The Lifecycle of Ocean Waves

from *The Book of Waves: Form and Beauty on the Ocean*, by Drew Kampion, used with permission.

Under heaven nothing is more soft and yielding than water.
Yet for attacking the solid and strong, nothing is better;
It has no equal.

- Lao Tsu

We are surrounded and influenced everywhere by waves. From the radiations of light and color, to the sounds that vibrate through our atmosphere, to the cycles of the tides, and of night and day, and of the movements of our lives — it seems that everything comes in waves, or as cycles moving within waves.

Clearly, wave action is the fundamental way in which energy is transported and transmitted in this world. Waves are an expression of the universal rhythm that orchestrates and propels all creation and the development of life on earth. Perhaps this is why the contemplation and study of ocean waves is so attractive, so compelling.

Ocean waves are among the earth's most complicated natural phenomena, yet when we picture waves in the abstract, our minds might conjure an image of the perfect concentric ripples that echo the point of entry of a pebble into smooth pond waters. Those waves—the ideal waves of our conceptual imagination—are elongated sinusoidal oscillations [Fig. 1], and although they do exist in relatively pure form in controlled conditions, they are not likely to be found in the more complex ocean environment [Fig 2]. This is why waves are usually studied in laboratory tanks, where a single train of waves can be generated and where the mechanics of wave motion can be isolated and simplified.

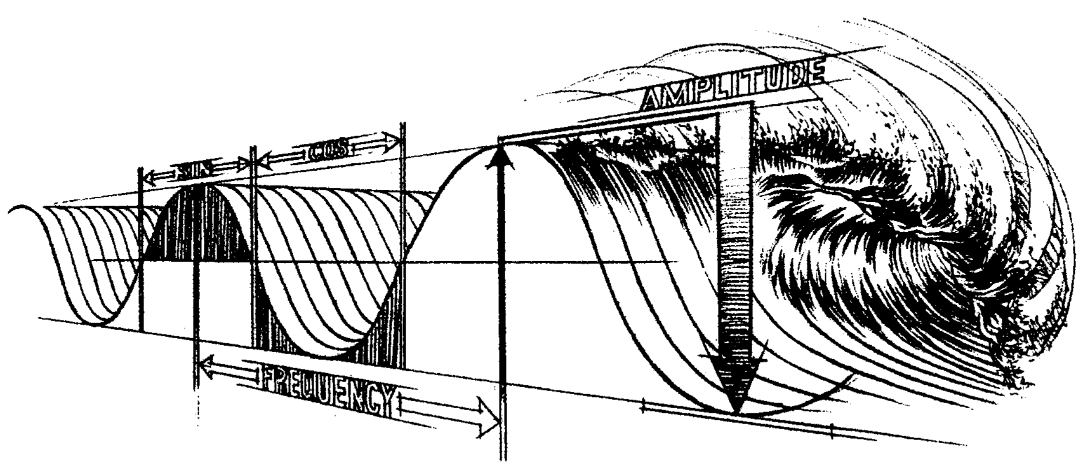


Figure 1 - An ideal wave: This familiar sinusoidal pattern is echoes throughout nature, although this simplified model exists only in theory or in the laboratory.

Ocean waves and laboratory waves share the same basic features: a crest (the highest point of the wave), a trough (the lowest point), a height (the vertical distance from the trough to the crest), a wave length (the horizontal distance between two wave crests, and a period (the time it takes for a wave crest to travel one wave length) [Fig 3].

Standing on a pier or jetty, or sitting astride a surfboard, the swift approach of an ocean wave gives the impression of a wall of water moving in your direction. In actuality, although the wave is moving toward you, the water is not. If the water were moving with the wave, the ocean and everything on it would be racing into the shore with catastrophic results. Instead, the wave moves through the water, leaving the water about where it was.

Spread a blanket on the floor. Kneel at one end and take the edge of the blanket in your hands, then slowly snap waves down its length. The blanket doesn't move, the waves ripple through it. The energy crosses the blanket in an oscillating wave pattern, diminishing (or decaying) as it moves toward the opposite end.

An ocean wave passing through deep water causes a particle on the surface to move in a roughly circular orbit, drawing the particle first toward the advancing wave, then up into the wave, then forward with it, then—as the wave leaves the particle behind—back to its starting point [Fig. 4].

Because the speed is greater at the top of the orbit than at the bottom, the particle is not returned exactly to its original position after the passing of a wave, but has moved slightly in the direction of the wave motion.

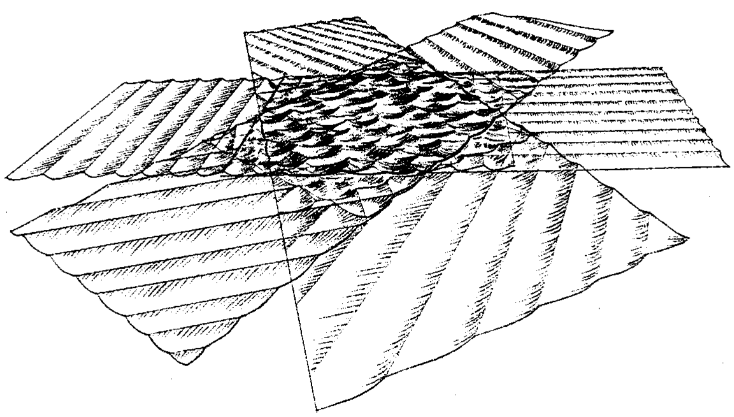


Figure 2 - The surface of the sea: The interaction of many simple sine wave patterns creates a sea.

The radius of this circular orbit decreases with depth. In shallower water the orbits become increasingly elliptical until, in very shallow water—at a beach—the vertical motion disappears almost completely.

Its final destruction in shallow water culminates the three phases in the life of a wave. From birth to maturity to death, a wave is subject to the same laws as any other "living" thing, and—like other living things—each wave assumes for a time a miraculous individuality that, in the end, is reabsorbed into the great ocean of life.

The Origins of Waves

Undulating ocean surface waves are primarily generated by three natural causes: wind, seismic disturbances and the gravitational pull of the moon and the sun. Oceanographers call all three "gravity" waves, since once they have been generated gravity is the force that drives them in an attempt to restore the ocean surface to a flat plain.

There are other waves, too, in the ocean. At the boundaries of cold and warm currents, submarine streams of different density undulate past each other in slow-moving "internal" waves. The evidence of internal waves can sometimes be seen in calm conditions since their currents affect the reflectivity of the ocean's surface, producing alternating areas of glassy slickness and ruffled texture.

Although significant seismic-wave disturbances (tsunamis) are still popularly known as "tidal waves," the term more accurately describes the daily cycles of high and low tides. The greatest ocean waves of all—with a period of 12 hours and 25 minutes and a wave length of half the circumference of the earth — these colossal oceanic bulges travel around the world at up to 700 or 800 miles per hour. The tides are created when the massive gravitational pulls of the moon and the sun actually lift the oceans while the earth rotates by underneath. The crests of these waves are the high tides, the troughs low tides.

One unusual tidal wave phenomenon is a "bore," the sudden surge with which the incoming tide arrives in some parts of the world. Bores occur in streams or rivers (like Britain's Severn River) or bays (like the Bay of Fundy in Newfoundland) with funnel-shaped shores and shoaling bottoms where tidal ranges are high. If the incoming tide is retarded by friction in the shallowing water until it moves more slowly than the outgoing current, the tidal surge can build up into a turbulent crest. The resulting bore wave may drive up a narrowing passage with great energy and force.

Augmented by a west wind and spring tides, the bore on France's river Seine (called the mascaret) has been known to arrive at Paris as a great wall of water moving at high speed. One report claims a 24-foot-high wall of water traveling 15 miles per hour. This is the tidal bore that drowned Victor Hugo's newly married daughter and her husband, who were caught while sailing on the river in front of Hugo's home.

The other "tidal waves"—seismic sea waves, or tsunamis—are "impulsively generated" waves, most commonly by earthquakes, volcanic eruptions or massive underwater land- slides. The waves created by such abrupt forces can be very long and low with periods between crests of up to ten minutes and wave lengths as long as 150 miles. Yet the waves are usually only a foot or two high in deep ocean water, and the slope of a tsunami wave face can be so gradual that ships at sea are unlikely to even notice its passage.

Tsunami waves travel extremely fast—about 500 miles per hour in the mid-Pacific—and the energy they transmit can be massive indeed. But as stealthy and swift as they are through the ocean, these seismic waves assume a completely different character when they encounter a shoaling bottom.

The most notable example of the destructive power of an explosively-generated tsunami is the volcanic eruption in 1883 of the northern portion of Krakatoa, an island located in the Sunda Strait between Java and Sumatra. Some five cubic miles of lava, pumice and ash were blown out in a massive and sudden eruption, leaving a 900-foot-deep crater where a 700-foot-high land mass had been. The blast was heard in Madagascar 3,000 miles away. Although immense physical destruction was caused by the explosion, the real catastrophe was caused by the resulting tsunami, which ranged from 60 to 120 feet high. Some 300 towns and villages on the shores of nearby islands were destroyed; over 36,000 people were killed. The gunboat Berouw, anchored off Sumatra, was carried nearly two miles inland, and gauges in France and Britain recorded a rise in the sea level.

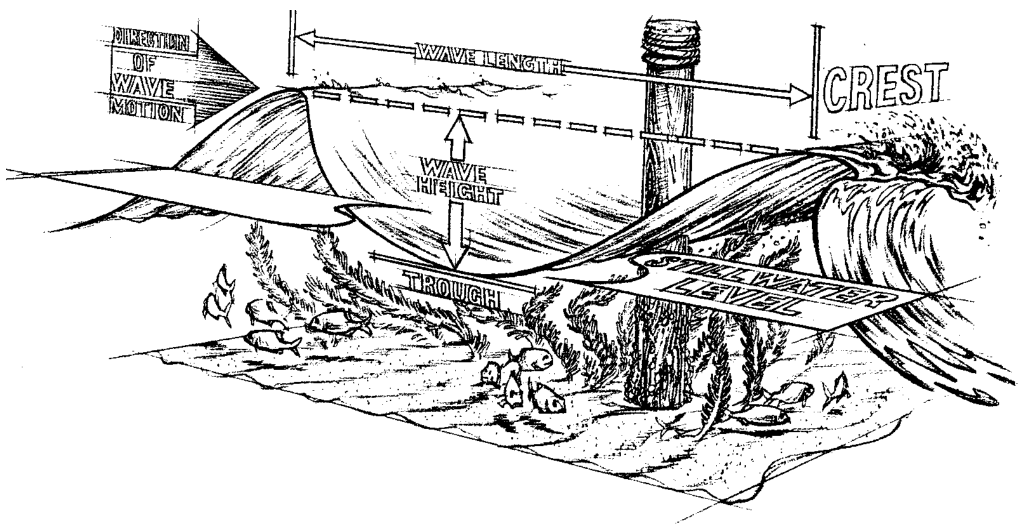


Figure 3 — The anatomy of an ocean wave: Whatever the medium they move through, all waves share the same basic physical characteristics.

In 1960, a violent earthquake in Chile (magnitude 8.5) caused a great subsidence of the undersea fault that parallels the coast there, generating a catastrophic tsunami that affected nearly all of the Pacific basin. Australia, New Zealand, the Philippines, Okinawa and California experienced significant coastal flooding or damage. Fifteen-foot waves were hurled against Japan, some 9,000 miles from Chile, and the city of Hilo on the island of Hawaii (which had been devastated by a tremendous tsunami as recently as April 1, 1946) was virtually washed away by a series of massive seismic sea waves that began to hit less than three hours after the quake. Hilo has since been rebuilt on higher ground, dedicating the former site—now called "Tsunami Park"—for recreational use.

The Lifecycle of Ocean Waves

Genesis: Winds blowing across the water's surface raise ripples, then chop. If wind strength, duration and fetch are sufficient, a "sea" develops.

Fetch: The area over which the wind blows to raise up waves; most (but not all) of the atmospheric energy transferred to the water by frictional forces is concentrated at or near the surface.

Maturity: Once the seas leave the fetch area, the locally confused patterns organize themselves into lines of swell that radiate downwind from the area of genesis.

Particle movement: Waves passing through water cause particles near the surface to rotate in circular orbits. The diameters of these orbits diminish as depth increases.

Landfall: As swells begin to be affected by a shoaling bottom, their character begins to change; they begin to slow, the wave length shortens and, when the bottom is shallow enough, they break.

Breaking waves: When a shoaling bottom causes waves to become critically steep, they peak up and break; the shallow water no longer allows the complete internal rotation of the water particles.

Final moments: The momentum of the plunging breakers pushes water toward the shore, expending the last of the wave energy.

Although tsunamis are certainly spectacular if you're in the right place at the wrong time, they are relatively rare. And the tides (although they're always with us) are relatively slow to shift and difficult to observe as waves. On a day-to-day basis, wind-generated waves are the most visible to us. Ripples, chop, rough seas or plunging breakers, these are what we think of when we hear the word "waves," and their source is the movement of air across water.

Wind is the result of solar energy acting on the earth's atmosphere. The great patterns of circulation — the global winds—give rise to the various dynamics of high and low pressure, of calm and storm. Huge North Pacific or North Atlantic or Antarctic systems generate enormous waves. More localized thermal differentials excite the ocean's surface with racing patterns of energy. Smooth coastal waters oscillate gently with the decaying echoes of storms half a world away.

How does the wind make waves? The primary mechanism of wave genesis is the friction between the atmosphere and the surface of the ocean. A puff of less than two knots will raise miniscule wrinkles (called capillary waves) on the surface almost immediately. As the puff dies, these waves quickly disappear due to the resistance of the water's surface tension, which tends to restore the smooth surface. However, when a breeze of two knots or more develops and is sustained for a time, "gravity waves" begin to form as the wind drags across the water. Ripples at first, these waves continue to grow as the wind continues to blow. In fact, it becomes increasingly easy for the wind to transfer its energy to the water since it can now push directly against the backs of the ripples. The more jagged and uneven the surface, the more there is for the wind to push against. Ripples develop into chop (periods of one to four seconds) until, when the wave length of the chop in a given area stretches beyond five seconds or so, it is called "sea" [Fig. 5].

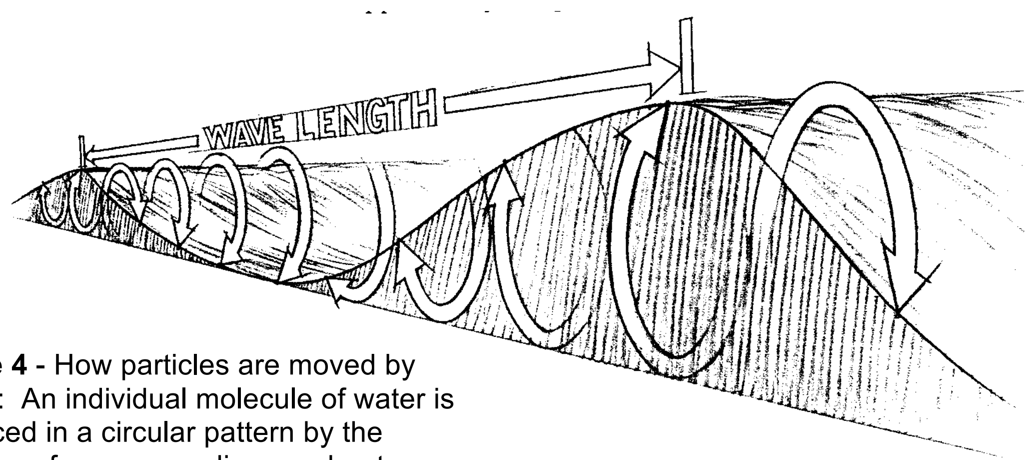


Figure 4 - How particles are moved by waves: An individual molecule of water is displaced in a circular pattern by the passage of a wave, ending up about where it started.

As the waves continue to grow, the surface resisting the wind becomes steeper and higher, making the wind's work of transferring energy to the water still more efficient. But there is a limit to how large these waves can grow. Steepness is a ratio of the height of a w ave to its length which, it turns out, can't exceed approximately 1:7. This means that a seven-foot-long wave can't have a crest taller than a foot. In fact, the maximum stable profile angle of a wave crest is about 120 degrees. Beyond this point the wave will begin to break into whitecaps.

How large wind waves become is a function of three factors: the strength of the wind (force), the length of time it blows (duration), and the amount of open water over which it blows (the fetch). If the wind is strong enough and blows long enough, waves of considerable size can develop. However, there is a limit to the amount of energy that can be transferred from the atmosphere to the ocean for a given wind strength, and when that limit has been reached, the seas are said to be fully developed or fully aroused. For instance, an accepted mathematical model suggests that if the wind blows at a velocity of 30 knots over a fetch of some 280 nautical miles for at least 23 hours, a fully-arisen sea will be the result, with average waves of 13 feet and the highest waves approaching 30 feet.

Waves generated by the kinds of storms that actually happen seldom need fetches of more than 600 to 700 nautical miles to reach full height. According to oceanographer Blair Kinsman, 900 nautical miles is probably room enough to develop the largest storm waves that have ever been reliably estimated. Occasional open-ocean waves of 40 to 50 feet do occur, he says, but they are not common, and even in the worst storms the run is much smaller.

Kinsman developed an estimate for the "whole ocean" based on a frequency study for wave heights (over 40 thousand extracts) developed by Bigelow and Edmondson in 1947, which seems reasonable:

Wave height	0-3'	3'-4'	4'-7'	7'-12'	12'-20'	over 20
Frequency of occurrence	20%	25%	20%	15%	10%	10%

This would indicate that 45 percent of all ocean waves are less than 4 feet high, and 80 percent are less than 12 feet high. Just 10 percent are over 20 feet. The largest wave ever reliably reported had an estimated height of 112 feet. It was encountered on 7 February 1933, during a long stretch of stormy weather, by the *U.S.S. Ramapo* in the North Pacific.

In all their immense variety, waves give texture, motion and character to the world's seas. Having been aroused by the wind and gathered into radiating bands of energy, waves can travel great distances, carrying nearly intact their messages from the sun.

Maturity

Once a pattern of waves radiates free of the winds that created it, the confused chaos of apparently random sea organizes itself into even lines of "swell." The original wind waves decay, and their energy is consolidated into waves of greater length and increasing speed.

As waves increase in height, wave length also increases. In fact, even after wave height has stabilized, the lengths may continue to increase. As a rule, a ten-second period is the dividing line between sea and swell, although there is naturally some overlap. Sea is shorter in wave length, steeper, more jagged and more confused than swell. Like those ripples in the puddle, the crests of open-ocean swell are more rounded and regular, having absorbed the energies of many decaying wave oscillations into relatively unified and orderly packages capable of traveling great distances.

Swell moves across the open ocean in trains of waves of similar period that radiate downwind from a wind source. Responding to the downward force of gravity, the lines of some of their energy sideways, lengthening the wave front as they expand away from their source. The process is called maturing.

Most open-ocean waves are deep-water waves. This means that the depth of the water the waves are traveling in is greater than half the distance between crests (the wave length). Waves moving in water shallower than half their wave length are known as shallow-water waves. The wave lengths of some seismic waves (generated by earthquakes, for instance) are so long that for them even the deepest ocean is shallow. The dynamics of shallow-water} waves are affected by the ocean's bottom, whereas deep-water waves can be studied independent of this influence.

In deep water, the wave length (L) in feet can theoretically be related to the period (P) in seconds by the formula: $L = 5.12\ P^2$, Actual wave length has been found to be somewhat less than this for swell and about two-thirds the value for sea. When waves leave the generating area and continue to move on as free waves, the wave length and period continue to increase while the height decreases. Speed also increases as period increases and is virtually independent of wave height and steepness [Fig. 6].

This theoretical description of the relationship between wave speed, wave length and wave period describes deep-water waves only. The relationship between these characteristics in shallow or shoaling water can be quite different.

Storm waves in the North Atlantic average about 500 feet long; in the North Pacific they may be a bit longer. In the Antarctic waves spawned in the Roaring Forties can have wave lengths greater than 1,000 feet. Lines of swell can have much greater wave length than waves in sea. Kinsman reports swell with lengths of 1,320 feet in the Bay of Biscay, 2,549 feet on the south coast of England, and, the longest on record, 2,719 feet in the equatorial Atlantic. Where fetches are more restricted, wave lengths are naturally smaller. The longest wave length recorded in the Mediterranean Sea, for example, was 328 feet.

Under favorable conditions, swells move indefinitely in the direction of the originating wind. However, if a swell encounters new winds, the shape and heading of the waves may be altered. A strong enough opposing wind can dissipate the waves entirely, while wind or swell moving in the same direction can have an augmenting effect.

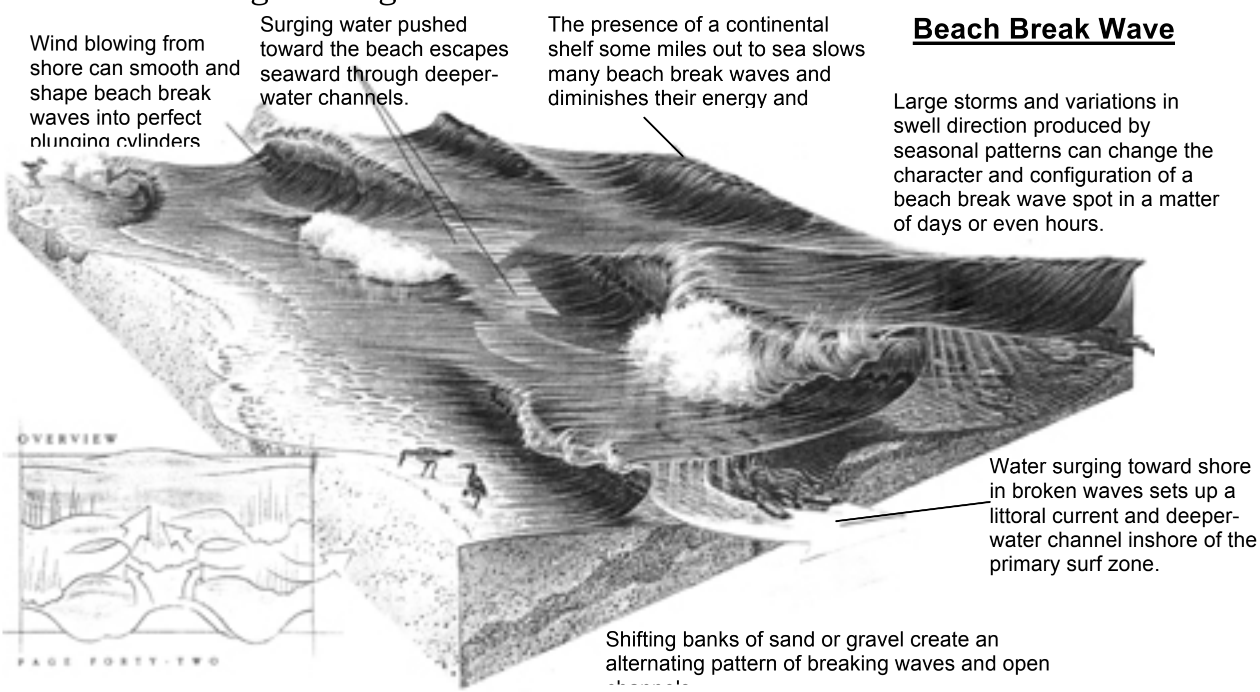
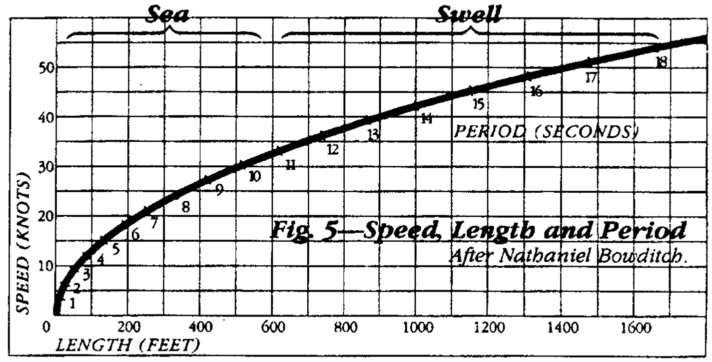


Fig. 5 - Speed, Length and Period



Because the length, period and speed of waves all increase as the swell moves away from the generating area, it is possible to have a fairly good idea how far away from a point of observation waves were spawned. However, when making the necessary calculations, it is important to know that the time needed for a wave system to travel a given distance is double what it would take an individual wave to go as far. This is because the front wave of an advancing swell gradually disappears, transferring its energy to the following waves. The process is followed by each leading wave in succession at such a rate that the wave train advances at a speed which is just half that of individual waves. The speed at which the wave system advances is called the group velocity [Fig. 7].

Still, for all their apparent symmetry, both theoretical and actual, wind waves are irregular phenomena. Even in trains of open-ocean swell, successive waves can and do differ markedly in height. For instance, in the mathematical model mentioned above, the average wave height created by winds blowing 30 knots for 23 hours over a fetch of 280 nautical miles will be 13.5 feet, however this same model tells us that the "significant wave height" generated will be 21.6 feet. "Significant wave height" is defined as the mean height of the highest one-third of the well-defined waves observed at a given point on the ocean's surface. Usually, as in this example, the significant wave height is about one-and-a-half times the average wave height. However, the average height of the top ten percent of these significant waves will be 27.6 feet. This means that, within a particular wave train, about one wave in a thousand (perhaps one every four hours) will be twice the average size!

One explanation for observed differences in wave height is the interference of one wave train with another. When the peak of one wave synchronizes with the trough of another wave, there is a distinct dampening effect. Conversely, the synchronicity of crests causes wave energies to combine so that the resulting wave can be much larger than either of the two waves that coincided. The swell pattern resulting from the confluence of two or more open-ocean wave trains results in a cycle of larger and smaller waves. Closer to shore this pattern is termed surf beat" and the larger groups of waves thus created are called "sets."

The most spectacular example of the synchronicity of wave crests (often in combination with other factors) is the phenomenon of "rogue" waves. Rogue waves are statistical probabilities that on rare occasions emerge out of the land of the theoretical to haunt some of the most trafficked sea lanes of the world.

Rogue waves are solitary giants formed out of the convergence of extreme natural forces; they rise to unusual height and mass. Inevitably ships at sea come into contact with some of these wind-generated, gravity-propelled monsters. There are a number of remarkable stories of such encounters in nautical records, but how many other encounters left no tongue alive to tell is food for speculation.

In his authoritative book, , Willard Bascom cites a number of meetings with rogue waves. A sampler:

"In February 1883, the 320-foot steamship *Glamorgan* out of Liverpool was beating through heavy Atlantic seas at night when it was 'totally submerged by one tremendous wave.' The wave swept away the foremast, all the deckhouses and the bridge (with the captain and seven crew in it). It stove in all the hatches and the engine room was flooded. The ship sank the next morning, and the 44 who escaped in lifeboats told the tale of the one great wave.

"On another Atlantic crossing, the 1,000' *Queen Mary* was serving as a World War II troopship in 1942 when, with 15,000 American soldiers aboard, she encountered a winter gale 700 miles off the coast of Scotland. The seas were quite large but also quite manageable for the huge ship. Suddenly 'one freak mountainous wave' slammed broadside into the *Mary*, and she 'listed until her upper decks were awash, and those who had sailed in her since she first took to sea were convinced she would never right herself.' After hanging on the brink of capsizing for a few eternal seconds, the great ship finally righted herself again.

"More recently off Greenland, the Mary's sister ship, *Queen Elizabeth*, took a wave over the bow that was so large it flooded the bridge 90' above the waterline.

"In 1966, 800 miles off New York, the Italian liner *Michelangelo* plunged into a gigantic trough that was followed by a huge solitary wave that crumpled the flare of the ship's bow and broke out the inch-thick glass in the bridge windows some 80 feet above the waterline, injuring hundreds of passengers (and killing three).

"In July 1976, the tanker *Cretan Star*, loaded with 29,000 tons of light crude oil, was struck by a huge wave and sunk in the Indian Ocean not far from Bombay. An inquiry reported that the southwest monsoon reaches its greatest strength in July off Bombay and periodically piles up 'episodic waves of vast proportions.'"

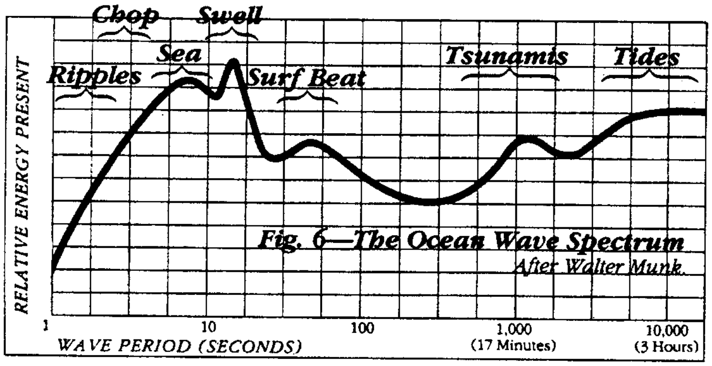


Fig. 6 - The Ocean Wave Spectrum

Lighter than cork I danced on waves in the salt air -
Waves, those eternal victim-tossers, so to say . . .
- Arthur Rimbaud

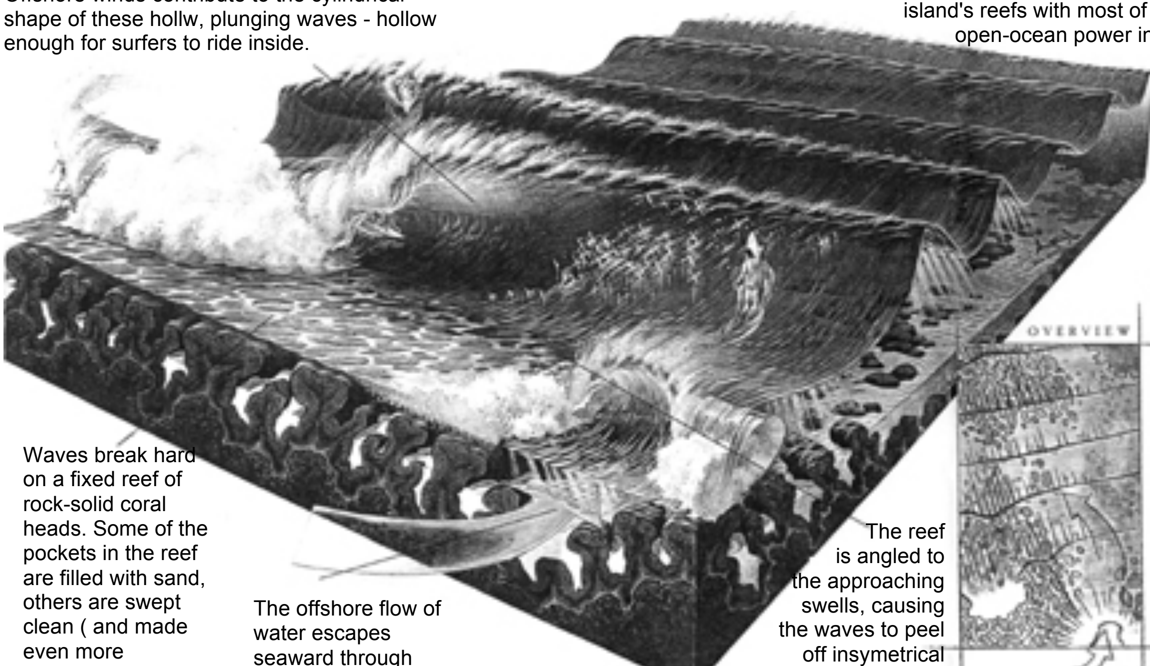
In exploring the probability of the occurrence of single large waves, Dr. Lawrence Draper of the National Institute of Oceanography in England used the "Statistics of a Stationary Random Process" to show that one wave in 23 is over twice the height of the average wave, one in 1,175 is over three times the average height, and one in 300,000 is more than four times the average wave height. Put these statistics to work along a stretch of water known as South Africa's "Wild Coast" and you might expect calamity a plenty, and, indeed, that's what you get.

One characteristic of waves is that a following current increases wave lengths and decreases wave heights, while an opposing current has the opposite effect, decreasing the length and increasing the height, thus also steepening the face of the wave. A strong opposing current may well cause the waves to break, even in deep water. Off that southeastern coast of Africa, where the continental shelf abruptly drops away, the Agulhas Current sweeps in hard against this immovable barrier, concentrating the massive southwest flow of water into a relatively narrow stream. The current moves at four to six knots, providing a fast, economical shipping lane for ships moving south. However, when storms to the southwest pump waves around the Cape of Good Hope and up into the channel, the wave length of the swell can be shortened dramatically and the wave steepness increased to precipitous angles. Under certain conditions the unusually swift current here actually doubles the height of the waves pushing upstream. The giants that are created are called "Cape Rollers," and when the statistically predictable rogue wave moves into the current, the result can be catastrophic.

To make matters even worse, waves are refracted, or bent, toward the higher-velocity current, concentrating more wave energy over the strongest current, and possibly even trapping waves there. As Bascom points out, when a ship moving in the current at 18 knots (nine meters per second), assisted by the current of four meters per second, encounters a wave moving at ten meters per second, the velocity of the collision is the sum of these, or 23 meters per second. Since the force of impact is proportional to the square of the velocity, the current nearly doubles that force. "If," says Bascom, "the wave is twice as high as an ordinary storm wave, a ship is likely to be in trouble."

Untold vessels have been lost off the Wild Coast over the centuries. One account from Bascom of a ship that survived conveys the essence of the situation: In December 1969, the middle of the southern summer, the 102,000-ton Swedish tanker *Artemis* ran through a storm on its way down the Wild Coast. Captain L.J. Tarp reported that one wave came over the ship's bow and continued rolling down the deck at such height that it hit and flooded the wheelhouse five decks up.

Reef Break Wave Banzai Pipeline, Hawaii



The complex network of wave relationships — combining, dampening, crossing, overtaking—is a continual dynamic of the ocean surface. It is part of what has made the ocean an enduring frontier and a mystery. Always, far beyond the horizon, new storms pinwheel into being, urging up new waves, new swells, out from the otherwise vast, implacable face of the world's oceans.

Most of us will be completely unaware of their distant arising, their silent passage across the empty miles. Most of us will only become aware of them as they emerge out of the distance, touch bottom, rise and finally burst into white glory. Only then, as breaking waves, will their full potential be revealed to us.

Breaking Waves

When long, fast, smooth open-ocean swells move into shallower water, their character begins to undergo a significant transformation. When the depth of the ocean becomes less than half the length between the crests of two successive waves, the speed of a wave is no longer governed by its length, but by the depth of the water; the speed of a wave is now proportional to the square root of the depth of the water it is moving through. It is at this point that ocean swell changes to ground swell. This is where the study of deep-water waves ends and the study of shallow-water waves begins. This is the transition zone between swell and breaking waves.

When swell moves into water less than half its wave length deep, the wave begins to "feel" and be affected by the bottom. The contours of the basin within which the wave travels begin to modify the wave's behavior through a process called "refraction." Refraction here refers to the result of the slowing of waves as they move into shallowing water. This results in a bending of the wave fronts to align themselves to the contours of the shoaling bottom.

Because the speed of a wave in shallow water is a function of the depth, swell refracts as it responds to submarine contours. Since waves slow as the bottom shoals, swells moving laterally toward a sloping coast are bent toward the shore. Similarly, wave energy converges and focuses over shallow ridges [Fig. 8a, 8b], while it diverges and disperses over deeper submarine trenches.

Blair Kinsman reminds us that, "the only feature of a wave as we see it from the beach that has been left unaltered from its deep-water state is the period. You can't tell what direction the waves are running offshore from the angle at which they approach the beach." In fact, as waves move into increasingly shoal water, they begin to slow, the wave length shortens, and the low, sloping mounds begin to rise up out of themselves.

Certainly some amount of drag is produced by the interaction of wave energy with a shoaling bottom; some energy is certain to be released in this way. However, the popular belief that friction slows waves down in shallow water while the crests continue to move more rapidly, and so trip over themselves, seems less popular today than in the past.

Surfer-author-musician John Kelly, Jr. of Hawaii ascribes the change in speed—and in wave height—to deflection, to the idea that ocean wave energy obeys the same laws that control the deflection or reflection of light waves, and that the angle of reflection equals the angle of incidence.

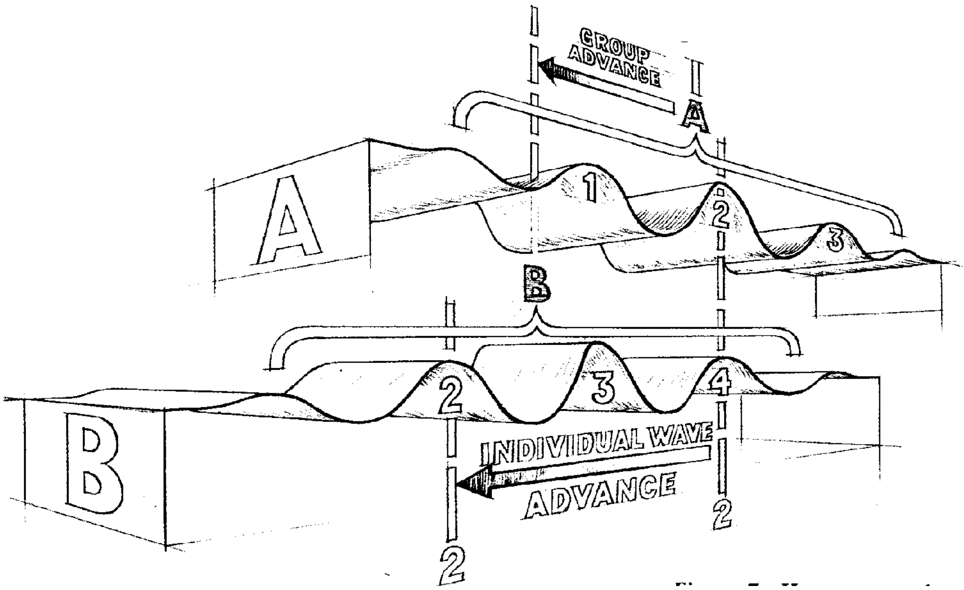


Figure 7 - How wave trains travel: Waves die out over distance and are replaced by following waves at such a rate that the group advances at just half the speed of the individual waves.

In *Surf and Sea* Kelly writes: "Since the ocean bottom is a fixed boundary, the deflected wave energy is focused upward to a degree that depends on the angle of the rising bottom and appears at the other, flexible boundary of the medium in the form of the rising crest—in effect, an inversion of the wave's energy. As more and more of the wave energy is deflected upward by the confining space of shoaling water, the crest mounts proportionately higher. Here we find an explanation for the slowing of the wave: It is due to the fact that the wave energy, bouncing, as it were, off the bottom and being deflected to the crest, travels a greater distance. The detour consumes time, thus slowing the advance of the wave form even though the energy itself continues to travel in its watery medium at a constant speed."

Although this description might impress some oceanographers as a mere fight of fancy, it does portray a clear (if untrue) image of the dynamics that lead to the breaking of the ocean wave.

As was said earlier, waves in deep water will begin to break when their height is greater than a seventh of their wave length. The maximum stable profile angle of the crest of a wave is, therefore, about 120 degrees. Steeper than this, the wave character begins its final dramatic transformation. In very shallow water! when waves break as they approach land, they will reach this critical angle in a water depth of about 1.3 times the wave height. In other words, a three-foot-high wave will break in approximately four feet of water. It is as waves approach this "limit of their containment" that the most dramatic moments of their lives are played out in the surf zone.

Whatever the lawful causes—friction or deflection—as waves encounter the rapidly shoaling water associated with most beaches, they are said to peak up. That is, their height increases rapidly. At the same time the shallow water causes the wave length to decrease (because as a wave is slowing, the waves behind are catching up); the result is a suddenly steepened wave Therefore, in a very short distance, the crest angle decreases below the critical 120 degrees and the wave becomes unstable. The crest, moving more rapidly than the water below, falls forward and the wave form collapses into turbulent confusion, which uses up most of the wave's energy.

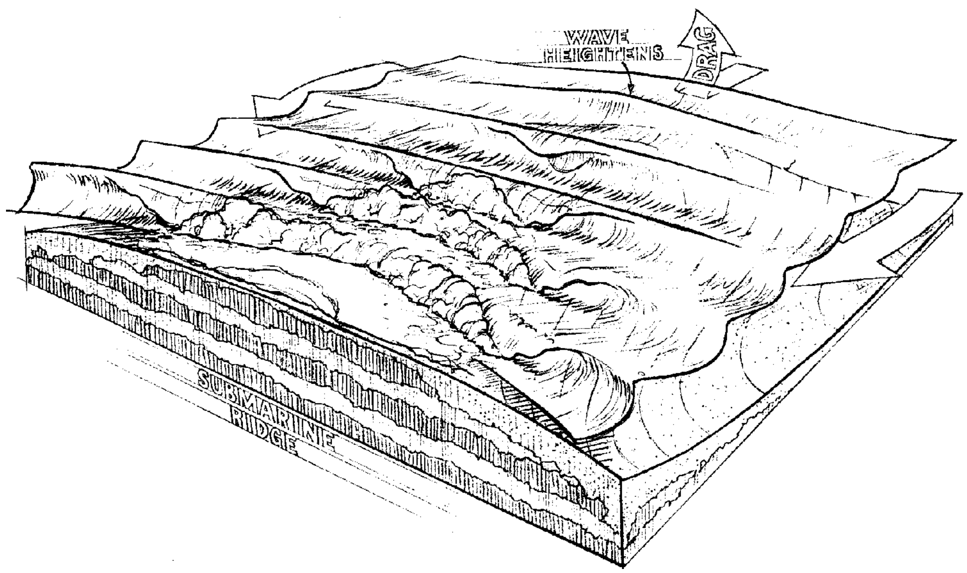


Figure 8 - Refraction of waves over a submarine ridge: The bending of waves as they slow in shallowing water focuses their energy over the shoal area.

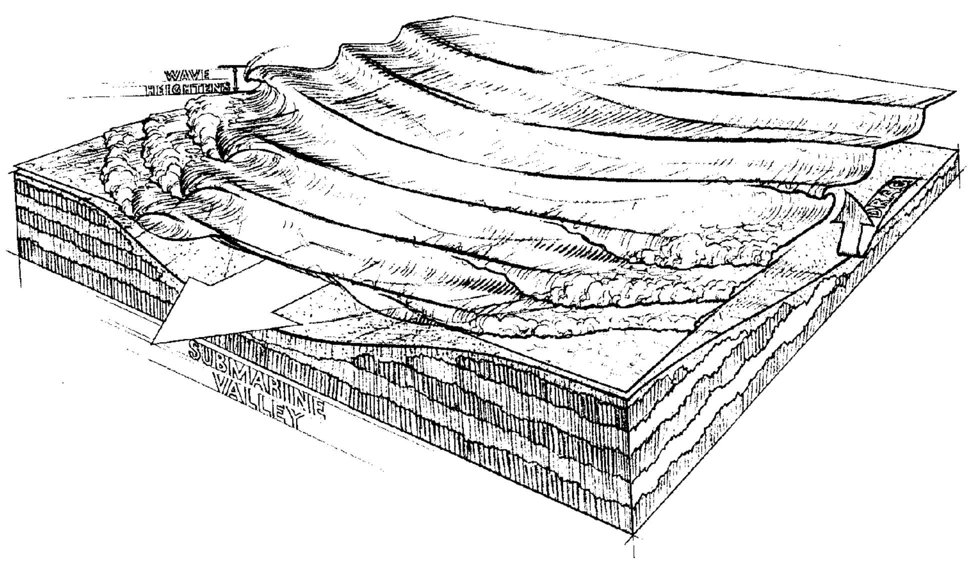


Figure 9 - Refraction of waves over a submarine canyon: The bending of waves as they slow in shallowing water disperses their energy away from the deep water and toward the shoals.

Perhaps the leading popular authority on ocean wave phenomena is Willard Bascom. Some thoughts from his Waves and Beaches on the dynamics of breaking waves:

> "As the swell moves into very shallow water, it is traveling at a speed of 15 to 20 miles an hour, and the changes in its character over the final few dozen yards to shore come very rapidly.
>
> "In the approach to shore, the drag of the bottom causes the phenomenon of refraction...and one of its effects is to shorten the wave length. As length decreases, wave steepness increases, tending to make the waves less stable. Moreover, as a wave crest moves into water whose depth is about twice the wave height, another effect is observed which further increases wave steepness. The crest 'peaks up.' That is, the rounded crest that is identified with swell is transformed into a higher, more pointed mass of water with steeper flanks. As the depth of water continues to decrease, the circular orbits (the movement of a particle of water within the wave) are squeezed into a tilted ellipse and the orbital velocity at the crest increases with the increasing wave height.
>
> "This sequence of changes in wave length and steepness is the prelude to breaking. Finally, at a depth of water roughly equal to 1.3 times the wave height, the wave becomes unstable. This happens when not enough water is available in the shallow water ahead to fill in the crest and complete a symmetrical wave form. The top of the onrushing crest becomes unsupported and it collapses, falling in uncompleted orbits. The wave has broken; the result is surf."

The energy released in a breaking wave is tremendous. All of that stored wind power—transported silently for so many miles—at last bursts out of its liquid confines with a thunderous roar of liberation. The total energy of a wave ten feet high and 500 feet long can be as high as 400,000 pounds per linear foot of its crest. The impact pressure of such a breaking wave can vary from 250 to as much as 1,150 pounds per square foot. Larger waves have been recorded to exert a force of more than three tons - 6,OOO pounds of pressure—per square foot in the surf zone!

Echoing the combined energies of the many forces out to sea, ocean waves approach the shore in irregular patterns—cycles of smaller waves and larger waves created by the reinforcing or canceling interaction of different wave trains. Groups of bigger waves are called sets; long intervals between sets are called lulls. The pattern of sets and lulls — the surf beat — is the pronounced rhythm of the ocean's language, the cadence of its voice.

Waves and Surf

In general, there are three forms of breaking waves: surging breakers, spilling breakers and plunging breakers [*Figs. 9a, 9b, 9c*].

Surging waves are associated with relatively deep-water approaches to steep beaches. The incoming wave peaks up, but surges onto the beach without spilling or breaking.

Spilling waves are generally produced by a very gradually sloping underwater configuration. The wave peaks up, the crest angle shrinks to less than 120 degrees, but the release of energy from the wave is relatively slow. Spilling waves typically have concave surfaces on both front and back sides.

Plunging breakers are the most dynamic, exciting manifestations of wave action on the ocean. Their rounded backs and concave, hollowing fronts result where an abrupt shoaling of the bottom creates a sudden deficiency of water ahead of the waves, which can be moving at near open-ocean velocity; water in the trough rushes seaward with great force to fill the cavity in the oncoming wave. When there is insufficient water to complete the wave form, the water in the crest, attempting to complete its orbit, is hurled ahead of its steep forward side, landing in the shallow trough. The curling mass of water (called a "tube" by surfers) surrounds a volume of air, often trapping and compressing it. When the trapped air breaks through the curtain of water that surrounds it, there is often a geyser-like burst of spray and mist. Often, too, the mist is expelled out of the open end of a well-defined tube, like smoke from the barrel of a gun. Riding ahead of such a blast of vapor is where a lot of surfers would like to be.

Surfers, animals (including porpoises and seals) and boats are able to ride waves due to the resultant of three forces—the total weight of the vehicle (i.e., surfer and surfboard), the total buoyancy of the vehicle (including planing force), and the "slope drag" created by the angle of the wave's face. When this slope drag is greater than the hydrodynamic drag (water resistance), the vehicle moves at the approximate speed of the wave crest.

One of the major skills required for a surfer is getting the surfboard moving fast enough at an angle precise enough so that the slope drag takes over the work of propelling the vehicle just as the wave rises up beneath him. Once he's up and riding, the surfer can move considerably faster than wave-crest speed by maneuvering sideways across the face of the wave. Although humans are the most common surfers today, the act of riding waves is an ancient custom for porpoises, seals, sharks, killer whales, and fish and birds of all kinds. Seals and porpoises are terrific surfers; their instinctive familiarity with the liquid medium allows them to be the most subtle and eloquent wave riders of all.

Because porpoises and seals have neutral buoyancy, they are able to tilt themselves to the correct slope angles of underwater constant-pressure surfaces (literally wave planes within wave planes) and catch the waves there, so that often they are seen in a subsurface mode, imbedded in the wave face as they surf across a transparent wall of water. However, these creatures are also able to break through the plane of the wave face and surf on the outside surface of the wave in a more conventional manner.