SECTION III

FACTORS IN THE DEVELOPMENT OF
TASMANIAN SHORE PLATFORMS
INTRODUCTION

Tasmanian shore platforms have been produced by a number of interrelated passive and active factors. Passive factors involve the attributes of the rock itself. Active factors include weathering, hydraulic action and environmental considerations such as climate, tidal regime and wave characteristics. Various aspects of shore platform development have been mentioned on previous pages in connection with specific platforms. In the following section the factors will be discussed systematically, drawing on field evidence, experimentation and the literature for background.
PART ONE

PASSIVE FACTORS
Chapter 13

BEDROCK CHARACTERISTICS

Rock characteristics are very important to the potential development of a shore platform. If the rock type is not suitable, even the most effective forces will have difficulty in establishing horizontality. Three attributes of the rock are significant: (1) Structure, (2) Texture and (3) Chemical composition. Structure here refers to jointing and bedding patterns, texture is concerned with the characteristics and arrangement of the component rock particles, and chemical composition includes the chemical make-up of both rock particles and cement.

STRUCTURE

In general, well developed high tide shore platforms do not occur in Tasmania when horizontal jointing or bedding is absent or widely spaced. Two rock types, granite and dolerite, commonly show these characteristics. Granite has widely spaced, curving joint planes and dolerite is often well jointed vertically but lacking in uniform horizontal jointing. It is probable that weathering alone is not effective enough to bevel a surface without some previous help by hydraulic quarrying to a zone of weakness in the rock. As was shown at Grant Point, granite is not very susceptible to peritidal weathering, and, for this
reason it could be argued that it is not so much the structure as the weathering properties which prevent the formation of well-developed platforms. However, dolerite weathers more rapidly in the peritidal environment and it too exhibits little horizontality, indicating that the jointing pattern may be the controlling consideration. The difference between the South Croppies Point and Don Heads platforms also suggests the importance of rock structure. South Croppies Point Basalts contain no consistent horizontal planes of weakness over much of their area and support no high tide platforms. Don Heads, on the other hand, is also composed of basalt, but the rock is well jointed both vertically and horizontally. In marked contrast to the very poorly developed South Croppies Point platform the Don Heads feature is the best developed horizontal shore platform included in this study. Further evidence for the importance of structure is the similarity of morphology between platforms cut in differing materials, but having closely spaced joint and bedding planes. Platforms in sandstones and basalts often show similar morphologies, and approximately the same relative height compared to mean higher high water.

In certain cases, the structure may even encourage a platform to develop independently of weathering. When a thick, massive and resistant bed is overlain by less resistant material, extensive platforms may result. An example occurs on the
cliffed coast seaward of the "blowhole", south of Eaglehawk Neck. A thick, poorly jointed bed of sandstone forms a platform at about twelve feet above mean higher high water at its highest point (Photo 31). The surface drops away along the coast to north and south, following a slight bowing of the formation. The beds above the resistant sandstone are thin and closely jointed - characteristics which promote effective removal.

TEXTURE

While the structure of the rock is probably of basic importance in determining the presence or absence of a high tide platform, the texture is significant in controlling the efficiency of the platform bevelling process. Bevelling, which puts the finishing touches on a surface already roughly planed by hydraulic action, is largely accomplished by salt crystallization. This process will be treated in detail in Chapter 16. In order for salt crystallization to be effective, the texture of the rock must allow salt water to enter for subsequent evaporation and crystal growth. Salt crystallization will be slow or nonexistent when rock texture is unfavorable for water entry, resulting in poorly developed horizontality.

The importance of the ability to take on water is demonstrated by the results of tests conducted on rock samples taken
Photograph 31
Supratidal Structural Platform. The platform is located three miles southeast of Eaglehawk Neck. The resistant sandstone bed is highest above sea level at the point shown in the photo and drops in elevation to north and south.

Photograph 32
High Tidal Structural Platform. The platform is located about 1000 feet north of the platform pictured in Photo 31. The high tidal structural platform is basically the top surface of the resistant sandstone bed of Photo 31. The bed occupies a lower level in Photo 32 because of gentle bowing of the formation. The increased dip brought the upper edge of the bed into the altitudinal zone where water-layer weathering is most effective. Weathering is now actively modifying a surface which was created largely by hydraulic action on differentially resistant beds.
from various coastal sites. Granite, dolerite, basalt and sandstone yielded data which indicated that the platforms which possessed greatest horizontality were carved in rocks which were most efficient at water intake (basalt and sandstone). Conversely, field evidence shows that even limited bevelling is rare in granite, the rock type least able to absorb water. A more complete discussion of the tests and conclusions drawn from them follows in the chapter on weathering, where the importance of rock texture is repeatedly apparent.

CHEMICAL COMPOSITION

The third important passive factor in shore platform development is the chemical composition of the rock. Chemical composition is significant in two ways: (1) If the rock is calcareous the platform elevation will be distinctly lower than in the case with non-calcareous rocks. (2) If the rock is non-calcareous the chemical composition determines the relative efficiency of the various chemical forces acting upon it. Revelle and Emery (1957), Kaye (1959) and others have described horizontal platforms in aeolianite, beach rock and exposed coral rock which are located at or below the level of low tide. The general consensus is that these platforms are formed by solution, either by fresh water floating on the denser sea water, biochemical reactions or solution by aerated sea water.
Unfortunately, the scarcity of limestone coasts in Tasmania has now allowed these observations to be verified in terms of the local environment.

Limestones are found on the coast of Tasmania in few places, notably Marawah in the northwest and Pt. Hibbs in the southwest. The Marawah formation is an intertidal platform which is obviously being modified by sand scour and thus can not furnish much information on solution processes or elevations of horizontal platforms. The Pt. Hibbs platform is said to be very well developed, but its relatively inaccessible location makes field study difficult. When questioned, geologists who had visited the area stated that it was their impression that the platform surface was deeply awash at high tide. The Pt. Hibbs problem will have to remain unresolved until precise measurements can be made.

Most of the rocks comprising the Tasmanian coast are non-calcareous, either in cementation or composition. Where these rocks show horizontality, the elevation is at or near the level of mean higher high water. The higher elevation of the non-calcareous platforms is probably due to the characteristics of the major bevelling mechanism, salt crystallization, which is limited by the saturation level.

Chemical composition of the non-calcareous rocks is not as important as texture in the process of bevelling by salt
crystallization, but can be a contributing factor. Mineral breakdown due to chemical activity may prepare the rock for more effective subsequent salt crystallization. The chemical composition of the constituent minerals is closely related to the type of reactions which will be most effective in breaking down the rock. For instance, orthoclase, a potassium aluminum silicate, is very susceptible to hydrolysis, while olivine, a magnesium iron silicate, is often involved in oxidation reactions.

Passive factors, inherent in the bedrock, exert a major control over the presence or absence of platforms on any rocky coast. In addition they are important in determining the processes which will be most effective in platform development.
PART TWO

ACTIVE FACTORS
Chapter 14

THE ENVIRONMENT

The environment exerts a tremendous influence over shore platform development. Many environmental components affect the growing platforms, but climate, wave characteristics and tidal regime are probably most important. These three aspects of the environment furnish broad outlines for the types of formational activities possible in a specific location and also control the rate at which the processes operate.

CLIMATE

Temperature

Climate, including temperature, precipitation and wind, is one of the most basic of the environmental considerations. Temperature exerts considerable control over type and rate of formational activity. If the climate is sufficiently cold for sea water to freeze, a powerful agent of erosion is created. Water freezing in joints and cracks will cause the rapid displacement of material and the attachment of an ice foot to coastal rocks results in effective plucking.

Tasmanian platforms are probably at present free of effective freezing phenomena. The coastal areas of Tasmania all have extreme lowest recorded temperatures above 25°F., and temperatures
below 32°F. are rare. Ice starts to crystallize at a temperature of about 28°F. in sea water of normal salinity. As the pure crystals grow, the salinity of the surrounding solution rises, lowering the freezing point. This characteristic combined with the few times that the Tasmanian coastal temperature reaches this low reading makes freezing in cracks almost impossible. Formation of an ice foot in present Tasmanian conditions is even more unlikely because of the same lack of low temperatures.

In the absence of the powerful effects of frost, the relationship of temperature to evaporation is the most significant climatic consideration in the production of Tasmanian shore platforms. Evaporation is one of the important processes upon which water-layer weathering depends, and any variation in the evaporation rate would greatly affect the efficiency of that agency. The link between temperature and evaporation was explained by Geiger (1959) in his statement: "The amount of evaporation depends principally, according to a law of Dalton, on the temperature of the evaporating surface." More effective evaporation resulting from higher temperatures may explain the asymmetric profiles of the Weymouth basalt pillars which have suffered more erosion on the sun-struck north side faces than on the shady south sides. A heated rock surface splashed by waves could undergo many more crystallization cycles per day
than a cooler surface. The cool rock would be subjected to a slower evaporation rate which might react only to tidal rise and fall.

Seasonal temperature fluctuations affect the evaporation rate, but Tasmanian temperatures appear high enough all year long to allow effective evaporation to continue. Measured evaporation rates on the east coast vary from 1.00 inch during the winter month of July to 4.9 inches in January. (Values taken from the station at Kelvedon, courtesy of the Hobart Bureau of Meteorology). Temperatures for these months were: July, average maximum 52.1°F., average minimum 38.8°F.; January, average maximum 71.5°F., average minimum of 54.8°F. The evaporation rates encountered on Tasmanian coasts all seem sufficient to allow salt crystallization, the chief component of water-layer weathering. The north, east and southeast coasts have rates of about 31 to 34 inches per year, while the southwest coast probably has a rate of approximately 22 inches per year. The difference in rates between the southwest and other coasts is due to the high incidence of cloud cover and moist conditions induced by cool southwesterly streams of air from the Southern Ocean. Even in regions affected by this air stream, honeycomb weathering is present and salt crystals can be seen on the rocks.
Precipitation

The influence of precipitation on shore platform development in Tasmania is less significant than temperature and often acts indirectly. Fresh water falling on the predominantly non-calcareous coastlines of Tasmania has little effect on the platform surface, although some erosion may be accomplished by rain water washing down a cliff face. Rain water might also impede salt crystallization by diluting the brine solution. However, the most important effect of precipitation is probably the inhibition of evaporation brought about by reduction of rock surface temperatures and increase in the relative humidity. The clouds from which the precipitation falls also act to limit evaporation by reducing the insolation by which rock surfaces are heated. Annual precipitation on the Tasmanian coast ranges from about 70 inches in the west to approximately 30 inches in the east. Weathering is active on all parts of the coast, but the rate is probably least in the humid western regions.

Wind

The third major climatic factor which influences Tasmanian shore platforms is the wind, which, like precipitation often exerts an indirect control. One way in which the wind affects shore platform development is by causing alterations in the
evaporation rate. Moderate wind travel can increase the rate by removing moisture laden air from the evaporating surface. Wind may also cool the evaporating surface which would tend to retard the rate, but the net effect is probably a gain in evaporation.

WAVES

Far more important than its effect on the evaporation rate, however, is the wind's ability to produce waves on the ocean surface. Three main types of winds affect the Tasmanian coast in this capacity: distant gales, local gales, and sea breezes. These winds cause swell, storm waves and chop, respectively.

Swell

An almost constant southwesterly swell affects about half of the Tasmanian coastline. Other waves may at times be superimposed upon the swell, but it is often the most prevalent wave type in a region. The swell is strongest on the southwest coast of Tasmania and weakens through refraction on reaching the northwest and southeast coasts. Although no precise information is available, average height on the west coast is probably about 8 feet and maximum height for swell alone may be about 15 feet. The southwesterly swell is generated by gales in the unbroken expanse of the Southern Ocean. Davies (1964) has shown that any wind blowing between south-southwest and northwest could produce
swell which, after traveling long distances over a great circle route, would strike the Tasmanian coast from the southwest. The great area of gale-frequented water and the varying wind directions with ultimate southwesterly swell potential combine to create the persistent long period waves. Northeasterly swell created by disturbances in the northern Tasman Sea and southwestern Pacific Ocean may also hit the Tasmanian coast, but this wave type is far less prevalent than the southwesterly occurrence.

**Storm Waves**

Storm waves, although not as persistent as swell, can reach many more portions of the Tasmanian coast. Bass Strait, for instance, contains very low swell, but can be whipped up into impressive storm waves by local northerly gales. Other gales from the southeast can transform the usually placid waters off the east coast of Tasmania into a very confused, powerful sea. Local southwesterly gales add their energy to the basic southwesterly swell in creating even larger waves. Other directions from which local gales may strike the coast are west to northwest, northeast, and southeast.

Unfortunately, no precise records have been kept on heights or occurrences of storm waves in Tasmania. Lighthouse keepers make an attempt to note conditions, but often they are located in sites where visual observation of the local sea conditions is
difficult, especially at night. A rough impression can be gained, however, by looking at their reports and talking to the fishermen in an area. When this information is matched with the theoretical wave heights obtained through using the known atmospheric conditions, a general estimate of wave characteristics can be obtained. On this basis, the Bass Strait coast of Tasmania probably is hit at least once every five years by waves 8 feet high and once every 100 years by waves 12 feet high.

The absence of swell and comparative low wave heights place the Bass Strait coast in Davies' (1964) "Low Energy Environment". The east and southeast coasts receive more energy, with waves reaching significant heights of 15 feet in a five year period and 25 feet over a 100 year time span. Some of this energy is contained in swell with easterly components which classes the coast in an "East Coast Swell Environment". Coasts exposed to the southwest receive even more wave energy, being struck by waves with significant heights of 30 feet about once every five years and masses of water 50 feet high once per century. The persistence of the southwesterly swell in this region puts the coast in the "West Coast Swell Environment".

**Chop**

Chop caused by the summer afternoon sea breeze is the third main Tasmanian wave type. It is distinctly less powerful than the storm waves and less prevalent over a yearly period than the
Sea breeze chop can be important however in certain bays which are sheltered from more powerful waves.

The sea breezes are far more common on the Tasmanian coast than gale force conditions. On most summer afternoons the heating inland causes a radial outflow of air at an altitude of several thousand feet which descends offshore and sweeps landward as a 20-25 knot wind. The direction of the wind depends on local topography, but net movement is toward the center of the island. If any more general air movement is taking place, the sea breeze will be deflected, accelerated, decelerated or blocked.

Maximum height attained by the sea breeze chop is probably about 4 feet in most locations because of the low wind speed and limited extent of travel. Even though the waves are relatively small, they can still cause considerable spray in the coastal areas and can displace unconsolidated material.

Influence of Wave Action

The amount of contained energy determines the way in which waves influence the development of Tasmanian shore platforms. Briefly, in a high wave energy environment hydraulic forces predominate and the platform is often sloping. In a low wave energy environment weathering forces are relatively most active, resulting in a bevelled, horizontal platform which is kept clear.
of debris by wave action. The differences of platform morphology on exposed and sheltered sides of small Tasmanian islands illustrate this point. The Doughboys, two basaltic islands off the northwestern tip of Tasmania, are exposed on one side to the full brunt of combined southwesterly swell and storm waves, while on the other side they are sheltered from such massive attack. On the exposed southwesterly sides, the basalt has been shaped into a sloping ramp extending from beneath mean sea level to a height of about 15 feet above. In contrast, the north sides of the islands have been carved into a very horizontal platform at about the level of mean higher high water. A similar example occurs on Nuroo Island at Eaglehawk Neck. Here Permian sandstones have been quarried into a sloping platform on the seaward side, but bevelled across the bedding to form a horizontal platform on the sheltered portion. Notching was present at the base of the cliff on the sheltered side, but not on the exposed side where a rounded transition occurred between platform and cliff.

In addition to accounting directly for hydraulic erosion, waves also aid weathering processes. One of the functions of waves in this context is the removal of weathering products. In many locations the weathering process would slow down or cease entirely if the debris were allowed to accumulate. Waves may also aid salt crystallization weathering by splashing hot,
exposed rock surfaces from which evaporation is rapid, increasing the number of wet-dry cycles.

**TIDES**

The manner in which the tide affects the formation of Tasmanian shore platforms is far less obvious than the influence exerted by waves. Tidal range between MHHW and MLLW varies from 2.6 feet ("Microtidal" in the Davies system) on the exposed coasts to 9.1 feet ("Mesotidal") in the confines of Bass Strait, but similar platform morphologies occur in both locations. Tidal characteristics vary from \( \frac{K_1 + O_1}{M_1 + M_2} = 0.21 \) (Semidiurnal form) on Bass Strait to \( \frac{K_1 + O_1}{M_1 + M_2} = 1.01 \) (mixed, predominantly semidiurnal form) on the open coasts and again, similar morphologies are present.

The constancy of the relationship between the level of mean higher high water and the bevelled platform surface in different tidal ranges may offer a clue to the nature of tidal influence. All the bevelled platforms studied, from the basalt features on Bass Strait to the sandstone platforms at Eaglehawk Neck had horizontal surfaces located within one foot of the level of mean higher high water. From this observation, it appears that the level of mean higher high water is linked to the height of the saturation level in the rock, which in turn establishes the base level for salt crystallization weathering. The minor
variations in the level of horizontality could be due to differences in wave activity, but other considerations such as rock characteristics could also be involved. Even the 9.1 foot range on the Bass Strait coast is not particularly great by world standards. It is possible that as the range increases, the relationship between mean higher high water and the rock water table is destroyed, resulting in a migrating saturation level. If this were the case, fewer bevelled, horizontal platforms would be encountered in these regions.

Another consideration might be the characteristics of high and low waters over a 24 hour period. All of the Tasmanian tides have semidiurnal components, some stronger than others. Even with fairly low wave activity, the platforms of Tasmania are usually moistened twice per day. Frequent moistening may have two effects: an increase in the wetting and drying leading to more effective salt crystallization; and frequent replenishment of the water table to maintain a constant level. However, twice-daily wetting of the platform might be unfavorable to weathering in a more humid climate than Tasmania possesses. In a humid climate, diurnal tides would provide a better chance for the rock surface to dry before becoming re-moistened. Whether or not this is significant, the presence of horizontal shore platforms in Tasmania indicates that low range, semidiurnal tides are favorable for their development in the Tasmanian climate.
Chapter 15

HYDRAULIC PROCESSES

The processes involved in shore platform development fall into two broad categories, hydraulic action and weathering. They do not operate independently, but interact with each other and are ultimately controlled by rock characteristics and environmental considerations. In many instances, hydraulic action removes bedrock which has been loosened by weathering in joints and bedding planes. Weathering then operates on the surface created by hydraulic action to produce a bevelled platform, with wave action providing transportation to prevent the buildup of weathering products.

Hydraulic erosion and hydraulic transportation are both important in shore platform formation. Without them the number of shore platforms occurring in Tasmania would be greatly reduced. A vast body of literature exists on the characteristics of moving water, but comparatively little systematic work has been done on the possible effects of wave activity in the bedrock shore environment. In spite of the scarcity of facts, coastal geomorphologists have been eager to attribute many coastal features to wave action.

C. K. Wentworth (Hoffmeister and Wentworth, 1940) examined the problem in some detail and compiled a listing of hydraulic
factors which he considered to be important in coastal erosion. These were: (1) The direct impact of waves on rock, (2) Plucking effect of wave and current movement parallel to the surface, (3) Hydrostatic effects of air or water in fissures and cracks, (4) Rill action of sea water running back down cliffs, and (5) Abrasion by means of sand, gravel or blocks. Wentworth's list is broad enough to contain all of the factors important in hydraulic erosion and can be used as a base for the present discussion.

WAVE IMPACT

The topic of direct impact of waves on rock is very complex. To make the subject more manageable, it helps to make a division between the action of non-breaking waves, breaking waves, and broken waves. Forces exerted by non-breaking waves will be essentially hydrostatic, while breaking and broken waves exert additional pressures due to the dynamic effects of the turbulent water in motion and the compression of entrapped air. These effects occur on massive, unjointed surfaces. When, as is often the case with bedrock, the surface is broken by bedding or jointing, additional forces are generated by water hammer and air compression in cracks.

Non-breaking Waves

Sainflou, a French breakwater designer, in 1928 presented
an analysis of forces involved in non-breaking waves impinging on a vertical wall. The U.S. Beach Erosion Board included his views in "Shore Protection Planning and Design" as the most workable method for dealing with the problem. Sainflou is quoted in this translation as saying that a clapotis or standing wave condition of a vertical wall will be set up when the depth of water is at least approximately 1.25 times the height of the wave (depending on wave and bottom characteristics). In the clapotis condition, pressures are essentially hydrostatic as the waves themselves are almost completely reflected. Sainflou showed that the mean level of the clapotis was higher than the still water condition by an increment determined by a formula utilizing hyperbolic trigonometric functions, but approximating one third of the wave height for large (30 foot) storm waves.

Although the positive hydrostatic pressures generated by clapotis are probably not high enough in themselves to cause erosion, clapotis may still contribute to displacement of rock in shore platform environment. The main action would be due to hydrostatic pressure exerted by water entrapped in joints as the water receded. As Wentworth pointed out, "A pressure of one atmosphere applied to the lower surface of a 10-foot cube of rock will lift it; or a pressure of one atmosphere applied to the side of a firmly bedded cube of 20 to 25 feet will cause it to slide". This movement may take place, but breaking waves
Breaking Waves

Tremendous forces can be generated when a breaking wave strikes a vertical wall. The matter is of vital concern to designers of marine structures, but actual data on magnitudes and causes is scant. The most widely accepted authority on the subject is R. A. Bagnold, who conducted a series of experiments in England just before World War Two. He was trying to duplicate in the laboratory the intensities, up to 100 pounds per square inch, measured by field investigators at Dieppe and Genoa. Utilizing a wave tank and a piezo-electric pressure transducer, Bagnold ultimately obtained pressures of 80 pounds per square inch. In his 1939 paper, he attributed these high momentary shock pressures to the "violent simultaneous retardation of a certain limited mass of water which is brought to rest by the action of a thin cushion of air, which in the process becomes compressed by the advancing wave front." Bagnold claimed that shock pressures some 10 times greater than the ordinary hydrostatic wave pressure could be generated, but only in a very limited zone. The mechanism can only operate when the breaking crest strikes the wall in a manner such that the entrapped air cannot escape upwards. A spectacular display of spray and noise may result if the air escapes, but shock pressures are low.
Pressures of 80 or 100 pounds per square inch are probably not enough to affect a solid mass of rock, but may bring about movement in jointed or bedded material. Cracks in the rock encourage two mechanisms, air compression and water-hammer which could cause dislocation. A. H. Gibson conducted experiments in 1912 which apparently still stand as the chief reference on the subject. He found that if the energy of the wave were devoted to the compression of air in open joints, pressures about twice that of the hydrostatic value could be produced.

More spectacularly, Gibson stated, "If, however, conditions are favorable to the production of water-hammer, considerably greater internal pressures, up to some fifteen times the face-pressure with very high velocities of impact, are to be regarded as possible."

**Broken Waves**

Broken waves, the third type of force producing mechanism, are probably not as explosively destructive as breaking waves. The wave form is distorted and cannot exert the solid blow of Bagnold's breaking forms. When the wave breaks, the water mass moves forward with the velocity of wave propagation before breaking and the water particle motion changes from oscillatory to translatory. This rolling mass of water then moves across the shoreline until gravity or an obstruction stops it. According
to the Beach Erosion Board (1961), the pressures generated by the broken wave will be both static and dynamic. The static pressures will be due to the head and the dynamic pressures result from the deceleration of the mass of advancing water. The BEB stated that model tests have shown that approximately 70 percent of the full breaking wave height is above the still water level. On this basis they develop an engineering formula for total wave thrust on a structure as:

$$\text{Thrust} = \frac{wd_b (h_c)}{2} + \frac{w}{2} (d + h_c)^2$$

where $w$ is the unit weight of water, $d_b$ is the breaking wave depth, $h_c$ is height above still water level (0.7 times the full breaking wave height), and $d$ is the depth of water at the structure. For the case of a 20 foot high breaking wave in 10 feet of water the calculated combined pressure will be 180 pounds per square inch. This value seems high and probably includes a safety factor to make up for the difficulties of actual measurement. However, even if the real value were only a third in this particular example, these pressures combined with water hammer could do considerable work.

PLUCKING AND CAVITATION

Following the direct impact of waves on rock, Wentworth suggested that the "Plucking effect of wave and current movement parallel to the surface" might be important. He felt that
irregularities in the rock could force a speeding up of the adjacent fluid, with attendant reduced pressures plucking the rock from its position.

Some plucking might take place through this reduction of pressure, but hydraulic engineers believe that "cavitation" is far more efficient in destroying a surface. Rouse (1950) explained that cavitation results from the disturbance of high velocity flows in a fluid. When the flow is deflected over an obstacle, the pressure may be reduced to the point where it is less than the vapor pressure of water. A cavity filled with water vapor will then be produced. Downstream from the obstacle, the pressure will rise again and the cavity will collapse - a strong implosion. Extremely high pressures created by the implosion are capable of eroding steel or etching glass.

Two conditions must be met before this powerful potential agent of erosion can take place: (1) The velocity of the water must exceed 25 feet per second and (2) The water must contain very few air bubbles. The minimum velocity is easily attainable in the shore platform environment. The equation

$$C = \sqrt{\frac{gL}{2\pi}} \tan h \frac{2\pi d}{L}$$

(BEB) shows that in depths of water from 20 to 30 feet, waves having periods of over 6 seconds reach the required velocity. When an additional increment
is added for increased speed upon breaking, even shorter period waves may reach the critical 25 feet per second velocity. Minikin (1950) pointed out that Sainflou's analysis of clapotis indicated that high speeds could also be attained even if the wave did not break. Sainflou showed that at a distance of a quarter of a wavelength from a vertical wall the movement of water on the seabed is at a maximum and may reach a velocity, backwards and forwards, double the velocity of the wave.

If the water in the coastal zone were not considerably aerated, cavitation might be a formidable force in coastal erosion. However, the presence of great numbers of bubbles produced by breaking waves inhibits the process. (Even in the clapotis condition, part of the wave usually breaks). Aerated water will not support the exceptionally high shock pressures encountered elsewhere, for instance in mountain streams and on dam faces, because of a cushioning effect. Even though most of the water is aerated, some probably contain few enough bubbles to allow cavitation. Such activity could result in removal of small blocks or cause pits which might encourage weathering processes, when the waves subside.

HYDROSTATIC PRESSURE

Another of Wentworth's mechanisms, "Hydrostatic effects of air or water in fissures and cracks", has already been briefly mentioned in relation to clapotis. However, this factor is not
limited to the clapotis condition as it operates any time a difference in head exists. This difference can be brought about by fluctuations of waves or tides or combinations of both. In terms of efficiency of erosion, hydrostatic effects are probably most pronounced when the water level changes due to waves or tides, leaving water in cracks and joints which is still under a pressure equal to the atmospheric value plus the weight of the entrapped fluid. The generated force may be a contributing factor in quarrying of blocks in the shore platform environment.

ACTION OF RAPIDLY MOVING WATER

The action of water running across a rock surface is yet another factor in marine attack on the coast, according to Wentworth. During a storm, wave splash combines with driving rain to pour a phenomenal mass of water up and down a sea cliff and across the platform. Sea water is deflected to great heights during storm conditions. Minikin (1950) reported that 23 foot waves striking the Genoa breakwater forced jets of solid green water to heights of 80 feet.

Falling Water Impact

Minikin also told of the conditions which led to the destruction of the Alderney breakwater in 1871. Observers claimed that water rose to 200 feet above the structure upon wave impact,
shattering the roadway as it fell. Since engineers have measured velocities of 290 feet per second at Dieppe and Le Havre in smaller columns, cascading water must be included as a potent force on jointed material.

Water Friction

The impact is probably not violent enough to shatter solid rock, but another mechanism may take place. W. F. Navin of the Tasmanian Hydro Electric Commission Hydraulics Laboratory claims that dam spillways are eroded by water friction alone. Such friction acts like sandpaper in smoothing rock surfaces. Complexities of the mechanisms and almost infinite variations in rock structure make measurement of the effects of water abrasion and falling water impact difficult. It does seem likely, however, that the action of water moving at great velocities in the coastal environment is an effective factor in erosion. At the very least, this action is important in the removal of weathered material.

ABRASION

The final factor in Wentworth's catalog of marine erosion forces is "abrasion by means of sand, gravel, or blocks" propelled by wave action. This is an attractive mechanism for coastal erosion and has long been considered a very important factor. Gilbert (1884), Davis (1886), Gulliver (1889) and
Fenneman (1902) favored the process and D. W. Johnson (1919) based his entire theory of Marine Planation on the alleged action of abrasion to "wave base". Though the process may be significant in specific locations, abrasion by tool material is probably not of prime importance on a world wide scale. Tasmania in particular shows relatively little evidence for erosion through abrasion.

Past Acceptance of Theory

Abrasion has probably been widely accepted in the past for two main reasons. First, when it occurs, abrasion is generally easy to observe. No special underwater equipment is required and widespread evidence of the process exists in the form of rounded tool stones and "emerged wave-cut benches". The wave-cut bench, wave built terrace concept is appealing in its simplicity and appears fairly tenable as long as only the sub-aerial portion of the profile can be seen.

The second main reason for the popularity of the abrasion theory may be that considerable portions of Britain are obviously being eroded in this manner. It is easy to see why British geomorphologists attach such importance to abrasion, when writers such as Matthews (1934) estimated that waves erode 2,000,000 tons of cliff annually on the Holderness coast of Yorkshire. Steers (1948) typifies the traditional British view in his
statement on page 64 "They (the waves) erode the bottom, loose material is produced, and this, under wave action, has great cutting power. Hence, it is not long before a fairly level submarine platform is chiselled out." Abrasion may well be significant in a location where large waves strike soft rocks or unconsolidated Pleistocene sediments, although even here sub-aerial factors probably play a part. The combination of ease of observation in most parts of the world and actual importance of the process in Britain insured continuing popularity for the wave abrasion concept through the years.

Lack of Tasmanian Evidence for Abrasion

The Tasmanian coastline shows little evidence of active abrasion on shore platforms. Tool stones are rare on both the sub-aerial and submarine platforms. In addition, the submarine platforms are protected by a mat of plant and animal life (Photo 33). Ricketts and Calvin (1962) presented a good description of the teeming scene: "So keen is the struggle for existence that not only is every square inch of shore surface likely to be utilized, but the holdfasts and stipes of kelp also are occupied, and many such forms as sponges, tube worms, and barnacles occupy positions on the shells of larger animals." The density of cover indicates that rock abrasion is very infrequent. In addition, the profusion of biota would inhibit the movement of rock and protect the bedrock surface if movement
did occur. The few tool stones present are wedged into cracks and are themselves covered with organic material. Personal underwater inspection on the coasts of California, Hawaii and Tahiti, where similar conditions were found, suggests that the Tasmanian offshore characteristics are not unique.

Examination of the sub-aerial portion of the Tasmanian coast also yields little support for rock abrasion. In addition to the scarcity of tool rocks, delicate ridges of limonite often protrude from joints, indicating freedom from rock impact. Rounded tool stones do exist, but only on the flanks of platforms where they grate against one another on small pocket beaches. Blocks removed from the cliff or quarried from lower levels are apparently swept laterally along the platform by wave action, instead of grinding to and fro across the surface.

**Availability of Tool Stones**

The availability of tool stones could be the key to erosion by rock abrasion. When the supply of tools exceeds the capability of wave action to quickly move them laterally into storage, abrasion may result. Absence of debris on the platform and scarcity of such material off the platform edge suggest that transportation is usually rapid. However, if the load increased, transportation would eventually slow down. Abrasion could then result from the combination of more tools and the increased time
Photograph 33

Submarine Organic Cover. The photo is of the submarine portion of the Apex Point dolerite platform, at a depth of about 15 feet. Such density of cover is commonplace on Tasmanian submarine platforms.
that each fragment would spend before entering a storage area.

Erosion of unconsolidated Pleistocene sediments is a good example of the case where the supply of tools exceeds the lateral transportation ability of wave action. A large input of rock fragments into the system insures efficient erosion by abrasion. In Tasmania, the input of tool rocks onto shore platforms in most locations is fairly low and lateral transportation is well able to cope with the debris.

**Abrasion by Sand**

Even though abrasion is not omnipotent, it can still exert an influence on shore platform morphology. The most prevalent abrasive agent on shore platforms is probably water-borne sand. This mechanism is most active in locations where a platform is in contact with encroaching beach sediments and produces unique erosional forms. An example of this type of erosion occurs at Eaglehawk Neck on the southern end of the Tessellated Pavement. The part of the platform which is presently under attack by wave-propelled sand shows long, shallow grooves leading seaward; quite different from the typical weathering morphologies found elsewhere on the same platform (Photo 51). Abrasion does occur in the shore platform environment, but it is probably one of the least important factors present.
SUMMARY OF HYDRAULIC FORCES

The various hydraulic forces and the conditions under which they occur are depicted in Figure 17. The conditions include clapotis, breaking waves and broken waves impinging on a vertical cliff, in addition to the special case of a shore platform profile. The platform profile as drawn combines characteristics of the three main conditions. The lower part of the wave undergoes clapotis, while the upper part of the wave breaks and becomes a wave of translation. At a higher relative sea level, more of the wave would break; conversely, if sea level were lower, a greater proportion of the wave would be reflected. (Assuming a remaining depth greater than 1.25 H.)

The diagrams list only the forces and the various zones in which they operate without reference to erosion potential. Relative efficiencies of the forces are difficult to ascertain as they are dependent on a number of variables. In general, breaking wave shock, water hammer and air compression in joints are probably the most effective forces, with hydrostatic pressure, cavitation and the various forms of abrasion only occasionally important. In terms of effectiveness versus possible area of operation, the most effective forces operate in the most limited zones, while the least effective are most widespread. High shock pressures from breaking waves can only occur in a narrow zone approximately between still water level and the wave crest.
Figure 17

SUMMARY OF HYDRAULIC FORCES
WAVES STRIKING A VERTICAL CLIFF

CLAPOTIS CONDITION of SAINFILOU

BREAKING WAVE CONDITION of BAGNOLD

Water Abrasion
Water + Rock Abrasion
Cavitation
Water Hammer
Air Compression in Joints
Breaking Wave Shock
Positive Hydrostatic Pressure
(Constantly Submerged)
Alternating Hydrostatic Pressure
(Periodically Emerged)

WAVES STRIKING A PLATFORM

Upper part of wave is sheared, forming wave of translation across platform

Lower part of wave is reflected, forming clapotis

Cavitation may occur in un-aerated masses of water

At slightly higher relative sea levels, amount of clapotis is reduced. At slightly lower relative sea levels, amount of clapotis is increased.
Water hammer and air compression in joints depend on alternate presence and absence of water and have a wider range. High positive and negative hydrostatic pressures which also require repeated submergence and emergence operate in the same zone. Cavitation is possible wherever high water velocities occur and the water is not aerated, the most favorable conditions taking place from wave crest to 1/4 wave length in front of the cliff in the clapotis situation. Abrasion can occur from the top of the wave splash zone to a point seaward of the cliff by means of un-armed water friction. Water-powered tools might cause erosion in the same area, chiefly on horizontal surfaces.

If this analysis of hydraulic forces is correct, a belief that shore platforms are formed solely by storm wave action might be vindicated. The most powerful hydraulic agents operate at elevations from a little below still water level to consider-ably above, even in normal conditions. With piling up of water due to low atmospheric pressures and on-shore winds, the effect-ive zone could be still higher. Intuitively, it would seem that the waves might form a platform in well bedded level material, but that horizontal bevelling would not take place in tilted strata or homogeneous material.

WAVE TANK EXPERIMENT

In order to gain a better insight into the erosion profiles
produced solely by hydraulic action an experimental model study was undertaken. The method involved the direction of artificially produced waves of known characteristics against a series of erodable blocks representing cliffs and platforms. Experiments continued over a period of several months in a wave tank assembled for the purpose.

Construction of Wave Tank

Construction of the wave tank was simplified by the generous loan of a flume by the Engineering Department at the University of Tasmania. The flume, normally used for experiments in hydraulic flow, consisted of a tank with perspex sides of 9'6" length, 8" width and 16½" height (Photo 34). It was only necessary to seal the flume at both ends in order to use it as a wave tank. The remaining construction work consisted principally of producing a paddle and driving arrangement to generate waves. The chief difficulty was that no alteration could be made to the existing flume and the paddle and drive units were fabricated to meet this requirement.

Out of the many different ways of making waves, it was decided to utilize a paddle pivoting on hinges fastened to a block at the bottom of the tank. The paddle was driven by a rod attached to a plywood disc by means of a nylon bushing turning on a stainless steel bolt. The bolt could be adjusted
Photograph 34
Experimental Wave Tank. The paddle is just completing its forward stroke.

Photograph 35
Simulated Offshore Profile. The steel plate placed on the bed of gravel establishes the experimental profile. The eroding block is visible in the extreme left of the photograph.
in a slot to vary the length of throw and hence the wave amplitude. The disc was driven by a stainless steel shaft on which was mounted a four-sheave V-belt pulley. Power for the V-belt was provided by a reduction box turned by an 1/8 H.P. electric motor. A variation in the period of the waves was attainable by moving the V-belt from one sheave to another.

The simulated offshore profiles offered minor difficulties. No holes could be drilled in the bottom of the wave tank for securing an adjustable profile ramp. Consequently it was necessary to use a gravel bed to form the required slopes. Gravel was placed in the tank and a steel plate laid on the surface to simulate an offshore profile (Photo 35). The plate was positioned by scooping gravel from one location to another until the desired profile was obtained. The gravel also served to hold the erodable blocks upright and in this capacity fixed the blocks securely enough to avoid movement upon wave impact. Wave reflections were reduced to an acceptable level by placing rubber-covered horsehair pads in both ends of the tank.

**Block Casting**

Production of the model cliffs themselves followed completion of the tank. A block was needed which was firm enough to stand unsupported in the water but incompetent enough to erode in this small-wave environment in a reasonable time. The first block contained a mixture of one-part of mortar to 70 parts of sand.
This mixture had been used successfully by the Tasmanian Hydro Electric Commission hydraulics laboratory in model spillway erosion tests, but the block proved to be too weak to stand by itself in the tank when wet.

The second attempt utilized a stronger mortar mix; 1 part mortar to 35 parts sand. This block stood competently in the tank, even when wet, but was practically unerodible. It seemed evident that somewhere between a ratio of 1:70 and 1:35 would be found a mixture which would stand in the tank and also erode easily. However, the time necessary to mix and cure the mortar (on the order of 4 days) indicated that another type of block would be more advantageous.

A suggestion was made to try plaster mixtures and a number of samples were prepared. A mixture of 50% plaster and 50% fine grained quartz sand resulted in a block which was much too hard. A mix of 25% plaster to 75% quartz sand was softer and more erodible, although the erosion rate was still fairly slow. The next block had a composition of 15% plaster to 85% quartz sand which had better erosion properties. A block composed of 10% plaster and 90% quartz sand was difficult to handle without breaking, but yielded rapid erosion. The final test mixture of 5% plaster to 95% quartz sand was extremely fragile and tended to crumble upon water contact.

A block containing 25% plaster and 75% sand was prepared and
placed in the tank for the first run. This block and subsequent models were cast in the same mould and had dimensions of $16\frac{3}{4}" \times 5\frac{1}{4}" \times 2\frac{3}{4}"$. The block was installed in the tank with its broad dimension ($5\frac{1}{4}"$) facing the oncoming waves. Distance from block face to wave generating paddle was 6 feet, a dimension which was held constant for all the plaster block experiments.

**Bottom Profile and Wave Characteristics**

With the block in place it was necessary to establish profile and wave characteristics. An offshore profile was needed which would produce properly breaking waves in the tank as well as simulate conditions found in the field. A deep profile, in which the depth of the shallow end was more than 1.25 of the wave amplitude, would create a reflective clapotis situation. A very shallow profile, on the other hand, would result in complete waves of translation. In this small tank proper water return for a complete wave of translation was not possible. In addition, many rocky coasts are fronted by depths of water sufficient to prevent waves from breaking completely. A profile depth was finally chosen which would yield a partial wave of translation superimposed upon a wave of oscillation. The steel plate which established the profile was placed $2\frac{1}{2}"$ below still water level at the cliff face and $4\frac{1}{2}"$ below the datum at a distance 24" from the block. The gravel bed under the plate sloped abruptly to the tank bottom at this point.
Wave characteristics were established to be compatible with the selected profile. Deep water wave height was 3-3/16" and wave length was 19\(\frac{1}{2}\)". Thus the waves were oversteepened, with a value of 0.164, which would be similar to natural conditions in a storm. Wave period was 0.652 seconds. These parameters yielded a wave which started to break about 14" from the block face and which had broken through half of its height when it struck the vertical surface. Upon reaching the block, the total height of the broken wave between crest and trough had decreased to 2-3/8" from the unbroken amplitude of 3-3/16".

**Operation**

The tank was filled and the wave paddle activated for run number Pl when the preparations were complete. The block was observed closely during this initial period for any signs of erosion. Within 20 minutes sand grains could be detected by feel on the previously smooth front face of the plaster-sand model. Water was shooting up the face to a height of 6 inches above still water level, but no visible notch was present. In the first hour of operation numerous pits, having an average diameter of about 1/16", formed on the face. After four hours of continuous operation the pits had enlarged until a few had reached 3/32" in diameter. A notch of 1/32" average depth had formed on the face, in addition to other notches on the sides of
the block. The side notches apparently resulted from the speeding up of the water movement as the breaking waves became constricted between the block and the tank sides. As the experiment progressed, the notches deepened through coalescence of the numerous pits. The paddle was stopped after a running time of 18 hours and 22 minutes at which point the block had spent a total of 31 hours and 47 minutes in the water. A profile was obtained by a tedious process of cutting and recutting a cardboard template until template and block surface matched. In order to avoid possible errors through inclusion of the side notches in the frontal profile, the template was cut in the center of the block face. The profile resulting from this experiment is shown in Figure 18.

Another block was prepared with a mixture of 10% plaster to 90% quartz sand. This weaker mixture was intended to hasten the erosion process in order to get a better insight into the notching mechanism. Wave characteristics and the offshore profile were as identical as possible to run P1. The rate of erosion proved to be greater on the new block, but the other characteristics remained the same. Sand grains were first evident on the face, followed by pitting, grooving and notching. Block P2 was eroded for 30 hours and 14 minutes before being removed from the tank. In contrast to run P1, run P2 was continuous, with the immersion time equalling the running time.
Figure 18

EROSION PROFILES OF VERTICAL CLIFF MODELS P1, P2 and P3.
Level of Maximum Erosion

Steel Plate

Original Block Outline

Erosion Profile

Still Water Level

P1.
25% Plaster
75% Sand
18 Hrs. 22 Mins.

P2.
10% Plaster
90% Sand
30 Hrs. 14 Mins.

P3.
15% Plaster
85% Crushed Rock
16 Hrs. 37 Mins.
Block P2 shows a profile with greater depth and more irregularity than P1.

The third run, P3, was made with a plaster and crushed dolerite mixture. This was an attempt to simulate a natural condition in which jointing and bedding would be present. Crushed dolerite held in a matrix of plaster would furnish a coarser texture upon which the hydraulic action could work. The block was composed of 15% plaster and 85% crushed dolerite with an average diameter of 1/8". This mixture was mechanically sound and yielded a block which suffered no crumbling in water and eroded satisfactorily. The offshore profile and wave conditions were identical to previous runs. The surface pitted rapidly on the new block and the material appeared more permeable. The notching continued as usual on the face, but exceptionally rapid erosion took place on the side of the block. Apparently the mixture was not uniform and the side of the block was less well cemented than the front. Throughout this run the side notch continued to cut across the face, with a greater cutting rate than on the front. The side notch cut higher as it neared the center of the block and also undercut the face notch to a depth of about 3/4". The experiment was allowed to continue for 16 hours and 37 minutes over a period of 2 days and one night. The tank was drained during the time it was not in operation. In general the frontal profile attained is very similar
to those of the plaster and sand blocks, except that the level of maximum erosion is higher (Figure 18).

Run P4 was an ill-fated experiment with a very rapidly eroding mixture. A block was produced which was 5% plaster and 95% quartz sand. The block started to crumble as the tank was being filled and was cracked even before installation. The top half of the block was held in place by hand and wave generation initiated. Erosion was rapid, especially laterally about 3/4" behind the face. Before the block collapsed completely in about 3 to 4 minutes, a one inch notch had been produced on the struck face. Erosion was very rapid indeed but the block was mechanically too weak to stand in the tank.

Run P5 was conducted with a block which was 15% plaster and 85% quartz sand, cast in a platform shape. Unfortunately, before the block was placed in the tank the top half broke from the bottom section, leaving a joint where the two pieces fitted together. The block was set in the tank in spite of the fracture to allow experimentation to continue while a new block was being cast. The top section was clamped to a wooden support which braced the model sufficiently to withstand wave impact. As in the previous plaster blocks, sand grains were detectable within a few minutes and pitting, grooving and notching followed. The notching, however, was of a different nature than in previous runs due to the platform configuration of the model.
Cutting during run P5 occurred in three separate areas: the leading edge of the platform, the platform surface and the cliff face. Considerable erosion also took place along the fracture at the base of the cliff.

After 3 hours of operation, the leading edge of the platform was rounded to a half inch radius and notching was very apparent at the rear of the platform. Waves of translation were rolling across the platform and were deflected both upward and downward by the cliff. The waves that were deflected upward were removing material to a height of two or three inches above the platform surface and the portion of the wave which was deflected downward appeared to be scouring a notch in the platform surface itself, as well as into the base of the cliff.

The tank was drained after three hours and re-started on the following day. However, the tank was allowed to run for only five more hours before the final draining. The erosion patterns being created in this platform-shaped block warranted further study, but the top of the block was becoming insecure and it was necessary to stop. The profile attained during this 8 hour experiment is shown in Figure 19.

Another platform block was shaped in order to ascertain if the notching on the P5 platform surface was related to jointing in the broken block. The new block, P6, was also a 15%-85%
Figure 19

EROSION PROFILES OF PLATFORM MODELS P5 and P6.
plaster-sand mixture, but the platform profile was cut with a hacksaw instead of being cast in place as in the previous experiment. Cutting produced a markedly improved profile over that obtained by casting. Edges were completely square on the cut profile, while some rounding was inevitable with the casting technique.

The block was set in place, as previously, with the platform surface about 1/8" above still water level. Shortly after starting the experiment the usual pitting and grooving occurred, becoming most pronounced at the rear of the platform. A notch cutting into the rear of the platform surface became evident after about two hours of operation. Erosion continued in this area throughout the 14 hour and 30 minute run, indicating that notching into the rear of the platform was not caused by the jointing in block P5. The final profile (Fig. 19) shows deep cutting into the platform surface, leaving the leading edge area standing as almost a "rampart".

Blocks No. 5 and 6, in contrast to earlier models, had been placed in the tank with their narrow dimension facing the oncoming waves. The new position had the effect of reducing the reflected waves, and changing the standing wave condition in the tank to allow a purer incoming wave form. Some experimentation appeared necessary to determine the type of notching which would occur in a straight faced block (instead of a
Figure 20

EROSION PROFILE OF VERTICAL CLIFF MODEL P7.
Original Block Outline

7 Hrs. 10 Mins.

19 Hrs. 55 Mins.

30 Hrs. 45 Mins.

Wave Crest

1/16" Breaking Portion of Wave

Still Water Level

Wave Trough

Steel Plate

P7.

15% Plaster

85% Sand
platform shape) inserted in this manner. Therefore, another plaster block was cast with a 15% plaster to 85% sand mixture.

The new block, No. P7, was installed in the tank and allowed to erode for a total time of 30 hours and 45 minutes over a 3 day period, during which the tank was drained when not in operation. The results indicated that a similarity does exist in the notching forms of this block and the blocks with their broad dimension facing the waves. In both cases the maximum frontal notch development showed a good height correspondence with the portion of the wave which had broken (Figure 20). The greatest notching occurred between the level of the broken wave crest and the base of the turbulent zone. As the base of the turbulent zone was about halfway between the wave crest and the wave trough, maximum notching took place in the area struck by the upper half of the wave. Further examination of this phenomenon would have been useful, but the Engineering Department required the flume at this time for its own studies.

Analysis of Results

The wave tank experiments indicated several characteristics of hydraulic action in a model coastal environment. The first aspect was the occurrence, in all blocks, of the maximum erosion at an elevation above still water level. A similar situation
Photograph 36
Model Wave Just After Breaking; oblique view. The wave form has been displaced upward with respect to still water level (represented by the top edges of the horizontal white lines on both sides of the tank). The block, No. P7, shows deep side and front notches and well developed pits. Eroded block material has accumulated offshore from the block on the steel profile plate.

Photograph 37
Model Wave Striking Block; oblique view. Broken portion of wave neatly fits into notch created by wave action. Greatest depth of notching is about 3/4" below wave crest at striking. Part of the wave has already passed the block and is being channelled between the block and the tank walls.
has been noted by engineers measuring the intensities of pressures created by waves breaking against upright surfaces in the shore zone. Two factors are involved in this phenomenon: (1) The entire wave form is shifted upward when decreasing depths are encountered (Photo 36) and (2) The upper part of the wave produces the highest pressures upon breaking. Bagnold, (1939) in his wave tank experiments on the pressures produced by breaking waves on vertical walls, found maximum shock pressures between the wave crest and 0.6 H above the wave trough. The waves used were of 10 inch amplitude and had been displaced 4 inches upward in relation to still water level during progress up an incline before striking the wall.

Although conditions in the present experiment were not identical to Bagnold's, a general correlation between the zones of highest shock pressure and greatest erosion exists. On block P7, a breaking wave 2-3/8" high repeatedly struck the vertical face. In contrast to Bagnold's wave, this wave was displaced only 0.1 of its total height above still water level. The maximum erosion was centered in the upper half of the wave, 3/4 inch below the crest (Photo 37). Inflection points between the concave curve of the zone of maximum erosion and the convex curve in adjacent areas occurred at the top of the breaking wave and at still water level. The zone of maximum erosion is thus extended further downward than Bagnold's maximum pressure area.
Two reasons for the difference may be that wave and bottom characteristics are not identical and that Bagnold was measuring only shock pressures, while the plaster block cliff was reacting to wave shock combined with other activities associated with moving, turbulent water.

Other phenomena appeared when platform shapes were exposed to wave attack. A notch formed in the cliff face as expected, but cutting also occurred on the platform surface, especially at the rear. Cutting on the surface degraded the horizontality to a point where the horizontal plane of the platform had disappeared by the end of the experiment. The tendency for hydraulic action to establish smooth curves whenever possible became very apparent. Angular junctions of the surfaces at both front and rear of the platform were rounded into shapes approaching the elliptical "ogee curve" which offers least resistance to flow.

General Conclusions

Difficulty is always encountered when the attempt is made to relate a model study to the full-scale environment. The only thing that such a study really shows is that model waves of certain characteristics striking plaster-sand cliffs have a particular effect. For this reason no detailed analysis of the individual profiles was made, and only general conclusions were drawn. These general results, however, may be applicable
in the real environment.

Workers in the field of shore platform study have stated that the greatest "storm wave" erosion would take place above mean sea level and these experiments suggest that this opinion may be correct. Bartram (1924) typified this view when he ascribed platforms 2 feet above mean high water level to storm wave activity, acting on "homogeneous and resistant" rock. This concept has also been voiced by Jutson (1939) and other, more recent authors.

While the experiments support the contention that erosion is greatest at elevations above mean sea level, they fail to provide evidence that platforms may be produced by hydraulic action alone in a homogeneous, un-bedded and un-jointed material. Wave activity on the vertical model cliffs produced a rounded form with a deep notch and little horizontality. The lower half of the notch contained no horizontal component and was located below still water level. In addition, the pre-existing horizontality on the platform models was badly degraded by wave attack. If rounded notches with bases below mean sea level are produced in a similar manner by wave action in the real environment, some additional processes involving mechanical and chemical weathering will be required for the formation of level, elevated surfaces in many coastal rocks.
The notches created by accelerated flow along the sides of the blocks may also have full scale analogues. Formation of these notches, often as deep or deeper than the frontal depressions, may be related to the production of sea caves, arches and stacks. As the waves in the model study funnelled between the plaster-sand blocks and the tank walls, the water velocity was locally increased. The resulting pattern of erosion showed the greatest vertical dimension of the notch at the point nearest the wave source, but the maximum horizontal cutting at a point further towards the rear of the block where velocity was greatest. The relatively rapid erosion of arches and closely spaced stacks may be due to a similar increase in water velocity as wave energy becomes concentrated in narrow channels.

Another phenomenon which might have significance in the real environment was the behavior of the material removed from the eroding blocks. The material was immediately swept away from the block face and deposited in a break-point bar and a series of small ridges offshore. At no time was there a tendency for material to pile up at the base of the cliff as suggested by Cotton (1945). Cotton wrote that wave attack on a steep coast would not produce notching until sufficient talus had accumulated at the cliff base to act as cutting tools. The present experiments suggest that the talus would probably be
transported offshore until a tremendous mass had accumulated and that erosion by unarmed hydraulic activity would have taken place in the interim.

Much more information could be derived from further wave tank experiments on erodable blocks. Throughout the present experiments, the wave characteristics and offshore profile were kept as identical as possible from run to run. Significant data might result from noting variations in erosion patterns as these parameters were changed. Experiments on multi-layered blocks containing differentially resistant material would also be worthwhile, as would additional studies on jointed blocks. Finally, further refinement of method could add more quantitative information to the qualitative data already received, although scaling these occurrences in terms of material, time, size and distance would be difficult.

Experimental and field evidence suggests that hydraulic action alone can not produce a horizontal shore platform except possibly by quarrying in well bedded, horizontally structured material. Even here, another condition might be required - differential resistivity of beds. Some shore platforms can be accounted for by hydraulic erosion, but many others cut in dipping rocks show marked horizontality which could not be created independently by hydraulic activity. However, when hydraulic action is joined by weathering phenomena, a powerful mechanism for planation results.
Chapter 16

WEATHERING

Tasmanian high tidal shore platforms are particularly dependent on weathering for the production of horizontality. In addition, the process also contributes to the development of intertidal platforms. Weathering is a broad term embracing a number of inter-related activities which are basically mechanical, chemical or biological in operation. All three types of weathering are combined in the complex mechanism which helps shape Tasmanian shore platforms.

WATER-LAYER WEATHERING

Water-layer weathering is generally accepted as being very significant in shore platform development. The present term is a variation of the original "water level weathering", proposed by C. K. Wentworth in 1938 as a name for the process which he believed had levelled basalts and tuffs into shore platforms in Hawaii. In later years Wentworth's term has given way to water-layer weathering as suggested by Hills in 1949 to avoid a possible confusing association with sea level.

The process has been named and renamed, but its detailed workings are still not certain. Many writers seem content to accept water-layer weathering as an explanation for coastal erosion without attempting to explain the activities involved.
Those that do delve into the problem have little to add to the original ideas of Wentworth, though most agree that recurring wetting and drying is important. Wentworth himself had difficulty in explaining the mechanism, as he spent some 31 pages of his 1938 paper describing the results of water-layer weathering, but only two paragraphs on the process. In those paragraphs he outlined the basic character of water-layer weathering: that it is dependent on repeated wetting and drying, and possibly operates through "surface tension phenomena, and colloidal and dilation behaviors" (akin to the slaking of shales when exposed to water and with rock pressure released); or crystallization of salts from sea water - which tends to break up the rock.

Wentworth's explanation is brief, but what he may have meant was that "surface tension phenomena" would keep moisture in contact with the rock surface for subsequent "colloidal and dilation behaviors". Colloidal activity could then take place in which clay particles would enter into suspension in the surrounding water, without actually going into solution. Dilation behaviors would probably include hydration of clay minerals, resulting in volume increase and breakdown of rock structure. Colloidal and dilation behaviors, however, do not require repeated wetting and drying for their operation. They can take place in a saturated environment and for this reason are unlikely to be responsible for establishing platform
horizontality.

SALT CRYSTALLIZATION

The main levelling agency may be Wentworth's last mentioned process, salt crystallization. Salt crystallization is based on a varying concentration of saline solutions which could be provided by alternate flooding by sea water and subsequent evaporation. The process is strictly limited by a saturation level below which it cannot act, so providing an explanation for the bevelled surfaces found on shore platforms. Salt crystallization alone could be fairly effective in rock breakdown, but when interaction takes place with chemical, biochemical and biological phenomena, weathering is probably speeded up considerably. Water-layer weathering is a complicated combination of processes, with salt crystallization acting to complete the final destruction of the rock fabric.

Salt crystallization is gaining acceptance in the literature as an important factor in the breakdown of coastal rocks. This view is not unanimous, however, as Emery (1960) stated, "Expansion of scales and loosening of grains by growth of salt crystals has been suggested in the literature, but neither field nor laboratory tests seem to support the suggestion." Nevertheless, researchers such as Blackwelder (1954), Pedro (1957), Wellman and Wilson (1965) and Coleman, Gagliano and Smith (1966)
are positive that salt crystal growth is an outstanding cause of rock breakdown. Blackwelder observed that the expansive action of salts crystallizing from brine solutions near the surfaces of desert playas was "rapidly destructive to porous, fractured, or cleavable rocks." Coleman, Gagliano and Smith stated that gravels and other sedimentary material on tidal flats in Northern Queensland showed physical disintegration by crystal wedging. Blackwelder; Coleman Gagliano and Smith and Wellman and Wilson based their opinions on natural evidence and reasoning, while Pedro wrote from his experimental experience.

**Pedro's Salt Crystallization Experiments**

Pedro carried out a series of experiments in which he placed samples of granite and volcanic lava in contact with various salt solutions and repeatedly dried the rocks at high temperatures. The wet-and-dry cycling was continued for four months. At the end of this time, rocks which had been in contact with the salt solutions were compared with a control group saturated only with fresh water. Pedro reached four basic conclusions as a result of his experiments, all of which have application in the shore platform environment:

1. Alternate wetting and drying with associated salt crystallization is effective in the disintegration of rocks.
2. The resistance of rocks to this action is more dependent on
petrographic structure (because of permeability and pore size) than on chemical composition.

3. Pure water is less effective than salt solutions in rock disintegration.

4. Sodium chloride, which crystallizes easily, has a more marked disintegration effect than imperfectly crystallized salts such as magnesium chloride.

Pedro's results were obtained at drying temperatures of 80°C., which might at first seem to have little bearing on actual shore platform conditions. However, rocks exposed to direct sunlight absorb considerable heat and can become much hotter than ambient temperatures. Geiger (1959) showed data obtained on an August day in Finland where the temperature of a granite surface was found to be 34°C. Another worker in Riverside, Illinois was reported to have measured a surface temperature of 52°C. on an asphalt street in mid summer. Geiger concluded, "The midday temperatures of more than 50°C. are by no means the highest experienced in our (mid-latitude) climate... surface temperatures of 70°C. and even more have been repeatedly observed. On southern exposures in our climate temperatures of up to 80°C. can be expected under favorable conditions."

The experimental conditions created by Pedro may not be so radically different from those found on some shore platforms.
Theoretical Background

While Pedro actually disintegrated rocks, Wellman and Wilson took a less direct approach to the problem. First they commented upon how crystal growth could cause the disintegration of rock and then gave examples of such action. They began by stating that in a system containing crystals in equilibrium with a saturated solution, larger crystals will grow at the expense of the smaller due to the tendency for any system to reduce the area of its interfaces to a minimum.

Wellman and Wilson explained, "The work required to be done during crystal growth on one face of a crystal is equal to $(P_1 - P_s)dV$, where $P_1$ is the pressure in the liquid, $P_s$ the pressure in the solid, and $dV$ the increase in volume. This must equal the work done in extending the surface, which is equal to $\sigma dA$, where $\sigma$ is the interfacial tension between the crystal face and its saturated solution and $dA$ is the increment of volume. Then since $\sigma$ is independent of $V$:

$$P_1 - P_s = \sigma \frac{dA}{dV}$$

The authors then went on to consider the special case of crystallization in a porous solid with both large and small pores filled with the saturated salt solution. Water is allowed to evaporate and escape from the system or crystallization is induced by a temperature change, with the result that, "First
the larger crystals in the large pores will grow at the expense of small crystals in the small pores. Let the process continue until salt crystals completely fill the large pores. Now since \( P_s - P_l = \sigma \frac{dA}{dV} \) for the crystal to grow down the capillary pores, it would greatly increase the area of the crystal, but only slightly increase its volume. The crystal will therefore grow in the large pore until the pressure builds up to such an extent that either mechanical fracture occurs or \((P_s - P_l) \sigma \) becomes greater than the necessary \( \frac{dA}{dV} \) to make the crystal grow down the capillary pore. Thus (for a given crystal and therefore a given \( \sigma \)) whether or not fracture occurs depends on smallness of the small pores and the value of \( \sigma \) compared with the mechanical strength of the porous material. Hence a large rock pore will be enlarged provided that the surface tension of the salt times the \( \frac{dA}{dV} \) of the micro pores is greater than the mechanical strength of the rock."

**Necessary Conditions and Examples of Occurrence**

Having given the theoretical background for the process of disintegration of rocks through salt crystallization, Wellman and Wilson listed the necessary conditions for such activity and gave examples of its occurrence. Necessary conditions are: a supply of salts, sites where salt can accumulate, and cyclic changes in humidity and/or temperature that include the crystallization point of the salt. They pointed out that for
erosion to take place, (in addition to rock breakdown) a transporting agent is required. Locations favored for salt weathering, Wellman and Wilson reasoned, would be regions where salts are being concentrated and regions where the concentration of salts is kept up by continuous supply.

The authors then stated that arid regions would represent the first of these locations. Salts are provided by air-borne salt particles, from rain or snow, from the rocks themselves and from percolating ground water. The second location, more pertinent to shore platform study, would be represented by the sea coasts in most parts of the world. Wellman and Wilson said that salts (mainly the sodium chloride noted for its effectiveness by Pedro) are provided at a rapid rate by wave splash, so that the rocks most affected are those that frequently become wet and subsequently dry - rocks in the zone immediately above the reach of waves at high water (Photo 38).

The two researchers gave numerous examples of the work accomplished by salt crystallization. The varied list ranged from pitting in the dry valleys of Antarctica and caverns in arid regions (including those on Ayers Rock, Australia) to decay of building foundations. They then pointed out that engineers have long been aware of the capabilities of salt crystallization, especially with respect to weathering of
Photograph 38
Salt Crystals on the Silver Gull Platform. Crystals have formed on the rock surface after heating by the mid-day sun has caused evaporation of sea water. The crystals are most numerous in areas flanking the joints.

Photograph 39
Weathering of Building Foundations. A notch has formed in sandstone blocks at the sloping contact between the buried, permanently saturated sandstone and the portions of the blocks which are subject to evaporation of moisture and subsequent salt crystallization. (Harrington Street, Hobart).
Wellman and Wilson ended their paper with the observation that salt weathering has a well defined base level - the water or permafrost level below which it cannot act. In addition, it acts most rapidly on the lower and not the upper side of rock surfaces. These two characteristics make the one process capable, according to the authors, of being both a powerful undercutting agent and a means whereby coastal platforms may be produced. They finished with the statement, "Although the action of salt weathering has been accepted in a few restricted localities, its relative importance and full extent are not yet appreciated."

Discussion

The evidence suggests that salt crystallization is the most effective of the processes included in water-layer weathering. Like many weathering activities salt crystallization breakdown is a combination of chemical and mechanical factors. Crystallization of salts from a solution obeys chemical laws, while the wedging apart of the particles by growing crystals is a mechanical process. On shore platforms, the mechanical forces appear to complete a weathering sequence started previously by predominantly chemical action. This action, most of which occurs beneath the surface, lays the foundation for rapid salt
crystallization weathering on exposed areas.

Given a surface already in the optimum wetting and drying zone near the elevation of mean higher high water, three conditions must be met before salt crystallization can bevel coastal rocks into horizontal shore platforms. They are:

1. Rocks must have characteristics allowing entry of sea water for salt crystallization, and, when the process reaches its final stages, to permit sufficient water flow to prevent crystallization at a certain level;
2. The rocks must contain a horizontal water table;
3. The process must be rapid enough to act before other mechanisms with lower base levels can degrade the surface. That these conditions are often met is shown by the number of horizontal high tide platforms in Tasmania.

**Permeability Experiment**

An indication of the possibility of meeting the first condition, entry of water into the rock, was obtained through tests on samples taken from areas showing differing degrees of platform formation. Samples included Permian sandstone, Tertiary basalts from two locations (Don Heads and Weymouth), Devonian granite, and Jurassic dolerite. The rocks were cut into one inch cubes to eliminate, as much as possible, variations in data due to irregular shapes and surface areas. After cutting,
the blocks were allowed to come to equilibrium with the ambient conditions. At the beginning of the experiment the samples contained the following percentages of moisture:

Don Heads Tertiary basalt, 3.59 percent; Permian sandstone, 1.84 percent; Weymouth Tertiary basalt, 0.760 percent; Jurassic dolerite, 0.491 percent; and Devonian granite, 0.0995 percent. This ranking was generally maintained in the experimental results, except that the sandstone ultimately absorbed a higher percentage of water than the Don Heads basalt (Figure 21). The testing procedure included the immersion of the blocks in sea water and determination of weight at intervals to ascertain the additional moisture gained. The rocks were not oven-dried immediately before the immersion because such conditions would not be found in the natural environment.

The testing method measures both the water intake into surface cracks and permeability - briefly defined as the capacity for transmittance of a fluid through interconnecting pores in the rock. Because both factors can lead to salt crystallization, and are difficult to measure separately, they will be grouped together as permeability in this discussion.

Data showed that the best developed shore platforms occurred in rocks capable of absorbing from 3.01 to 5.11 percent additional water by weight upon 70 hour immersion. As these tests were conducted on blocks cut from the interiors of large samples, the
surface permeability in the more weathered material would probably be even greater. The experiments indicated that one of the least productive rocks for the establishment of shore platforms, granite, also had the least permeability (0.259 percent absorption). Although the lack of platforms in this material may be due to unfavorable structure, the scarcity of any bevelled areas even when a joint surface exists at the most favorable elevation suggests that it may be too impermeable for rapid crystallization. As the Weymouth basalt, which absorbed only 0.816 percent water, is bevelled into level surfaces, it appears that the dividing line between permeabilities conducive to rapid salt crystallization and permeabilities not favorable for rapid operation of the process lies between 0.259 percent and 0.816 percent absorption over a 70 hour period. Dolerite had an absorption value in this zone, at 0.344 percent. Dolerite often shows pronounced pitting and may lie near the permeability borderline in many locations.

Short term water absorption may also be significant in determining the efficiency of the salt crystallization process. If the rock can gain large quantities of water rapidly for subsequent quick evaporation, the number of wetting and drying cycles could be increased on a warm, wave splashed surface. Rapid gains in moisture were shown in the first minute of immersion by all the samples, with sandstone and Don Heads basalt
Figure 21

RESULTS OF WATER ABSORPTION EXPERIMENT
taking on the most water. Weymouth basalt and granite were grouped together with lower percentages of intake, and dolerite remained almost unaffected. After one minute, the rates on all the samples slowed down in varying degrees. At five minutes, Don Heads basalt was absorbing only slightly less rapidly than during the first minute, the sandstone rate had fallen off considerably, and the other three samples were absorbing minute quantities of water. However, by this time the dolerite had caught up with the granite and Weymouth basalt in percentage water content.

After 10 hours, the Don Heads basalt rate had levelled off abruptly, the sandstone rate was falling off slowly and the other three samples were still gradually gaining water. During this period, the dolerite block showed a loss of 0.0092 gm. at one point which may have been the result of removal of weathered clays in cracks. The rapid rise of the Don Heads basalt rate and the subsequent early levelling off may reflect the characteristics of the pores in the rock. The vesicles are apparently interconnected and of about the same size. Thus, water moves rapidly through the rock by capillarity, but finds few smaller channels to enter at a slower rate. In contrast, the pores in the sandstone are probably of widely varying sizes, allowing water to enter over a long period at a gradually decreasing rate. The slower rates of the other samples
indicate smaller pores, poorer interconnections or both.

The data from these tests show that rocks which soaked up the most water at the greatest rate (Don Heads basalt and Permian sandstone) are those which support the best developed horizontal shore platforms. A more sophisticated approach using a greater number of samples obtained at various depths in the rock and studying the relative importance of true permeability and water movement in cracks would provide a more precise insight into the mechanisms of shore platform development. More quantitative data will add knowledge about details of the mechanism, but the present tests indicate that a relationship exists between platform horizontality and rock permeability.

Existence of Saturation Base Level

The second condition for salt crystallization levelling is the existence of a saturation base level in the bedrock. Without elaborate drilling and measuring equipment, it is difficult to obtain enough data to prove the presence of a water table within the rocks forming the platform. However, a few experiments performed on the Permian sandstones comprising a bevelled platform at Blackman's Bay, Tasmania, served to indicate that there is a strong probability that a saturation level exists. A hole was bored into the surface of the platform at about the level of mean higher high water, some 20 feet from the nearest
platform edge. Using a star drill and a sledge hammer, a depth of about 6 inches was attained. The material brought up seemed damp and was definitely salty to the taste. A rather naive hope that water would fill the hole through seepage from the surrounding rock was not fulfilled and the experiment yielded only the subjective impression that the rock appeared wet and contained salt.

A slightly more scientific investigation was then carried out in an attempt to gain definite information. A large rock sample was broken by sledge hammer from the edge of the platform at about the level of mean higher high water. The sample was immediately enclosed in a plastic bag and rushed to the laboratory where it was smashed and a small piece obtained from its center. The small piece was quickly weighed on a sensitive balance and then dried in an oven. The same sample was then immersed in sea water for several hours and weighed again. At first, moisture was visible on the rock surface and the total weight was 0.008 gm. more than when the piece was removed from the interior of the block. However, within two minutes the visible moisture had disappeared and the weight was identical with the original value before drying (2.252 gm.). Subsequently the sample lost weight at a decreased rate and took 6 minutes to lose 0.005 gm. This evidence seems to indicate that the original sample was saturated with moisture, even though water
was not dripping from its surface.  Proof of saturation of rock and the level of the water table will have to await more advanced techniques, but the results of simple experiments combined with striking occurrences of horizontality in the field lead to the conclusion that the rock is saturated and that the water table is often horizontal.

**Rapidity of Action**

Like the characteristics of rock saturation, the rapidity of salt crystallization weathering in the natural environment is not easy to prove. Hodgkin (1964) measured a rate of lowering and notching of limestone surfaces of 1 mm per year. Salt crystallization may have played a part in this erosion, but solution and biological factors may have also been prominent. Pedro (1957) in his previously mentioned experiments found that the granites and basalts lost 0.52% and 1.00% of their weights over the four month test period, which would probably represent the most favorable rate in the natural environment. Blackwelder, Pedro and Wellman and Wilson all believed that where salt crystallization was operative, it was the most active factor in rock breakdown. If this is the case, measurements of pitting on rock structures of known dates of emplacement may give some indication of the potential of salt crystallization as a weathering force.
Field Evidence of Weathering Rate

An old bridge abutment at St. Helens, Tasmania shows evidence for very rapid rock disintegration in the peritidal environment (Photo 40). The abutment is located in the western end of George Bay, flanking the Golden Fleece Rivulet. Exact date of construction is not known, but study of old maps indicates that the bridge was completed between 1860 and 1870. The large Triassic sandstone blocks of the abutment have been severely pitted, especially in the zone between the mean higher high water mark and the top of the abutment about three feet above this level. In addition to the pitting, many of the joints between the blocks have been widened considerably.

Differences in structure and composition of the various blocks may account for some of the variations in pitting, but overall patterns emerge which seem significant. In general, the blocks below the level of mean higher high water in this very low wave energy environment are the best preserved. Although some pitting is present, the blocks still retain fairly sharp, rectangular outlines. Blocks above MHHW are exceedingly altered from their original condition and show two distinct pitting morphologies. Most common are the small pits, about one inch in diameter and 3/4 inch deep. Many periwinkles, \textit{Bembicium nanum} and \textit{Melarapha unifasciata} occupy these depressions.
A few very large pits also occur in the blocks. These may be as much as 9 inches deep and 15 inches in diameter, cutting across two adjacent blocks (Photo 41).

Because of the obvious inhomogeneity of the material, it is not possible to determine the exact levels of greatest weathering activity. However, it is apparent that most alteration of the blocks has occurred above the level of mean higher high water. If another process besides salt crystallization were the cause of the weathering, the blocks in the lower portion of the abutment should be as weathered as those above, which is not the case. It seems likely, therefore, that a considerable amount of the weathering in the upper blocks is due to salt crystallization. This massive breakdown of material, causing pits 15 inches in diameter in 100 years has occurred under artificial conditions. The sandstone blocks are probably more susceptible to weathering that in situ rocks due to disturbance through quarrying. Even if this example does not strictly represent the attainable weathering rate on shore platforms, it still indicates the rapidity with which peritidal weathering forces probably lead by salt crystallization, can operate under ideal conditions.
Photograph 40

Pitting in Bridge Abutment, St. Helens. Mean higher high water mark is about two feet above the sand surface.

Photograph 41

Detail of Bridge Abutment Pitting.
CHEMICAL WEATHERING

Chemical weathering of rock is a very diverse problem which has attracted considerable attention. Although much of the literature is concerned with soil development, many of the processes can also be applied to the shore platform environment. For instance, the characteristics of parent material are of basic importance in both shore platform production and soil formation. Bayliss (1964) stated that three properties of the parent material were significant:

1. Porosity and permeability, which determines how much fluid can enter and flow through a rock.
2. The surface area exposed to the permeating fluid.
3. The mineral structure, including
   a. bonding energy
   b. solubility
   c. electrostatic stability
   d. steric hindrance

These properties determine the relative rapidity of weathering, as well as which types of chemical activity will be most significant. A parent material having low porosity and permeability, and small exposed surface area, composed of minerals having high bonding energy, low solubility, high electrostatic stability and showing steric hindrance would weather very slowly.
Materials possessing opposite characteristics would conversely weather quite rapidly.

**Stability Series**

Minerals have known degrees of susceptibility to chemical weathering, based on their structure and chemical composition. Goldich (1938) arranged common minerals into a stability series with the least stable on the top and the most stable at the bottom of the list.

Olivine

---------- Calcic plagioclase
Augite

---------- Calcic alkaline plagioclase
Hornblende ------- Alkalic-calcic plagioclase
---------- Alkalic plagioclase
Biotite

Potash Feldspar

Muscovite

Quartz

This series indicates the relative resistance of minerals to chemical weathering, and indicates that a rock composed entirely of quartz cemented with silica would be quite stable. However, it does not necessarily follow that simply because a rock is composed of stable minerals it will be resistant. As Sparks (1960) points out, factors such as texture and structure of the rock, the nature of the weathering process, and the available time control the total susceptibility of rocks to weathering.
In the shore platform environment, the chemical activities leading to the weathering of bedrock can be placed in four major groupings: solution, hydration and hydrolysis, oxidation-reduction, and exchange reactions. These groupings are not always mutually exclusive; solution often involves exchange reactions and hydration and is also dependent on prevailing oxidizing and reducing conditions. However, the groupings serve to emphasize basic types of chemical activities.

**Solution**

Solution is one obvious way in which the parent material may be altered. The often quoted results of Joly (1901) indicate that the process may affect a variety of rocks in a coastal environment. Guilcher (1958) stated that Joly found basalt, obsidian, hornblende and orthoclase to be 3-14 times more soluble in salt water than in fresh water.

Solution in the coastal environment is enhanced by the nature of salt water itself. The dissolved salts in sea water promote rock solution because they are very active chemically. The slightly alkaline (pH 7.6) sea waters react strongly with feldspars according to Carroll and Starkey (1960). In addition, Keller and Reesman (1963) reported that dissolved Na and K enhance the solubility of silica.

Although solution may be quite effective, it does not appear
to be the dominant force in the formation of Tasmanian platforms. Because the base level of solution is considerably lower than high tide, it would be difficult to account for the extreme horizontality exhibited on some of the features by this method. Solution with its low base level, is probably active as a platform destroying force in Tasmania, but it apparently works slowly enough that widespread reduction has not yet occurred. Although solution may degrade platforms, its most significant role is as a part of the process which originally produced the platform, possibly in the enlargement of pores for subsequent salt crystallization.

**Hydration and Hydrolysis**

Hydration and hydrolysis are two other means, both dependent on the presence of water, by which rock may be weathered. Hydration is the adsorption of water by mineral constituents and hydrolysis is a process in which a compound reacts with water in such a way as to disturb the normal concentration of the $\text{H}_3\text{O}$ and $\text{OH}$ ions formed through autoionization of the solvent (Hopkins and Bailar, 1956). These factors are important in the breakdown of sedimentary and igneous rocks alike. All clay minerals are able to adsorb large amounts of water between their structural layers, resulting in an increase in volume. Minerals in intrusive igneous rocks show marked increases in volume as they were formed at higher pressures and tend to be converted to lower
density minerals by hydration. In addition, expansion of the
crystal lattices may lead to the fracture of the crystals them­
selves.

Hydrolysis is significant as a weathering agent mainly
through its alteration of the feldspars to clay minerals, usually
kaolin. Hydrolysis is one of the processes by which solution is
accomplished and, in the case of kaolinization of feldspars, may
result in the complete decomposition of the solute. Not all
minerals are as susceptible to hydrolysis as the feldspars, and
some reactions may be only partial and reversible. Because
hydration and hydrolysis have an indefinite base level, they would
probably not in themselves produce horizontal shore platforms.
However, the two agents would greatly weaken the rock mechanically
and would increase permeability for subsequent salt crystallization
or redox reactions.

**Oxidation-Reduction Reactions**

Oxidation-reduction reactions, involving the transfer of
electrons from one atom or ion to another, are considered to be an
important factor in rock weathering. Loughnan (1962) stated that
the redox potentials of the environments encountered in weather­
ing are controlled for the most part by the presence or absence of
organic matter and the accessibility of atmospheric oxygen.
Organic matter, readily oxidized to carbon dioxide, is a strong
reducing agent and atmospheric oxygen is the principal oxidizing agent. Loughnan wrote that the depth of penetration of atmospheric oxygen in weathered profiles is generally a function of the water table. It is possible, therefore, that oxidation could be a direct factor in platform production, as well as operating indirectly by weakening rock structure for subsequent salt crystallization. Reduction, through organically derived carbon dioxide, probably acts in this indirect fashion. That oxidation-reduction reactions occur in the coastal environment is shown in a thin section of basalt taken from the northern coast of Tasmania. Iron minerals in the basalt have been heavily oxidized into ferric forms.

**Exchange Reactions**

Exchange reactions can also lead to the disintegration of previously solid bedrock. These reactions are those in which ions actually forming the minerals exchange with ions in the immediate surroundings. Exchange reactions depend upon the availability of exchangeable ions and the free bonding energy of the ions for operation of the process. The abundance of dissolved salts in sea water promotes the reactions, but sodium does not play the major role which might be expected. Carroll and Starkey found that for clays the bonding energy is in the order:

\[ \text{Ca Mg K H Na} \]
Even though availability of Na is much greater than Ca and Mg, the latter two ions will preferentially enter the exchange positions. The result of exchange reactions is the gradual replacement of the mineral surfaces with new material, leading to a weakening of the mineral structure. Exchange reactions occur in saturated rock conditions and probably have little to do with the production of horizontality on shore platforms.

**Base Levels of Processes**

From this discussion of weathering, it emerges that only two agents are limited in their activity by saturation level. All the rest are active in saturated conditions, and some are more active here than elsewhere. Of the two agents limited by saturation, salt crystallization and oxidation utilizing atmospheric oxygen, salt crystallization is probably dominant in the production of platform horizontality. Oxidation often enlarges interstices for subsequent salt crystallization, but it may also result in re-cementing with resistant substances such as limonite. The deep weathering capabilities of solution, hydration and hydrolysis, oxidation and reduction (with or without oxygen), and exchange reactions probably prepare the bedrock for subsequent surficial removal. The weathering starts in the joint and bedding planes and, given time, weakens the entire fabric to the point where the rock is relatively friable and quite permeable. In the shore platform environment, salt crystallization through wetting and
drying can then rapidly complete the weathering process which had been slowly operating over a long period. If wave energy is low, a horizontal platform results, bevelling any structure present. With higher wave energy, salt crystallization functions to loosen material for mass removal by quarrying, leaving a less uniform surface, but one which is still basically at the saturation level.

MECHANICAL WEATHERING

Mechanical weathering, the traditional companion of chemical weathering, does not show great diversity of form on Tasmanian shore platforms. As in other environments, the mechanical weathering forms which do exist are principally the final result of chemical activity and represent an interplay of forces rather than independent mechanisms. Of the main classic mechanical weathering types; frost wedging, temperature change, unloading and biotic breakdown, only the last three would be possible in the Tasmanian coastal environment. As mentioned previously, frost wedging is not now significant because the lowest recorded temperatures at all coastal stations are only slightly below the freezing point of sea water and entire years pass in many areas with temperatures constantly above 32°F.

Temperature Change Phenomena

Conditions on shore platforms would be suitable for mechanical weathering by temperature change phenomena (expansion and
contraction), if this activity really exists. Blackwelder (1925, 1933) performed experiments in California on basalts and granites which he subjected to rapid temperature changes of 195°C without noticeable effect on the rock. He concluded that sheet exfoliation was not brought about by this means, although some individual grains might be loosened. It is difficult to say with certainty that expansion and contraction does not operate on shore platforms, but its influence is probably slight.

Unloading

Unloading offers better possibilities for weathering on shore platforms. Hale (1961) reported extensive curved joints roughly parallel to the unloaded surface in Tasmanian dolerite and Matthes (1937) ascribed the exfoliation of granites in California to expansion of material upon pressure release. However, Blackwelder (1954) does not agree as he stated, "In the incipient stages of hydration the slight expansion of the exposed part of an outcrop or boulder tends to cause the separation of one or more shells from the interior of the rock, a process often called exfoliation." Longwell and Flint (1962) also take the view that exfoliation is due to the development of clay minerals beneath the rock surface and as such is a mechanical effect of chemical weathering. Even if unloading is not a direct cause of weathering on the platform through exfoliation, the process would still be significant in expanding joints for the passage of
solutions by which chemical weathering could take place.

BIOTIC ACTIVITY

Biotic activity is very significant in both the development and degradation of shore platforms in Tasmania. A part of this activity is mechanical, some is chemical and a large proportion contains elements of both. The mechanical factors include scraping, boring, plucking, and wedging while chemical action is largely in the form of solution. Barrows (1917) early recognized the importance of worms, pholads, chitons, limpets and sea urchins as agents of erosion. Other members of the biotic community which aid in the breakdown of rock are algae, lichen, periwinkles and various molluscs.

Boring and Abrasion

Pholads, limpets, sea urchins, periwinkles and possibly chitons accomplish erosion by direct abrasion. Emery (1960) reported that this activity is not restricted to soft sediments, but occurs also in gneiss, andesite and chert. The actual boring takes place by movement of some part of the animal against the bedrock. Pholads (close relatives to the *Teredo navalis* which devoured the wooden walls of the English Navy) bore by rocking, or rotating the anterior portions of their shells against the rock according to Ricketts and Calvin (1962). Ricketts and Calvin stated that a rock clam found in California "drills into
rock so hard that nothing short of a sledge hammer powerfully swung will break into the burrows, and it apparently drills without the aid of chemicals, using mechanical means only."

Chitons and limpets probably also abrade directly, but chemical action may play a part. Yonge (1949) noted that limpets rock their shells back and forth to excavate an elliptical shelter on exposed surfaces, while Mollison (University of Tasmania, personal communication) believes that chitons may enlarge their dwellings by movement of a girdle equipped with hard spicules. The hemispherical hollows created by sea urchins are fairly common and probably also result from the direct abrasive action of spines and teeth. (Dakin, 1966). Periwinkles do not actually bore into the rock, but, as shown by North (1954), continually plane the surface of the material in their search for algal food. The periwinkles are equipped with rasp-like 'teeth' which are capable of scraping loose considerable quantities of rock. (Possibly already weakened by some other process of weathering). North estimated that the concentration of periwinkles found on the sandstone near La Jolla, California, could account for about 1 foot of erosion in 1200 years. The evidence indicates that the activities of the borers and scrapers in their search for food and shelter are a major force in coastal rock breakdown.
Plucking

Another primarily mechanical, direct means of rock removal is plucking by algae undergoing wave attack. Large algae such as bull kelp (*Durvillea*) and *Macrocystis* attach themselves to bedrock by means of foot-like holdfasts. Often the bond between kelp and rock is stronger than the rock itself, particularly in well jointed formations. As a result, large waves in shallow water may drag kelp, holdfast and attached pieces of rock bodily away and leave them stranded on platforms or beaches (Photo 42).

Wedging

Wedging by organisms colonizing rock crevices is yet another possible means of promoting erosion. This activity may be important in the separation of well jointed blocks under wave attack on the exposed edges of platforms. Kensler and Crisp (1965) found rapid, prolific and diverse (some 132 species) colonization of artificial crevices. The biological activity quickly resulted in a collection of organic remains in the bottoms of the cracks. It is possible that this material tends to settle and compact into joints which open infinitesimally under each wave impact, preventing the rock from returning to its former position. In addition, the collective pressure of myriads of growing, hard-shelled organisms may in itself exert a force. (Photo 43).
Photograph 42

Rock Plucked by *Durvillea*. The kelp and attached rock were swept onto the surface of the Waffle Iron Platform during a storm. The holdfast is starting to dry out and is separating from the rock surface.

Photograph 43

Colonization of Cracks. Barnacles and limpets are inhabiting the opened joints.
Biochemical Action

It is difficult to determine the factors involved in chemical weathering of shore platforms through organic action. Direct solution is one possibility, as Yonge mentioned worms which produced acid to facilitate boring into limestone in Britain. Ricketts and Calvin also described the date mussel which is capable of excavating a home for itself in limestone with acid. (The calcareous shell is kept from dissolving by a thick brown layer of horny material). Many gastropods secrete mucus onto their exteriors, possibly to aid in attachment to the rock. The mucus contains enzymes which could accelerate chemical reactions on the rock surface. Ricketts and Calvin attested to the potency of these enzymes after observing the complete digestion of a fair-sized piece of chiton in 15 minutes by a sea anemone.

Biochemical activity may also be indirectly responsible for solution in tidal or peri-tidal zones. Emery (1946) determined that the pH was lower in "solution basins" at night than in the daytime. Emery explained that these variations are brought about by the presence or absence of photosynthetic activity in plants inhabiting tidal pools (Photo 44). In the daytime, CO$_2$ liberated by animals in the pool community is removed by the plants, but at night the CO$_2$ accumulates, lowering the pH. This considerable increase in alkalinity of the pool water at night
Photograph 44

Tide Pool on the Silver Gull Platform. Most common residents are the snails *Austrocochlea constricta* and *Bembicium nanum* and the limpet *Cellana solida*. Some algal species form a mat on the bottom of the pool and others take a more three-dimensional shape.

Photograph 45

Submarine Molluscs. Four abalone (*Haliotis*) can be seen in the crevice while a fifth is feeding on the exposed rock surface. Enzymes secreted by these gastropods may cause biochemical erosion of the bedrock.
favors solution, not only in limestones or calcium cemented rocks, but also in basalt. Emery estimated that the rate of deepening of "solution basins" in the sandstones of La Jolla, California was about 1 foot in 1000 years.

**Algal Activity**

Plants, too, aid in the chemical weathering process. Twenhofel (1961) stated, "Algae, lichens and mosses play some role in rock decomposition, but here quantitative data are scanty." He related that some algae were known to bore into rocks and that the ashes of lichen contained substances derived from the bedrock. Twenhofel was apparently unfamiliar with the work of Fry who conducted a series of experiments to discover how lichen (composite plants composed of algae and fungi) accomplished rock breakdown. In 1922, she determined that endolithic lichen bore into limestone by chemical action, using CO₂ derived from respiration combined with atmospheric water to yield carbonic acid.

Fry later found that chemical action was only a part of the erosive capabilities of lichen and that mechanical processes were also important. In 1924, Fry succeeded in tearing up the surface of a glass plate mechanically by drying a coating of gelatine which had been placed on the glass. Shale was also affected in this manner and, since lichens have a large proportion of gelatinous substance and periodically undergo drying in the sun, Fry believed that this action could take place in nature. Fry extended her
research into other rock types in 1927 and showed that lichens could cause rock breakdown in shale, schist, gneiss, limestone and even obsidian. She concluded that the process was brought about chiefly by gelatin-drying in three dimensions: radially inwards toward the center of the lichen and upwards, resulting in an arched form in the thallus. Chemical activity probably also contributed to the process. This phenomenon was repetitious and thin sections of lichen showed arched layers of rock within the thallus.

Although Fry did not extend her research into intertidal algal forms, they too may cause rock disintegration. These algae are quite gelatinous and could undergo considerable desiccation in a shore platform environment. Brown algae, ranging in size from microscopic forms to bull kelp, are very common in the intertidal zone and might be an important factor in rock breakdown. The rock-eating snails reported by North may merely be scraping up algae containing rock fragments previously loosened by gelatine drying or carbonic acid solution.

INFLUENCE OF PROCESSES

Mechanical, biological and biochemical weathering join chemical weathering in having a dual influence on shore platforms. In the early stages of platform development, these factors combine with salt crystallization to rapidly lower the rock surface
to the saturation base. As this elevation is approached, salt crystallization becomes less and less active until it almost ceases entirely. However, with a few exceptions due to biological zonation, all the other processes are still vigorous and thus become platform degrading forces. Biological zonation may account for the altitudinal phasing out of some biotic factors (lichen, for instance), but most of the other weathering agents are still above their base levels when saturation cuts off salt crystallization. Without the overall control of horizontality which salt crystallization provides, the processes which cooperated to make water-layer weathering a rapid and effective platform bevelling agency begin a slow, random degradation of the surface. Platforms which show extreme horizontality are probably fairly young features which have not yet succumbed to the host of vitiating forces.
Chapter 17

FORMATION OF THE TESSELLATED PAVEMENT:
AN EXAMPLE OF INTERACTING DEVELOPMENTAL FACTORS

Descriptions of Tasmanian shore platforms in previous chapters mentioned a number of passive, active and environmental factors, partly as a background for subsequent examination of formational mechanisms. Assumptions were made concerning the manner in which the platforms reached their present state of development, but these remarks received no particular emphasis. In this chapter the formation of a platform will be analyzed in detail to summarize the discussion of factors important to the development of shore platforms in Tasmania.

Many Tasmanian shore platforms contain examples of the various developmental factors involved. However, the formational processes are most clearly exhibited on a feature called the Tessellated Pavement near Eaglehawk Neck. Furthest south of the group of platforms which comprise the northern shore of Pirate's Bay, the Tessellated Pavement is located between the sand beach at Eaglehawk Neck and the Silver Gull platform. The officially recognized name, Tessellated Pavement, refers to the surface of very regularly jointed blocks which have the appearance of an artificial mosaic.
Figure 22

TESSELLATED PAVEMENT PROFILE AND SURFACE DETAILS
DESCRIPTION OF PLATFORM

The tessellated surface of the platform extends for a distance of about 500 feet along the coast and has an average width of approximately 70 feet. This surface is not continuous, as it is broken into two parts by a deep joint channel. Elevation of this extensive platform is generally within a few inches of 2.3 feet above mean sea level. As the range of the mixed, predominantly semidiurnal tide is 2.6 feet between mean higher high water and mean lower low water, the platform lies close to one foot above mean higher high water over most of its area. The landward boundary of the Tessellated Pavement is often formed by a stepped bedrock slope leading to another platform at an elevation of a little over 7 feet msl. This platform usually passes beneath a cover of soil and vegetation some 10 or 15 feet from its seaward edge. Most of the slope which rises from this point is heavily vegetated alluvial material, but some rock outcrops are visible above the southern parts of the platform.

Seaward, the Tessellated Pavement is fronted by another extensive surface at about the elevation of mean sea level. This surface drops in turn to other platforms which occur at depths decreasing in approximately 5 foot steps until a sand surface at about -40 feet msl is encountered 900 feet offshore.
FORMATIONAL FACTORS

Detailed examination of the surface of the Tessellated Pavement yields a number of clues to the processes involved in formation of the platform. It is immediately apparent that the rock characteristics exert considerable influence. In many cases the top of the bed in which the platform is best developed can still be traced, even though weathering has altered the surface. The rock is thinly bedded Permian sandstone which strikes N 40° W (140°) and has a dip of 2° at S 50° W (230°). Most of the beds average about 18 inches in thickness, although the bed which forms the bevelled platform surface is 27 inches thick. The jointing is markedly rectangular, generally outlining squares about 18 inches on each side (Photo 46).

Thinly bedded, well jointed rocks favor hydraulic action, and such activity is very prominent on the Tessellated Pavement. Waves up to 8 feet in height probably occur once every five years and phenomenal southeasterly gales might increase this height to about 12 feet once in a 100 year period. The presence of Macrocytis offshore probably prevents the waves from reaching greater heights on the platform. Wave action has completely loosened a number of blocks on the seaward edge of the Tessellated Pavement. Southeasterly waves sweeping obliquely across the platform will eventually move these blocks to the north of the platform into an already crowded storage area.
Varying Joint Separations

The northern end of the Tessellated Pavement shows evidence of a sequence in the quarrying of blocks, in the form of varying joint separations. Widest separations are shown by the blocks on the present seaward edge of the platform. Gaps of up to 3 inches between blocks occur, but the average distances are from \( \frac{1}{2} \) inch to \( 1\frac{1}{2} \) inches. A major joint cutting the platform parallel to, and about 10 feet from, the seaward edge marks the landward limit of this zone of very disturbed blocks. Moderately disturbed blocks having separations of about \( \frac{3}{8} \) inch lie in a band between the joint bounding the very disturbed blocks and another major joint about 20 feet from the seaward edge. A third area, of slightly disturbed blocks, extends from this joint to the landward limit of the platform. Block separation in the 20-foot-wide third zone averages about \( \frac{1}{8} \) inch.

The gaps between the blocks are probably formed by a number of interacting phenomena including pressure release in the rock, hydraulic action, and biotic activity. As one edge of the tightly packed bed is displaced, there is a possibility that tension will be eased in the rock through slight movement of the joint blocks. If the major joints were not present in the platform surface, a continuous sequence of gap spacing might occur. The present three part division is probably due to some readjustment of tension taking place in the major joints themselves.
Photograph 46

Tessellated Pavement.

Photograph 47

Surface in Area of Slightly Disturbed Blocks.
Widening of the joints will favor entry of water for subsequent water hammer and hydrostatic action which pushes the blocks still further apart. As the gap widens, plant and animal forms colonize the cracks, forming a wedge with their remains which tends to encourage further expansion through wave shock. All during this process, water will be draining from the platform surface through the top portions of the cracks, enhancing erosion by water and sand abrasion.

Weathering

The variations in joint spacing have also influenced sub-aerial weathering on the Tessellated Pavement. Weathering has bevelled the inner portion of the platform in the zone of slightly disturbed blocks, but has had only minor effect on the seaward rocks. The platform surface shows distinct differences in the three zones. The inner zone is comprised of flat-topped blocks with level centers and raised rims averaging about 3/4 inch in height (Photo 47). Water frequently lies in these basins between tides. Except for the raised ridges, the surface of the inner zone is horizontal.

The middle zone, with moderately disturbed blocks, also contains rims flanking the joints. However, the centers of the blocks are higher than the rims, and probably represent the original sloping bed surface (Photo 48). Between the rims and the high centers is a flat area usually about one inch wide
which is at the same elevation as the center portions of the blocks in the inner zone. The very disturbed blocks in the seaward area lack the rims and small flats of the middle zone and show only a rounded transition between block top and joint (Photo 49). Occasionally, however, the blocks are cut by a small joint which is flanked by the rim and flat characteristics of the moderately disturbed blocks (Photo 50).

**Operation of the Water-Layer Weathering Process**

Examination of block morphology on the Tessellated Pavement may give an insight into the operation of the water-layer weathering process. The inner portion of the platform, with raised rims and flat centers, represents the best developed area of water-layer weathering. It is difficult to postulate any other activity which would produce this particular morphology. Rock abrasion would not selectively lower the block centers and leave the edges untouched. Sand scour is another possibility, but the end of the Tessellated Pavement which is periodically buried by sand from a beach to the south shows grooved, depressed joints quite dissimilar in form to the raised rim, flat center shapes being examined (Photo 51). Solution in limestone sometimes forms this configuration, but the sandstones of the Tessellated Pavement contain very little calcium carbonate. An attribute which these sandstones do have, however, is high
Photograph 48

Surface in Area of Moderately Disturbed Blocks.

Photograph 49

Surface in Area of Very Disturbed Blocks.
permeability - a characteristic which encourages water-layer weathering.

If, then, the shaping was accomplished by a weathering process, the raised rims have undergone less weathering than the centers of the blocks. One obvious control over water-layer weathering is the number of wet-dry cycles possible - if the rock is either continuously wet or constantly dry, little water-layer weathering could be expected. An increase in the cycling rate enhances weathering until a point is reached where evaporation can no longer cope adequately with the influx of water and weathering slows. The raised rims may be more continuously moist than the other portions of the block and consequently undergo less weathering.

Moisture for the rims may be constantly supplied by capillary movement of water upward in the narrow joint. The supply of water in the joints would usually be renewed twice daily by the combined action of waves and tides. Persistent water movement in the joint would not only protect the rim but could furnish one of the means by which the block centers are removed. A thick layer of salt crystals can sometimes be seen in a band at the foot of the raised rim. This band of crystals may be the result of evaporation of the water which is continuously traveling up the joint. Solar heating in the morning and early afternoon encourages evaporation on the Tessellated Pavement,
Influence of Joint Gap over Block Morphology. Where the gap is wide, the block edges are rounded and the center is raised. Along the narrow joint cutting across the block, a raised rim has developed.

Erosion Forms Produced by Sand Scour. This portion of the Tessellated Pavement is periodically covered by sand from the beach to the south. Sand, propelled by wave action, has apparently caused these grooves along the joints.
even though the area is shaded by trees and high ground later in the day. Salt crystallization could be very effective in the saline zone at the foot of the rim. Evidence for the efficiency of weathering in this portion of the block is the undercutting of the remnant centers of blocks on the incompletely developed part of the platform.

The importance of water movement in joints is shown by the morphologies of the most seaward of the blocks comprising the Tessellated Pavement. As noted earlier, these blocks have intervening gaps of $\frac{1}{2}$ to $1\frac{1}{2}$ inches and possess very few flats and raised rims. None at all occur on the outer boundaries of the blocks where the profile includes a rounded transition from the top of the block to the vertical joint surface. The only place where the rim-flat combination can be seen is along a few transverse joints which have suffered little widening.

Horizontal cutting from the joints toward the center of the blocks is important in the formation of the level pans, but it is not the only mechanism taking place. Many of the remnant centers of the blocks are extensively pitted on their upper surfaces. The pitting is probably also a salt crystallization phenomenon, with action possibly enhanced by biological forces. A great number of the pits are inhabited by the periwinkle, _Melarapha unifasciata_ which may remove some rock material in their grazing activities. It is difficult to determine whether
the vertical or horizontal cutting is most effective in production of the level surface, but the combination of the two mechanisms constitutes a potent erosive force.

**STEPS IN PAST DEVELOPMENT**

The present Tessellated Pavement platform was developed by weathering and hydraulic action operating on responsive rocks in an environment which included favorable wave and tidal action and adequate evaporation. Using these factors and the present morphology, an attempt can be made to reconstruct the earlier profile and outline the major steps in the development of the present platform. It seems likely that at least part of the present Tessellated Pavement lay under the 7 foot msl bench which is still visible at the rear of the platform. This bench is not now being formed, as indicated by the heavy lichen cover and the mantle of soil and vegetation at the landward edge. There is no way to determine when the 7 foot bench itself was created, although it might have been during a previous interglacial high stand of the sea. In the time since its formation the 7 foot bench was probably covered by the alluvial fan material which backs many of the platforms in this region, much of which has now been removed.

**Wave Stripping**

Stripping of the overlying material and then the bench
itself started taking place when the sea neared its present level, several thousand years ago. The beds comprising the upper bench may have been stripped to the present Tessellated Pavement surface because of weakening of joints and bedding brought about by sub-aerial weathering and pressure release. The fresh surfaces and stepped shape of the leading edge of the bench suggest that weathering and hydraulic action are presently removing material in this area. A previous surface, possibly represented by the portion of the pavement which now has the most disturbed blocks, may have already existed at this level. If such a surface did exist, continued stripping at the same elevation would be favored. Pre-existence of at least a portion of the Tessellated Pavement is probable, as the exposure of the entire present surface would have entailed the removal of a tremendous mass of rock.

Waves may have accomplished the stripping of the upper bench in bursts spaced at wide intervals. The rear of the 7-foot bench is presently covered by a mantle of soil and vegetation which would be very vulnerable to attack by waves large enough to remove blocks from the leading edge of the bench. If massive storm waves struck the platform at intervals on the order of 100 years, quarrying could occur and alluvium could then slide over the platform in the interim.

A wave having an unbroken height of 12 feet just off the
platform might be possible in this location every 100 years. Such a wave could reach the top of the 7-foot bench, even though the crest would only be about 6 feet above the mean water level. Three factors would be involved: high tide, a rise in sea level due to decrease in atmospheric pressure (about 1 foot per inch of barometric depression), and the tendency for the wave form to shift upward as it breaks. Wind action might also raise the sea level, but the influence would be slight on this open coast. Given a high tide and an additional one foot sea level rise due to low atmospheric pressures, the still water level would be slightly above the Tessellated Pavement, only five feet below the upper bench surface. Masses of water should then be able to attain the top of the bench even though the wave had taken a translational form and travelled several hundred feet over shallow submarine platforms.

Weathering

As the overlying beds were stripped away, salt crystallization and other agencies involved in water-layer weathering quickly modified the exposed blocks to their present raised rim, depressed center morphologies. The slightly dipping surface was bevelled into its present horizontal configuration in the process. Seaward portions of the platform, even though exposed to weathering for a longer period, show less horizontal development. The slower weathering rate is probably caused by wider
joint openings between the blocks, although more continuous wetting by wave splash may be important on the leading edge of the platform.

FUTURE DEVELOPMENT

If sea level remains constant, the width of the sub-aerial Tessellated Pavement will probably decrease. Many blocks are loose and are only awaiting transportation from the seaward edge of the pavement, but erosion of the beds covering the rear of the platform appears much slower. This difference in rates may have already considerably reduced the width of the platform, as the exposed surface of the bed seaward of the Tessellated Pavement is extensive. Weathering will continue to modify the present moderately disturbed blocks at a decreasing rate as joints widen and seaward blocks are removed.

Long before the Tessellated Pavement loses all of its tourist potential, however, sea level will probably change. If the level rises, the present pavement would be covered by a growth of lithothamnion, kelp and other organisms and become just another submarine platform in the series. A fresh "Tessellated Pavement" would form near the new mean higher high water mark, while waves would strip the alluvial material from the rear of the 7-foot bench and might in time reach a bedrock cliff. A fall in sea level would also cause the obscuration
of the present surface, first under a cover of lichen and possibly later by alluvial material. The raised rims around the joints would gradually disappear as more random weathering forces acted on the blocks. Meanwhile, a platform at a lower elevation would be undergoing rejuvenation under the combined influence of hydraulic action and weathering, interacting again with the favorable rock structure and environment.
Chapter 18

CONCLUSION

A French proverb reads, "There is nothing new except what is forgotten." This study into the development of Tasmanian shore platforms points out the basic validity of that statement. No new, previously unmentioned processes were discovered - any which seemed original at the time were eventually unearthed somewhere in the literature. Dana (1849) mentioned the importance of sub-aerial weathering to a saturation base level in platform production. Bartram (1935) suggested the interaction of wave activity and sub-aerial weathering as an effective platform developing mechanism. Wentworth (1938) outlined the "water-level weathering" process which accomplishes much of the sub-aerial erosion on shore platforms and later, in conjunction with Hoffmeister (1940), set forth a list of almost every conceivable platform producing activity. Fairbridge (1952) attacked the supporters of the Fenneman profile of equilibrium with statements about the prevalence of the stepped profile and relative unimportance of rock abrasion as a force in coastal erosion.

Even though the processes have been mentioned previously, at least two opportunities are still present for useful work in shore platform research. One is the isolation of the details
of the processes by measurement, experimentation and underwater study; and the other is the colation of all the details into a coherent theory of shore platform production. Very few of the earlier workers related the surfaces of shore platforms to present sea levels with any more precision than "awash at high tide" and no detailed maps had ever been made. Experimentation with facets of the shore platform development problem has also been neglected. Underwater investigation of platforms, essential to the understanding of the processes involved in development, appears to have been neglected until the present study.

The previous students agreed on general processes, but differed on their application in a particular context. Wentworth thought that rock abrasion was active in the submarine zone in front of the platforms and that water level weathering was merely planing an emerged, "wave cut terrace". Bartrum felt that wave action alone could carve shore platforms in homogeneous rocks and Fairbridge wrote that high tidal platforms were indicators of a drop in sea level (he placed the base level of sub-aerial weathering at the low tide mark). The wide variation in theories indicates two things: no two shore platforms are formed in exactly the same way and a need exists for further detailed research into shore platform development. This study into the development of Tasmanian shore platforms has been an attempt to meet the need for more detailed knowledge
of formational processes through measurement, experimentation and underwater investigation.

FACTORS INVOLVED IN TASMANIAN SHORE PLATFORM DEVELOPMENT

Tasmanian shore platforms have been developed in response to a number of interacting passive and active factors. Passive factors are inherent in the rocks from which the platform is carved and active factors are forces such as weathering and hydraulic action which produce the platform morphology. Other important active factors are environmental considerations, including climate, tidal regime and wave characteristics, which control the platform producing forces.

Characteristics of Bedrock

Rock structure, texture and chemical composition exert a major influence over platform morphology. When horizontal or nearly horizontal jointing or bedding is present, horizontal platforms will generally develop. If jointing or bedding is steeply inclined, sloping platforms often occur. Horizontal platforms may be produced in dipping rocks if the beds are broken into small blocks by closely spaced joints or if the rock is particularly susceptible to sub-aerial weathering. When beds or joints are widely spaced and the rock is resistant to weathering, any platforms produced will usually be the result of wave stripping of soil to a buried planar bedrock surface.
Texture of the rock determines the relative susceptibility to weathering processes. Rocks which are capable of absorbing large amounts of water, such as basalt and sandstone, weather rapidly to base levels established by water saturation within the rock itself. Granite and dolerite, relatively impermeable rock types, weather more slowly and irregularly.

The chemical composition of the rock controls the effectiveness of the various types of weathering. If the rock is calcareous, solution will be the most important weathering agent. In non-calcareous rocks, the chemical composition influences the type of chemical action which will be most efficient in rock breakdown.

Environment

Hydraulic action and weathering, the two major forces which carve shore platforms from bedrock in Tasmania, are completely dependent on the environment for their operation. Climate, including temperature, precipitation and wind, controls both the type and rate of platform producing activity. If the temperature is low enough, ice action becomes an important developmental factor. In Tasmania, sufficiently low temperatures do not exist for ice formation and the chief influence of temperature is over the evaporation rate which, in turn, affects wetting and drying. Precipitation also helps to determine the evaporation rate and
the number of wetting and drying cycles. The wind further controls the evaporation rate and produces the waves which provide most of the hydraulic forces.

Waves include swell, storm waves and sea breeze chop. Storm waves and swell are generally most influential in shore platform production. The amount of energy contained in the waves determines the morphology of the developing platform. In high wave energy locations, hydraulic forces act more rapidly than weathering and the platforms are often sloping. Where waves are less powerful, weathering is most effective (in suitable rock types) and horizontal profiles are produced. Limited wave action enhances weathering by constantly removing weathered material from the bedrock surface.

Tidal regime helps to establish the elevations of horizontal shore platforms in Tasmania. Platforms produced or modified by weathering often have surfaces near the level of mean higher high water. Slightly higher extensive surfaces sometimes occur in fine grained rocks or rocks exposed to fairly high wave action. Differences in Tasmanian tidal ranges (from 2.6 feet between MHHW and MLW in the south to 9.1 feet in the north) are apparently not great enough to appreciably alter the relationship between level of platform and height of MHHW.
RELATIONSHIP OF HORIZONTAL, HIGH TIDAL
PLATFORM ELEVATIONS TO LEVEL OF MEAN
HIGHER HIGH WATER

<table>
<thead>
<tr>
<th>Platform</th>
<th>Elevational Difference</th>
<th>Tidal Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waffle Iron</td>
<td>1.0 foot above MHHW</td>
<td>2.6 feet</td>
</tr>
<tr>
<td>Tessellated Pavement</td>
<td>1.0 foot above MHHW</td>
<td>2.6 feet</td>
</tr>
<tr>
<td>Nuroo Island</td>
<td>0.7 foot above MHHW</td>
<td>2.6 feet</td>
</tr>
<tr>
<td>Silver Gull</td>
<td>0.6 foot above MHHW</td>
<td>2.6 feet</td>
</tr>
<tr>
<td>Kangaroo Bluff</td>
<td>0.1 foot above MHHW</td>
<td>3.0 feet</td>
</tr>
<tr>
<td>Don Heads</td>
<td>0.1 foot above MHHW</td>
<td>9.1 feet</td>
</tr>
<tr>
<td>Weymouth (Lower Surface)</td>
<td>1.0 foot below MHHW</td>
<td>8.6 feet</td>
</tr>
</tbody>
</table>

Hydraulic Processes

Hydraulic processes important in the production of Tasmanian shore platforms are breaking wave shock, water hammer, air compression in joints, hydrostatic pressure, plucking, cavitation and various types of abrasion. Breaking wave shock, water hammer and air compression in joints are the most effective hydraulic agents on Tasmanian platforms, although the other processes may be locally important. Very few rock surfaces, sub-aerial or submarine, are presently undergoing rock abrasion in Tasmania.

Breaking wave shock, water hammer and air compression in joints all are most active in a zone slightly above the still
water level and might be expected to form horizontal platforms at this height, unaided by weathering. However, wave tank studies with erodable model cliffs suggest that, although the erosion of a homogeneous vertical cliff is greatest in this zone, the resulting form is a notch with its base considerably below the level of still water. Platform shapes exposed to breaking waves were degraded by notching into the platform surface and the backing cliff, combined with rounding of the leading edge. Hydraulically produced platforms may be instituted or extended in the zone immediately above still water level if a resistant bed occupies that position.

As hydraulic activity aids weathering through the removal of weathered material, weathering may also allow hydraulic forces to act more efficiently. Shore platforms occur in Tasmania which have been quarried to levels near the elevation of mean higher high water. Weathering in joints and along bedding planes may allow wave action to remove blocks which would otherwise remain in place under hydraulic attack alone.

Weathering

Weathering is the force which puts the finishing touches on a surface which in some instances was roughly planed by hydraulic action. The water-layer weathering process outlined by Wentworth (1938) accomplishes the production of horizontality,
often bevelling dipping beds. The present study indicates that water-layer weathering can be defined as a complex interaction of chemical, mechanical, biological and biochemical processes which produce horizontality through the rapid activity of salt crystallization to a level where wetting and drying cycles are inhibited by water saturation within the bedrock. Such horizontality is transitory, because many of the processes involved in water-layer weathering can act below a level of saturation. Before that level is reached, they combine to facilitate salt crystallization by providing interstices in which crystals may grow. After the rapid removal of material by salt crystallization to the saturation level the other processes slowly continue to lower the surface of the platform. Water-layer weathering is most effective in the zone which undergoes the most wetting and drying cycles. This zone generally extends from the level of saturation (near MHHW) upward for about one foot. In areas where weathering is relatively more active than hydraulic activity, a notch occurs in this zone. Small notches are seldom formed by hydraulic activity alone in the zone immediately above the level of mean higher high water unless beds are less resistant at this elevation.
DEVELOPMENT OF PRINCIPAL TASMANIAN SHORE PLATFORM TYPES

The main types of Tasmanian shore platforms, classified by horizontality and elevation, are: horizontal, supratidal; sloping, supratidal; horizontal, high tidal; sloping intertidal; horizontal, subtidal; and transgressive. Low tidal platforms, common in calcareous rocks, are rare in Tasmania. Horizontal, supratidal platforms are not now being developed except in the case of wave stripping above a resistant bed. Most horizontal, supratidal features are relics of former past higher sea levels which are being degraded by weathering at present. Sloping supratidal platforms, on the other hand, may now be forming as a result of high energy wave attack on rocks with oblique jointing or bedding planes.

**Horizontal, High Tidal Platforms**

Most horizontal, high tidal platforms are presently in equilibrium with the level mean higher high water, amount of wave splash and permeability of the rock, all of which combine to control the saturation level in the platform. These platforms have been produced by water-layer weathering, chiefly through the activity of salt crystallization to the level of saturation. The horizontal high tidal platforms correspond to features reported by Bartrum (1924), Jutson (1931) Johnson (1933), Stearns (1935) and others. Bartrum and Stearns favored production by storm wave erosion, coupled with final bevelling
by sub-aerial weathering, while Johnson and Jutson ascribed
the platforms solely to storm wave activity. Rough planing by
storm waves with subsequent smoothing by weathering may have
occurred in some Tasmanian locations, but in others the present
platforms were probably lowered from slightly higher level sur-
faces relating to previous higher sea levels. The rate at
which water-layer weathering can lower a rock surface is not
known with certainty, but Emery (1960) indicated that a layer of
rock about one foot thick could be removed every 600 years.
Hodgkin (1964) and studies of Tasmanian coastal structures
suggest that the rate might be even more rapid.

The width of horizontal, high tidal platforms is dependent
both on the rates of the weathering and hydraulic processes and
the pre-existing morphology of the shoreline. Edwards (1941)
stated that the width of the platform is directly related to
the height of the sea cliff. The present study indicates that
the width of the platform is more dependent on whether a surface
existed from which weathering and hydraulic forces could produce
the contemporary high tidal feature. If such a surface did
exist, the platform width would be a function of both downward
cutting and sub-aerial retreat of the sea cliff. With no
previous horizontal surface occupying the zone slightly above
the level of mean higher high water, the platform could only
develop as sub-aerial weathering and hydraulic forces attacked
the sea cliff. The platform width would be more closely related to the height of the cliff in this special case. However, the stepped profiles on the Tasmanian coast furnish a number of surfaces from which new high tidal platforms can be rapidly formed and in only a few instances was weathering and hydraulic activity presented with the task of forming a horizontal surface from a vertical cliff.

Sloping, Intertidal Platforms

The few sloping, intertidal platforms occurring in Tasmania are caused by wave erosion of poorly consolidated material or abrasion by wave-powered rocks and sand. The rarity of this platform type and direct underwater investigation both indicate that rock abrasion is not a potent erosive force on the Tasmanian coast.

Horizontal, Subtidal Platforms

In contrast to the sloping, intertidal platforms, horizontal, subtidal platforms are common in Tasmania. These features are matted with thick organic growth and show few signs of any present formational activity. Tool stones are rare, and if present are usually wedged into crevices and covered with organisms. Subtidal platforms were probably formed sub-aerially in times of lower sea levels and have since been inundated. Now, their surfaces are gradually being degraded by slow chemical,
biochemical and biological activity. Offshore profiles often descend in a series of cliffs and platforms to depths of about -40 feet msl where sand covers the rock surfaces. If sea level were to drop, the subtidal platforms would be re-bevelled into horizontal surfaces by sub-aerial weathering. A rise in sea level would add the present high tidal platform to the subtidal platform series now in storage.

**Transgressive Platforms**

The transgressive platform, extending continuously from supratidal to subtidal zones, is the last basic Tasmanian platform type to be considered. This platform occurs in resistant igneous rock, such as granite and dolerite, and is less dependent on the sea for its formation than any of the previously mentioned platform types. The transgressive platform results from exhumation of a bedrock profile which is usually created either by structural control, sub-aerial weathering, or a combination of both. Wave action serves mainly to expose the bedrock surface underlying the weathered material. Hydraulic activity may subsequently quarry a few blocks and weathering may attack the surface, but the rates of erosion are slow.
RELATIONSHIP BETWEEN TASMANIAN SHORE PLATFORMS
AND THE PROFILE OF EQUILIBRIUM

As Bartrum (1926), Hills (1949) and others have shown, shore platforms often disturb the smoothly flowing classic profile of equilibrium. Fairbridge (1952) pointed out that not only did the platforms disturb that profile, but that the profile of equilibrium was less common on a worldwide scale than the stepped, shore platform profile. Tasmanian studies support this view, as the stepped, shore platform profile is far more prevalent than the Gilbert-Fenneman shape. The seaward edge of Tasmanian platforms is almost invariably vertical and the dense growth of organisms indicates that rock abrasion is not an effective force (Photo 52). Waves are reflected from the vertical wall with little loss of energy and chemical, biochemical and organic rock breakdown mechanisms act slowly, so that it is likely that the platform shape will endure for considerable periods. Long before the platform is degraded into anything resembling a profile of equilibrium, sea level will change and either completely drown the feature or allow its rejuvenation.

TASMANIAN SHORE PLATFORMS AS INDICATORS OF PAST SEA LEVELS

Tasmanian platforms are of limited value in determining past sea levels. The horizontal, high tidal platform is not
Photograph 52

Seaward Edge of Horizontal, High Tidal Platform, Submarine View. The stepped profile shown here is common on the Tasmanian coast. The heavy cover of kelp (*Durvillea*) indicates that rock abrasion is not an important force of erosion in this area.
an emerged, wave cut terrace but a feature which has recently been produced sub-aerially and which is now in equilibrium with present mean higher high water level. The horizontal supratidal platforms are better indicators of past sea levels, although they may have suffered considerable degradation since the time when the sea was near their elevation. Probably the best markers of past sea levels are the horizontal subtidal platforms, because they too were formed sub-aerially, but are being less actively degraded than the supratidal platforms. Sloping features such as the intertidal and transgressive platforms are generally very unreliable as past sea level indicators because they migrate with the rise or fall of the water surface.

APPLICABILITY OF FINDINGS TO OTHER LOCATIONS

Although this study has been limited to Tasmanian shore platforms, the results can be applied in other parts of the world. Personal examination of platforms in California, Hawaii and Tahiti suggests that the basic mechanisms involved in Tasmanian shore platform development were also responsible for shaping these coastal features. In addition, shore platforms which had morphologies similar to the Tasmanian examples have been described in the literature in numerous other locations. A mass of evidence indicates that the complex, combined action of environment, hydraulic activity and rapid sub-aerial
weathering to a saturation level within the bedrock has produced the horizontal, high tidal platforms encountered on many of the world's coasts.
CONSTRUCTION OF A SIMPLE, PORTABLE TIDE GAUGE

This study of Tasmanian shore platforms required fairly accurate levelling information which was not available from the sparse triangulation data. Operation of a portable tide gauge offered the best solution to the problem of establishing a sea-level datum for each of the widely scattered field locations. A graduated stake pounded into the sand serves in sheltered areas, but frequently data is needed on a more open coast. This requirement led to the successful development of a gauge which operates in wave heights up to three feet while automatically integrating individual waves to yield average sea level values.

The gauge consists of two main assemblies - the measuring column and a support. The measuring column is a transparent plastic tube, 8 feet long, 2 inches in diameter, with 1/8 inch wall thickness. Tightly fitting plastic caps seal the ends of the column so that the only water or air which can enter the tube must pass through a 1/16 inch hole located at each end. The size of the hole controls the time constant of the measuring column. Holes larger than 1/16 inch diameter tend to cause the gauge to be affected considerably by individual waves. The 1/16 inch diameter holes filter out the individual waves but
Portable Tide Gauge

Anchor

Column & Support

Clamp (Welded to Pipe)

3/8 Dia. Hole

1/2" Galv. Pipe

Steel Plate 1/2" x 5" Dia.

Vanes (3) 1/8" x 2"

1/16 Inlet Hole

2" Galv. Pipe

Triangular, Steel Fence Post Section

Lead-Filled Weight Tubes (2)

Driver
yield a time constant for the system which is inadequate to integrate surf beat (with its usual 120 second period). The surf beat was read and the curves smoothed graphically, although smaller holes in the gauge would have integrated even the long period waves. Smaller holes might, however, be prone to sand blockage in some locations. The 1/16 inch diameter holes have not as yet suffered any such difficulty with sand plugging.

Graduations were placed on the tube at one inch intervals, and a one-inch-wide band of vinyl tape located every six inches. The gauge is read by noting the level of water in the tube - a ping-pong ball floating in the column facilitates reading.

Designing a lightweight, yet solid support for the gauge was more difficult than developing the actual measuring column. Various steel and aluminium tubes were driven into beach sand to test feasibility, but tubes (with ends either open or flattened) proved to be very difficult to place and remove. The shape finally adopted for the anchor was a triangular section of steel normally used for fencing. This section both drives easily and is quickly removable. The anchor is welded to a steel plate and re-enforced with 1/8 inch thick steel vanes, four inches wide. A supporting pipe is welded on the top of the plate to receive another section of steel tube upon which is clamped the measuring column.
The unit is best installed at low tide in the most sheltered spot available. A hammer may be used to drive the anchor section, but an adaptation of the underwater core driving method was found to be better suited. A pipe which slides over the anchor tube has handles and smaller tubes filled with 15 pounds of lead welded on the sides. The anchor is then driven by sliding the collar up and down the anchor tube, striking the plate at the bottom. Removal is accomplished by screwing a cap on the anchor tube and striking upwards. When the anchor is in place - outside the breaker line - the tube supporting the measuring column is slipped over the anchor tube and secured by a bolt.

Once the gauge is installed, it can be levelled with any reasonably accurate levelling device to determine its elevation. Nothing remains except to record inflection points in the tidal curve for as long as patience or opportunity permit. The more readings obtained, the more accurate will be the ultimate results. When inflection points have been found, they may be correlated with data from a nearby fixed tide gauge, or less satisfactorily, with predicted values. If a large number of readings are taken, correlation may be unnecessary and an MSL datum can be obtained without noting short term aberrations in the tidal curve.

Obviously, data procured with this portable gauge over short
periods of time are not absolutely accurate. The fact that the gauge is necessarily located in shallow water is one source of error. Another is the difficulty in knowing exactly how winds and pressure are affecting local sea level. However it is felt that the results are probably within 0.3 feet of the true values, which is considerably more accurate than datum determining methods utilizing characteristic zoological specimens or casual observation of tide heights. While this portable tide gauge cannot compete with permanent recording tide gauges or a good triangulation net for precise levelling data, its low cost (under $10.00 for materials), ease of transportation, and ruggedness have made it a useful field tool.
Appendix 2

STEREO PHOTOGRAPHY FROM LIGHT AIRCRAFT

All of Tasmania's coastline is covered by aerial photographs, but often the scale is too small to be useful in the detailed study of shore platforms. With much of the field work concentrated in the Eaglehawk Neck area, it was advantageous to have large scale stereo aerial photographs. These photos were obtained using basic commercial aerial photographic techniques which were modified to meet the requirements of a small budget.

Good preparation is the key to successful stereo photography from light aircraft. The first step is to select a camera for the job, with prime consideration given to equipment already on hand. In general, any camera which has a fairly rapid film advance and an eye-level viewfinder may be used. 35 mm cameras usually meet these requirements and have an advantage over larger sizes through using 36 exposure film spools.

After making his choice of camera, the photographer must determine the field of view of his lens. This is accomplished with sufficient accuracy by sighting through the viewfinder at convenient distant objects and measuring the included angles. The procedure is repeated with the camera in the vertical position to obtain the complete field of view - about 35° by 26° for a 35 mm camera with a 50 mm focal length lens. If greater
accuracy is needed, a grid can be photographed and the angles measured exactly. (A brick wall makes a good target).

Plotting the desired coverage on a map is the next step. When the area to be covered is defined, the known field of view of the lens is superimposed graphically and a scale chosen. If a lens of only one focal length is available, the scale can be changed by varying the height of the aircraft. Flight altitude is also determined graphically, after the scale has been selected, by use of the field-of-view angles drawn on a piece of tracing paper.

All that remains in this initial phase of preparation is to determine the actual flight path and the interval at which to snap the shutter for stereo coverage. The flight path should be drawn plainly upon the reference map and the heading measured in terms of magnetic north. It is best, if possible, to plan the completion of photography in one run for ease of navigation. Parallel runs spaced to provide a 25% overlap must be flown when larger areas are photographed.

The required 60% forward lap is obtained by using the known field of view of the lens, the altitude, and the speed of the aircraft. Again, the easiest way to establish the interval is to use graphic plots of field-of-view angles on the map to determine the actual ground distance included in each photo.
Using an aircraft speed of 60 mph, which is easily maintained by most light planes, the time needed between each photograph to reproduce 60% of the previous picture can be established. The pertinent information should now be plotted on a map, preferably with stiff backing, which will be easily manageable in the airplane cockpit. Particular attention should be paid to the readability of course headings and local landmarks.

Choice of film, filters and shutter speeds is the next consideration. Black and white film is generally the cheapest, most convenient, and best suited for urban and general geographic photography. Panchromatic films are effective for unspecialised coverage and should be used in conjunction with a yellow (K2) filter. A low grain film such as Panatomic X is a good choice for 35 mm cameras, as high film speed is not as important as enlargement capability in this application. Color film is very useful for underwater features, vegetation, soils and other physical phenomena. Color reversal film (Kodachrome) may be used, but a color negative film (Kodacolor) which yields less expensive prints is more satisfactory. In either case, a skylight filter is necessary to cut the bluish haze which is almost always encountered.

Shutter speeds should be as fast as possible. Since depth of field is not important, the lens may be operated wide open
and speeds of at least 1/250 second are attainable with even the slowest films. A light meter is a definite necessity in determining the correct exposure.

Next, an airplane and pilot must be selected for the actual job. Almost any light aircraft can be used for oblique photography, but vertical photographs require a high-winged monoplane. Best of all are types with tail wheels such as the Cessna 170, 180 and the Super Cub. Planes with tricycle landing gear are less suitable because the main gear is located further aft which interferes with downward visibility. Time taken on the ground in talking over the project with a pilot is well spent, as he will be able to suggest the best airplane locally available, furnish pertinent aircraft characteristics and comment on the flight plan.

If ground preparation has been thorough, completion of the aircraft phase of the operation will pose few problems. The flying should be done when there is as little wind and cloud as possible, with the period before noon offering the best opportunities. Although obliques may be successfully taken through the aircraft windows, good verticals require that the door be removed. The photographer may feel a bit uneasy at first about the large amount of space immediately at hand, but as the airplane gains altitude a sense of detachment from the ground combines with reaffirmed faith in the seat belt to dispel any qualms. In
order to obtain a true vertical it may be necessary to ask the pilot to fly with one wing low - no problem for a commercial operator.

Index photos should be taken sometime during the flight. These can be either high altitude verticals or obliques, but should cover in one photo the entire area photographed in detail. Stereo obliques, which can be taken with less planning than vertical photos, are very useful for both indexing and actual geographic research and should be included in the photographic program whenever possible.
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