instruments have developed enormously, to the point where their use is integrated fully into many areas of life, from news reports to weather forecasting, and from scientific studies and environmental assessments to ship routing and oil and gas exploration.

It is in the monitoring of the dynamics and long-term changes of our planet that some of the most fascinating insights are now coming to light and, some 60 years after the first grainy photographs of the Earth from space, we take a look in this book at how satellites are starting to reveal significant changes occurring on and around our planet. Earth-orbiting satellites have become an essential tool for monitoring the Earth and its changing environment, from natural hazards, such as hurricanes and tropical cyclones, tornadoes, floods, tsunamis, fires, dust storms, and volcanic eruptions, to long-term changes such as the retreat of glaciers and Arctic sea ice and the reduction of tropical rain forests. Satellites, with their sophisticated instrumentation, also provide evidence of, and insight into, more subtle changes, for example in the Earth's protective ozone layer, urban and rural air quality, cloud cover and properties, land surface characteristics arising from land cover and land use change, sea level variation, land and sea surface temperature, ocean biology, atmospheric greenhouse gases and their concentration, rainfall, sea surface elevation to within 2–3 centimeters accuracy, and lightning. Some of these phenomena have been monitored from space for over 25 years, with ever-increasing sophistication, whereas the monitoring of others has only become possible in the last 5–10 years.

With the wide variety of satellites encircling the Earth, provided by many countries and government agencies, and their various orbits and instrumentation, satellites provide an

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The classic photograph of the Earth taken on December 7, 1972 by the Apollo 17 crew while traveling toward the moon, often referred to as 'the blue marble.' This photograph extends from the Mediterranean Sea to Antarctica and was the first time the Apollo trajectory made it possible to photograph the south polar ice cap. Almost the entire coastline of Africa is visible, with the Arabian Peninsula in view at the northeastern edge of Africa. (Image courtesy the Image Science & Analysis Laboratory, NASA Johnson Space Center, photograph number AS17-148-22727.)

invaluable means of monitoring our planet with a consistent measurement capability across national and other political boundaries. They play an essential role in alerting us to potentially detrimental or even catastrophic changes taking place on our planet that require actions from our politicians and other policymakers. They also provide important information for verifying compliance with international treaties and other agreements. Furthermore, satellite observations regularly reveal features of the planet that take scientists by surprise and remind us that we remain a long way from fully understanding the behavior of the complex web of physical, chemical, and biological processes that take place on our home planet.

This book attempts to present, in a readily understandable manner, a compilation of phenomena and changes observed through satellites, thereby providing both an indication of the impressive capabilities of satellites orbiting the Earth today and an indication of how our planet is changing. The core of the book is divided into the following five main sections: The Dynamic Atmosphere, The Vital Land, The Restless Ocean, The Frozen Caps, and Evidence of Our Tenure. These sections contain, in turn, a collection of articles contributed by prominent scientists worldwide, well illustrated with satellite images and data products, selected photographs, time series of changes in the environment (where appropriate), and historical photographs or drawings relevant to the subject at hand. The five main sections are followed by four appendices that provide, in turn, a description of

Satellite image of the same scene as the Apollo 17 photograph to the left. Satellites of today enable digital images of the entire globe to be produced every day. This image was created from digital data acquired on December 7, 2006, thus having the same solar illumination and seasonal meteorology as the Apollo 17 photograph, but with clouds and haze that occurred in 2006. (Data from the MODIS instruments on the Terra and Aqua satellites.)

"Satellites and Satellite Orbits," including how the "magic" of remote sensing and global coverage is achieved, a Glossary, a List of Acronyms, and a List of Contributors. In total, the book's illustrations employ data from 48 satellites and many more sensors, contributed by agencies and other organizations in the United States (U.S.), Japan, and Europe. The U.S. organizations include the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the U.S. military, and several commercial companies.

The book covers many aspects of environmental remote sensing from space and chronicles the state of our planet circa 2007. We hope that it will prove useful to scientists, policymakers, students of the environment, and anyone who shares a concern and interest in the Earth and the changes occurring on its surface and in its atmosphere.

Michael D. King
Claire L. Parkinson
Kim C. Partington
Robin G. Williams

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Sally Bensusen joined the team as production manager and designer during the second phase of the book. She was responsible for layout and design and for making sure that the book made it to publication on time. Extensive design and layout assistance from Debbi McLean was essential in making this possible.

The images and maps in this book are the product of an expert team of visualizers. The majority of these were created by Jesse Allen, Marit Jentoft-Nilsen, Reto Stöckli, Rob Simmon, and Mark Malanoski, unless otherwise noted. Debbi McLean and Sally Bensusen created several of the illustrations.

This team, from production manager to visualizer, was not only technically skilled but also a delight to work with and was a major reason for the high quality of the figures and the overall appearance of the book.

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