# Regions of the Sound Velocity Profile

When we plot the speed of sound as a function of depth in the ocean, it is called the sound velocity profile or SVP. An SVP is a very useful tool for being able to predict the path of propagation of sound in the ocean. A nominal SVP is shown in the following figure.

This example shows that the oceans waters are divided into three main layers. First, the surface or seasonal layer has varying depth and profiles depending on many conditions such as
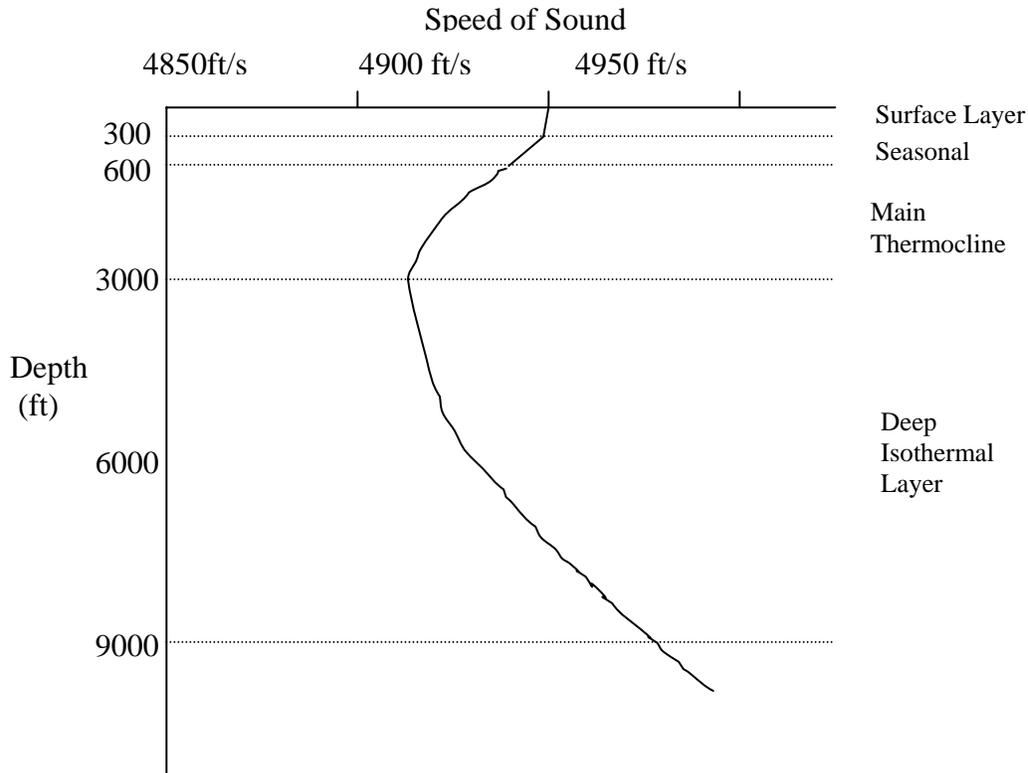
season, time of day, currents, latitude, etc. It is the most variable layer. The second layer, the Main Thermocline connects the seasonal layer to the deep isothermal layer. The deep isothermal layer, below about 500 to 1000 meters, is at a temperature of about 34°F and the speed of sound only increases due to the increase in pressure.

The layer of most interest is the surface layer because it is the one that varies most. During the warm summer months, the water near the oceans surface is warmer than the water below and there is a sharp negative gradient in the speed of sound. In the winter, the water is not heated as much because the air is cooler and the warmer water from below tends to rise and create more mixing in the upper layer. Additionally, there is more mixing of the surface layer due to effects of strong winter storms and larger waves.

Ray Tracing

Now that we know how the speed of sound varies as a function of depth, we can begin to predict the path of sound propagating through the ocean. As we said before, sound rays tend to

bend toward layers of water that are cooler (where speed of sound in the water is lower.) Let's develop some thumbrules for picturing the path of the sound rays. Knowing the gradient gives us insight into the direction the sound ray will refract or bend.

Constant Velocity Profile, $g = 0$

Acoustic rays are rectilinear, meaning rays travel in straight paths. This is not an isothermal layer. An isothermal layer would have a slight positive gradient due to the effect of the increase in pressure with increasing depth on the speed of sound.

$g = "+"$

Typical for the deep isothermal layer or surface layer in the winter. Temperature is constant or increasing. For isothermal case, c increases due to pressure with $g = 0.017 \text{ s}^{-1}$. Most often the water is isothermal because of the mixing effect of wind near the surface. Because of this isothermal layers are called "mixed layers." + g causes acoustic rays to be refracted upward and can result in a Surface Channel.
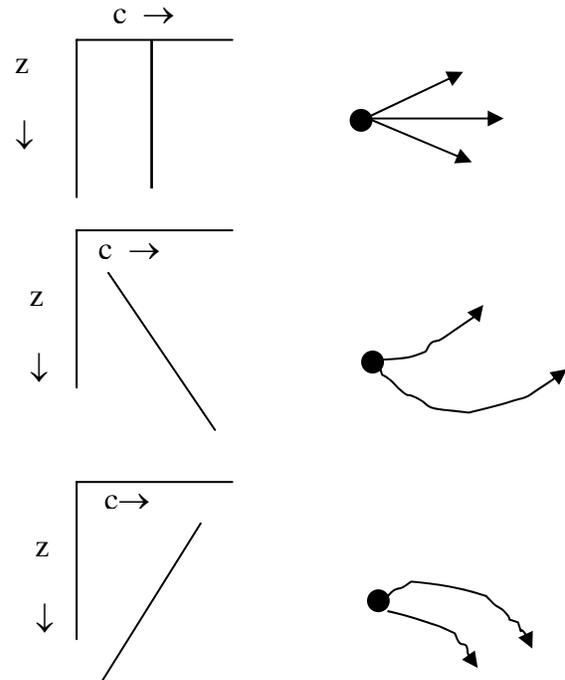
$g = "-"$

This is a typical SVP for the surface layer during the summer months. Results from temperature decreasing faster than pressure effect increases. A negative gradient produces shadow zones.

Note that when sound is generated by a source in the ocean, the sound is radiated in all directions spherically around the source. Thus sound may travel several different paths away from the source and may travel into other layers. Some common propagation modes of sound are shown below:
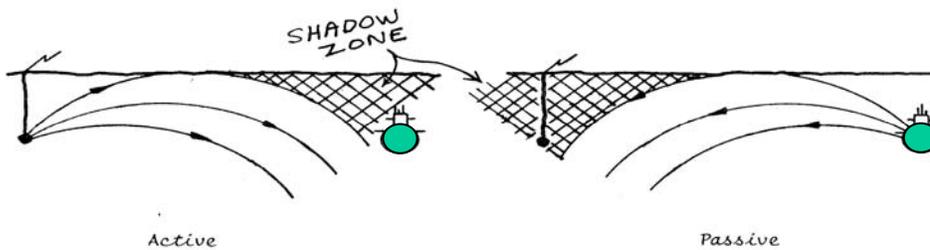
Surface Duct

If the surface layer has a positive gradient and that layer is deep enough, the sound may be bent back towards the surface then reflected back into the layer. After it is reflected back downward, it is bent back towards the surface again only to be reflected at the surface again. This effectively traps the sound in the surface layer.

SVP

Figure 15-11. Surface duct.
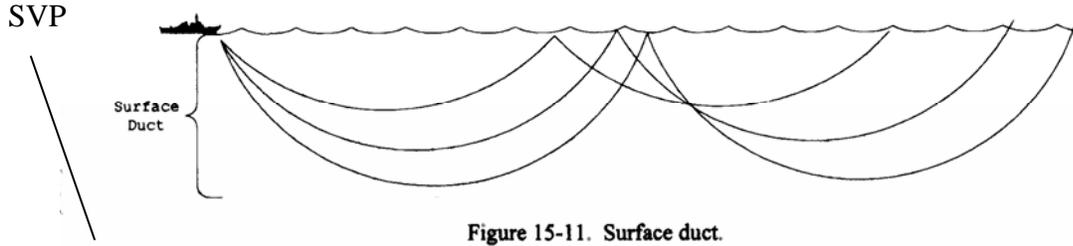
If, on the other hand, a negative SVP exists near the surface, surface shadow zones are created that provide safe havens for submerged platforms.

SVP
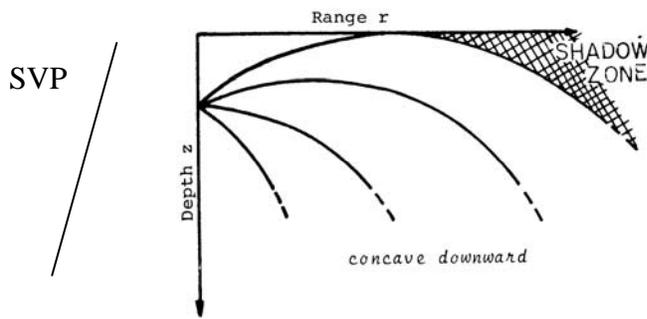
Originally referred to as the afternoon effect, the below sketch shows how a submarine cannot be detected by either a passive or an active sonobuoy.

Convergence Zone

The phenomenon of sound bending back towards the surface in a surface duct should not be confused with sound that is bent back towards the surface due to the positive sound speed gradient in the **deep isothermal layer**. If the ocean depth is great enough, sound rays that travel into the deep isothermal layer will also get bent back towards the surface. These rays travel great distances though before being bent back up to the surface.

The main difference between a surface duct and a convergence zone (CZ) is that in the latter case, all sound rays return to the surface in a small concentrated area called a convergence zone. These zones can be at distances of up to 60 km or more from the source (typically 40 km

in Mediterranean Sea and 60 km in Atlantic Ocean). In other words, the rays all follow more or less the same path and undergo very small geometric spreading, therefore a contact may only be detected when it is within the annulus of the convergence zone. Additionally, after the sound reflects from the surface at the first convergence zones, additional CZs may also occur at integer multiples of the first convergence zone distance with a widening of the beam causing a blurring of the CZ.
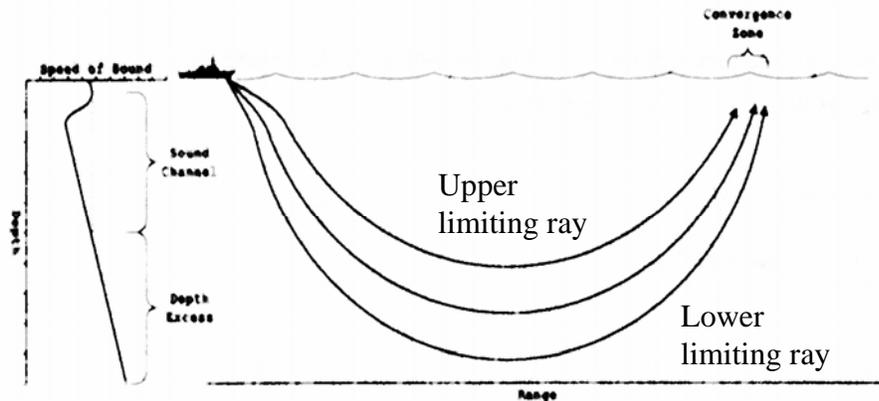

Figure 15-14. Convergence zone.

In the above figure, notice that there is a ray leaving the surface nearly horizontal that must be horizontal again when the sound speed is the same as that on the surface. This ray is termed the "upper limiting ray." Additionally, there is another ray leaving the surface at a downward angle that just barely grazes the bottom before being bent back to the surface. This ray is termed the "lower limiting ray. All sound energy leaving the source between these too limiting rays must return to the surface in the annulus of the convergence zone.

This lower limiting ray becomes horizontal at a higher sound speed than at the surface or horizontal depth of the upper limiting ray. Since it is the increasing pressure with depth that causes this higher sound speed to bring the lower limiting ray horizontal, there must be an adequate "depth excess" in order for the two limiting rays to bracket most of the energy leaving the source. As a practical rule of thumb, depth excess is generally considered adequate when it is greater than 300 fathoms. This will provide adequate velocity excess for the lower limiting ray to bracket most of the energy leaving the source. Seasonal decreases in the surface sound speed may cause adequate depth excess to exist in the winter in locations that do not support convergence zones in the summer when the surface sound speed is higher.

The significance of convergence zones is that they affect the transmission loss experienced by sound leaving a source. During our discussion of the passive sonar equation we pointed out that transmission loss is due principally to geometric spreading (we will soon develop equations to quantify this loss due to spreading). The dashed line in the below figure represents a nominal transmission loss as a function of distance from a source. Convergence zones modify this spreading effect by significantly reducing transmission loss in the areas where the sound is all focused back to the surface. This is termed "transmission gain" and is shown in the below diagram as solid spikes at multiples of the distance to the first convergence zone.

TL (dB)

Range in miles
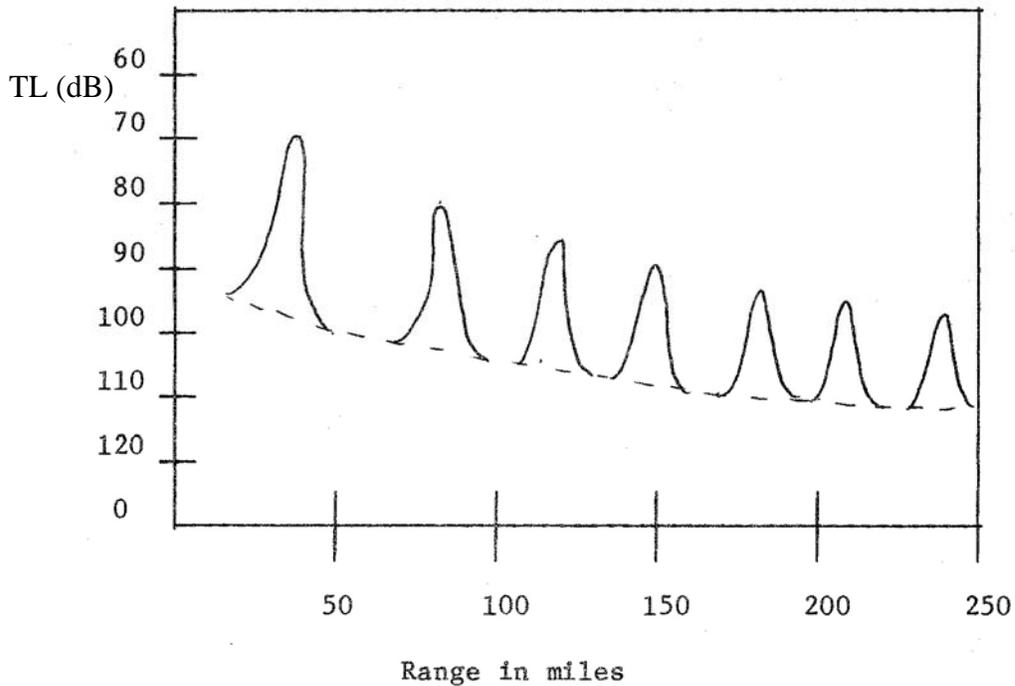
Deep Shadow Zone

Note that where the positive gradient changes to a negative gradient can create a sonic layer. Some of the rays from the surface or near the surface will travel into the negative gradient region but get bent downward more sharply. This will create a shadow zone where a receiver may not be able to detect a submerged source. Submariners have always sought to hide in these shadow zones.
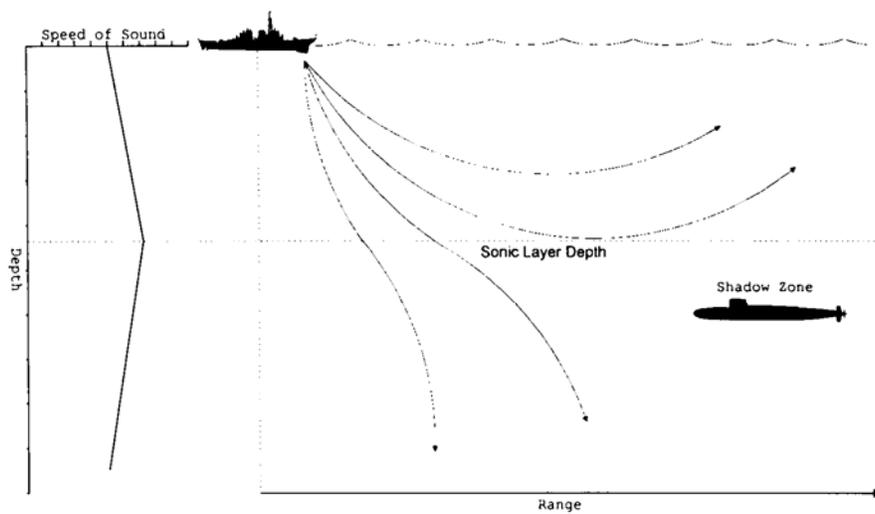

Figure 15-12. Sonic layer.

A thumbrule to select a best keel depth (BD) which keeps the entire submarine safely below the layer depth is called Amos' Rule:

$$BD = 17(LD)^{1/2} \quad \text{if } LD < 60m.$$
$$BD = LD + 60m \quad \text{if } LD > 60m.$$

Deep Sound Channel

Where the negative gradient of the main thermocline meets the positive gradient of the deep isothermal layer, a sound channel called the "deep sound channel" is created. Deep Sound Channels occur in most deep ocean basins. In the deep sound channel, sound traveling near the deep sound channel axis is continually bent back towards the axis and can travel down the axis for many miles. Above the depth of the axis of the deep sound channel, the temperature of the water has the most significant affect on sound velocity. As the water gets deeper, it reaches a steady temperature of 2-4° C at deep depths. Since the temperature is not changing, below the sound channel axis, pressure has the dominant affect on sound velocity. Thus as you go further down in depth, pressure increases and so does sound velocity. Hence the positive gradient of the sound velocity below the deep sound channel axis.

If the sound source is close to the channel axis (minimum *c*), acoustic rays are successively refracted by the two gradients without interacting with the interfaces. This type of propagation is called SOFAR (Sound Fixing And Ranging). It allows for very large transmission ranges because of the absence of energy loss by reflection at the interfaces and concentration of a large number of multiple paths, thereby minimizing geometric spreading. We can achieve ranges of several thousands of kilometers by using low frequencies.
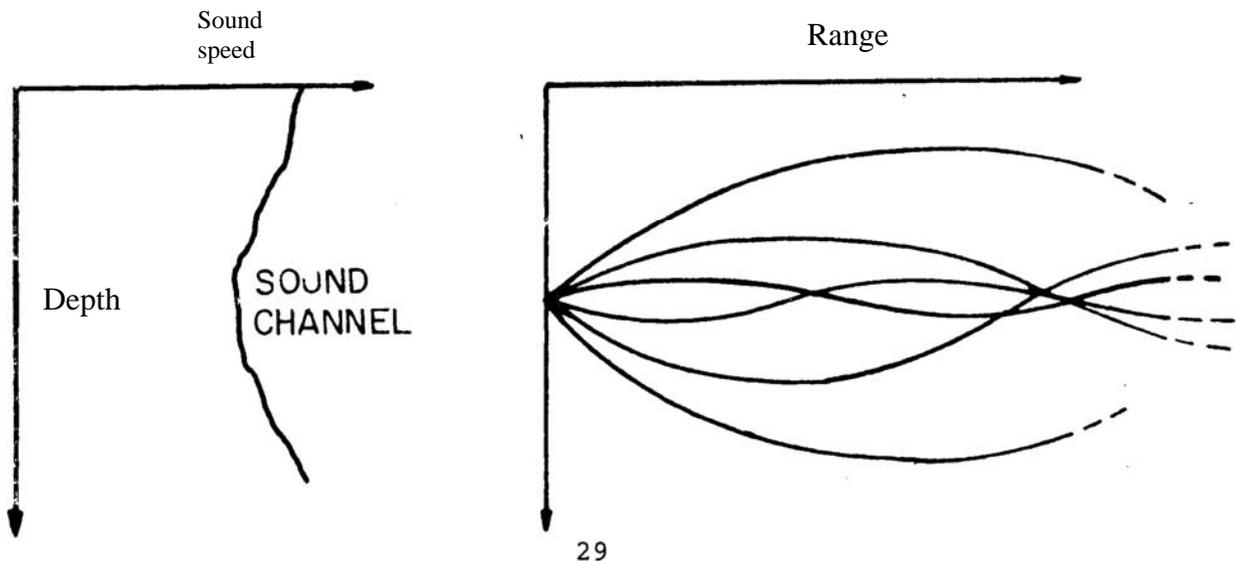

Downed pilots used this phenomenon during WW II. They carried small explosive charges that they would release if they were forced down into the water. These charges then

sank down and exploded. The sound from these explosions would then travel many miles across the oceans in the deep sound channel and would be picked up by several receivers to give an approximate location of the downed pilots.

An Example in the Surface Mixed Layer

Wind driven surface waves mix the water near the surface and can produce an isothermal layer of water. The depth of this layer can vary from zero to more than 100 m. As we pointed out earlier, the increase in pressure with depth causes a positive gradient of 0.017 s^{-1}. A mixed layer is capable of producing a surface duct discussed earlier. In this example we will describe the limiting rays of the trapped sound in the duct.

In the below figure, two sound rays from a source, S, at a depth, D, are is a mixed layer of depth, L. The two rays shown are the limiting rays in that any ray leaving S at an angle greater than θ_s will pass out the bottom of the mixed layer, creating the deep shadow zone discussed previously. These rays designated 1 and 2, leave at equal angles above and below the surface and can be seen in the following way. The angle θ_1 at which ray 1 strikes the surface is related to θ_s by Snell's law. The angle of reflection from the surface is also θ_1 since the angle of reflection is equal to the angle of incidence. The angle of reflection, θ_1, is also related by Snell's Law to the angle at which ray 1 crosses the depth of S, so this angle is also θ_s. Since both rays become horizontal at the bottom of the layer, again, by Snell's Law, they must have the same angle at the depth of the source. Thus we have shown that the two limiting rays just remaining in the surface duct start at S with angles of $\pm\theta_s$.

Bottom of the Mixed Layer
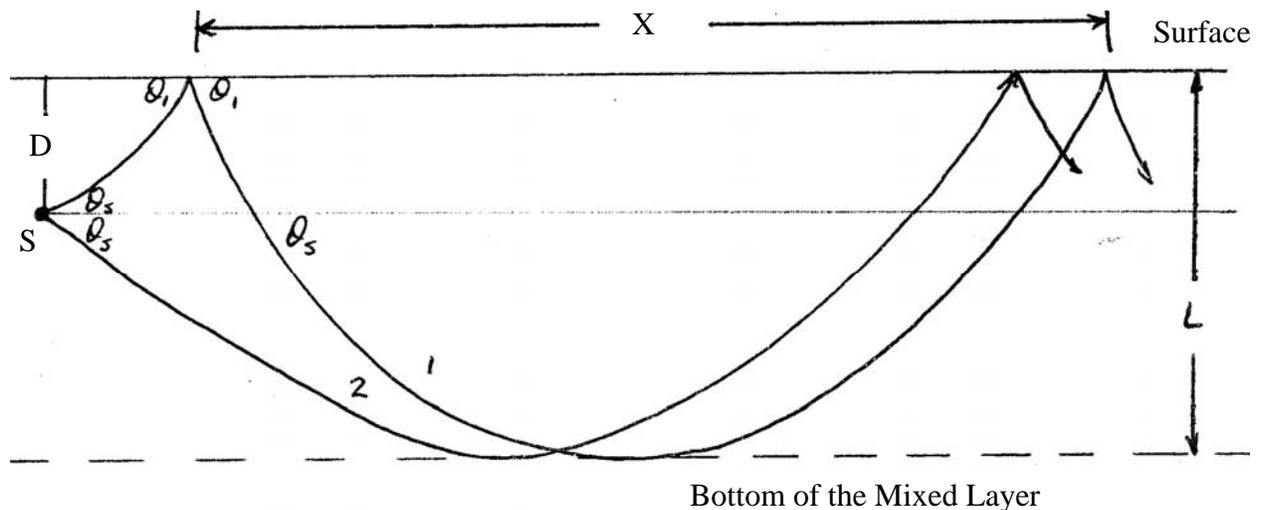
In this example, start with 3 items that are normally known:

$$\text{Source depth} = D = 40 \text{ m}$$
$$\text{Layer depth} = L = 100 \text{ m}$$
$$\text{Sound speed at the surface} = c_1 = 1500 \text{ m/s}$$

a. First find the speed of sound at the source (denoted by c_s) and at the bottom of the mixed layer (denoted by c_o).
Since the gradient is a constant, $g = 0.017 \text{ s}^{-1}$,

$$c_s = c_1 + 0.017D = 1500\frac{m}{s} + 0.017\text{s}^{-1}\text{x}40\text{m} = 1500.68\frac{m}{s}$$

and

$$c_o = c_1 + 0.017L = 1500\frac{m}{s} + 0.017\text{s}^{-1}\text{x}100\text{m} = 1501.7\frac{m}{s}$$

b. Find the angle of the rays at the source. This can be done using Snell's Law, applied between S and the bottom of the layer.

$$\frac{\cos\theta_s}{1500.68\frac{m}{s}} = \frac{1}{1501.7\frac{m}{s}}$$

$$\theta_s = 2.11°$$

c. Find the angle of the rays at the surface. This can be done by applying Snell's Law between the surface and the layer bottom.

$$\frac{\cos\theta_1}{1500\frac{m}{s}} = \frac{1}{1501.7\frac{m}{s}}$$

$$\theta_1 = 2.73°$$

d. Find the Radius of curvature of the ray.

$$R = \frac{c_o}{g} = \frac{1501.7\frac{m}{s}}{0.017\text{s}^{-1}} = 88335.3\text{m}$$

e. Find the skip distance, X. this is the distance between two successive reflections off the surface.

$$X = x - x_1 = R\left(\sin\theta - \sin\theta_1\right) = 88335.3\text{m}\left[\sin(2.73) - \sin(-2.73)\right] = 8404\text{m}$$

Definitions:

Surface Layer: Heated daily by the sun and mixed by the wind. Usually isothermal. Depth proportional to the winds. Daytime heating effects. Also known as the Mixed Layer.

Seasonal Thermocline: Temperature decreases with depth. During the winter, it may not exist due to deep mixing of the surface layer.

Main (Permanent) Thermocline: Start of the layering not affected by mixing. Characterized by decreasing temperature and sound speed. Minimum temperature is 4°C (39°F). Associated with the minimum sound speed. (At higher latitudes the depth of the minimum, sound speed is much shallower.

Deep Isothermal Layer: Deep ocean. Constant water temperature: 4°C (39°F). Sound speed increases as depth increases due to increase in pressure.

Thermocline: A constant temperature variation with depth, most often a negative change (temperature decreasing with depth). Can be seasonal or permanent.

Surface Limited Ray: A ray that has a zero angle at the surface ($\theta_{surface} = 0°$) where the ray is refracted and not reflected at the surface. Any ray with an initial angle greater than that of the Surface Limited Ray will reflect off the surface and will not be refracted. Any ray with an initial angle less than the Surface Limited Ray will not reflect off the surface.

Bottom Limited Ray: A ray that will refract back upwards just as it reaches the bottom ($\theta_{bottom} = 0°$). Any ray with an initial angle greater than the Bottom Limited Ray will reflect off the bottom, not refract.

Surface Channel: Corresponds to a layer with sound velocity increasing from the surface down. Caused by a shallow isothermal layer appearing during winter, can also be caused by very cold water at the surface (melting ice or river influx)
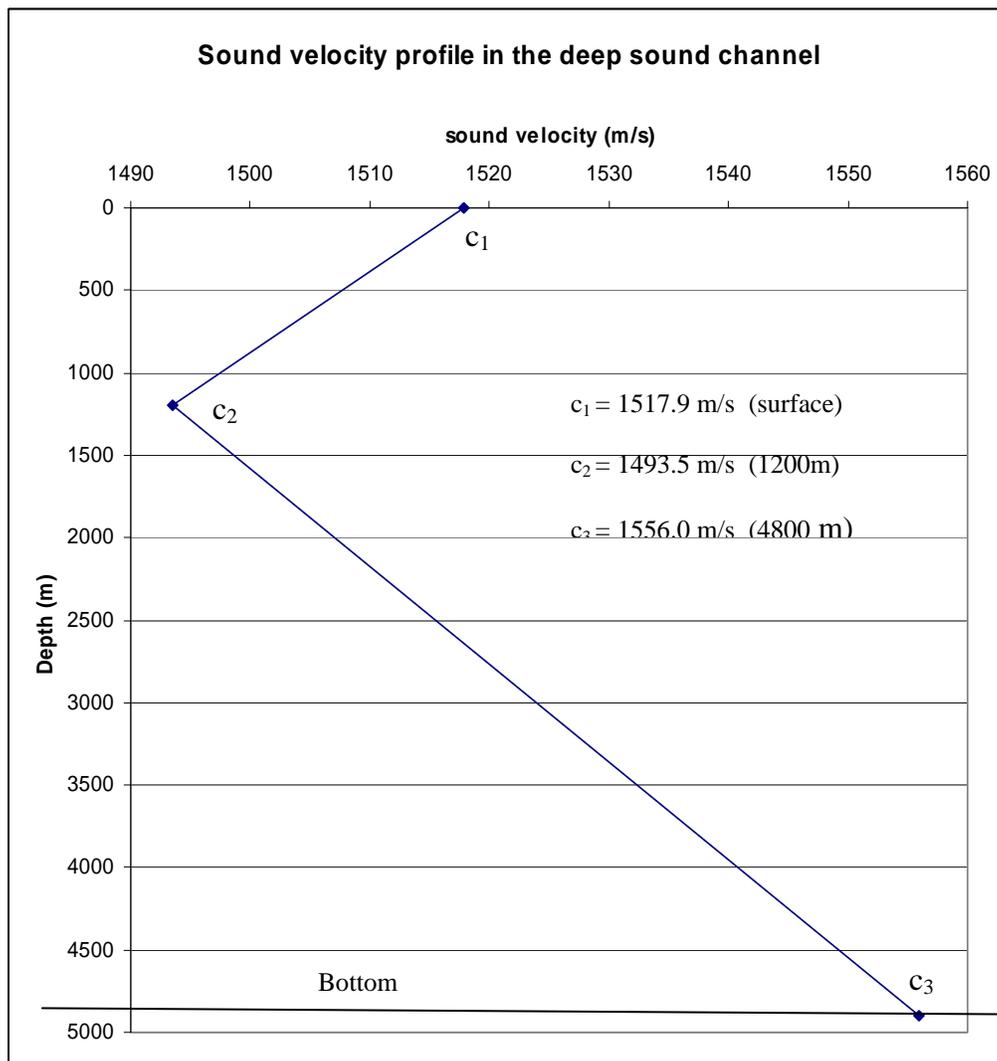
Deep Sound Channel Axis: The depth where the speed of sound is a minimum. This depth marks the end of the Main Thermocline and the beginning of the Deep Isothermal Layer. SVP of large ocean basins has Deep Channel Axis between @200 m and 2000 m.

The following image provided courtesy of NAVOCEANO provides a good visual representation of the effects we have discussed in this section.
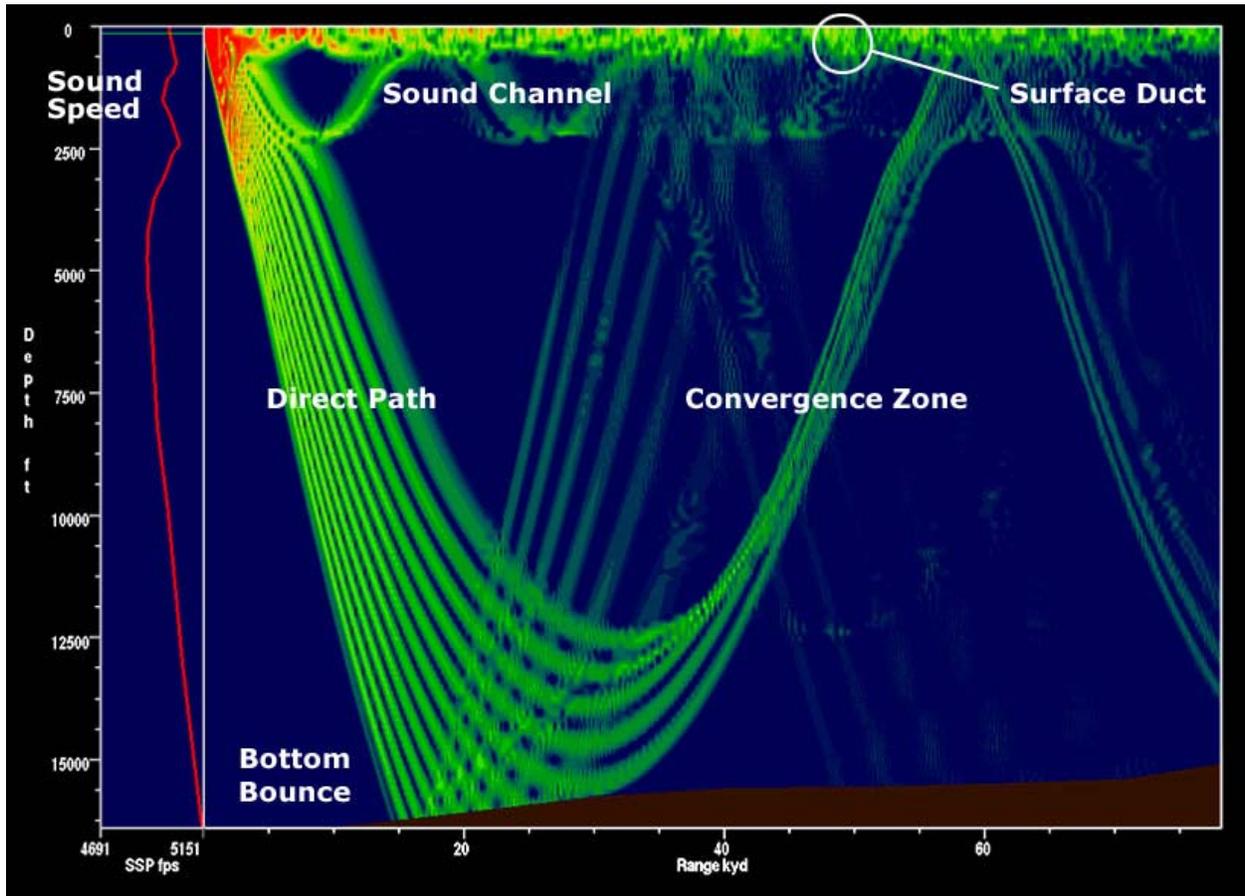
Problems:

1. State whether the gradient for each of the following layers is positive, negative or zero and state why?
   a) Surface layer,
   b) Seasonal Thermocline
   c) Main Thermocline
   d) Deep Isothermal Layer.

2. What happens to the range at which the shadow zone occurs when the source (or receiver) is moved from the top to the bottom of the mixed layer?

3. Since the speed of sound increases as depth increases solely due to increasing pressure in the deep isothermal layer, what is the gradient in the deep isothermal layer?

Sound velocity profile in the deep sound channel

sound velocity (m/s)

$c_1 = 1517.9$ m/s (surface)

$c_2 = 1493.5$ m/s (1200m)

$c_3 = 1556.0$ m/s (4800 m)

Depth (m)

Bottom

c_1

c_2

c_3

4. A sound source is at a depth of 0 m (just below the surface). There are two primarily important rays that form the boundaries of a convergence zone. One is called the "upper limiting ray." The other is called the "lower limiting ray."
   a) Draw a ray from the source making an angle of 0 degrees with respect to the horizontal and draw it until it reaches the surface again (the upper limiting ray)
   b) Draw a ray from the source making an angle of θ with respect to the horizontal. The angle, θ is chosen such that the ray just grazes the bottom and can return to the surface again. Draw the ray until it reaches the surface again. Compute the angle, θ below.

   Upper Limiting Ray
   c) What is the radius of the upper limiting ray between the surface and 1200 m?
   d) At what angle does this ray reach 1200 m?
   e) What is the horizontal distance traveled by this ray between the surface and 1200m?
   f) What is the radius of the upper limiting ray below 1200 m?
   g) At what depth does the ray become horizontal?
   h) What is the horizontal distance traveled by the ray between the point where the ray is at the depth of 1200 m and the point where it is horizontal?
   i) What is the horizontal distance traveled by the ray between the source and the point where it is horizontal?

   Lower Limiting Ray
   j) At what angle does the lower limiting ray leave the surface?
   k) At what angle does this ray reach 1200 m?
   l) What is the radius of the upper limiting ray between the surface and 1200 m?
   m) At what horizontal range does the ray reach 1200 m?
   n) What is the radius of the lower limiting ray below 1200 m?
   o) What is the horizontal distance traveled by the ray between the point where the ray is at a depth of 1200 m and the point where the ray grazes the bottom.
   p) What is the total horizontal distance traveled by the ray from the surface until it grazes the bottom?

   Convergence Zone
   q) What is the distance to the first convergence zone?

5. On the SVP below, draw the continuation of the rays from the source until they hit the bottom, surface or reach the right hand side of the page. Draw and label any limiting rays and any shadow zones.
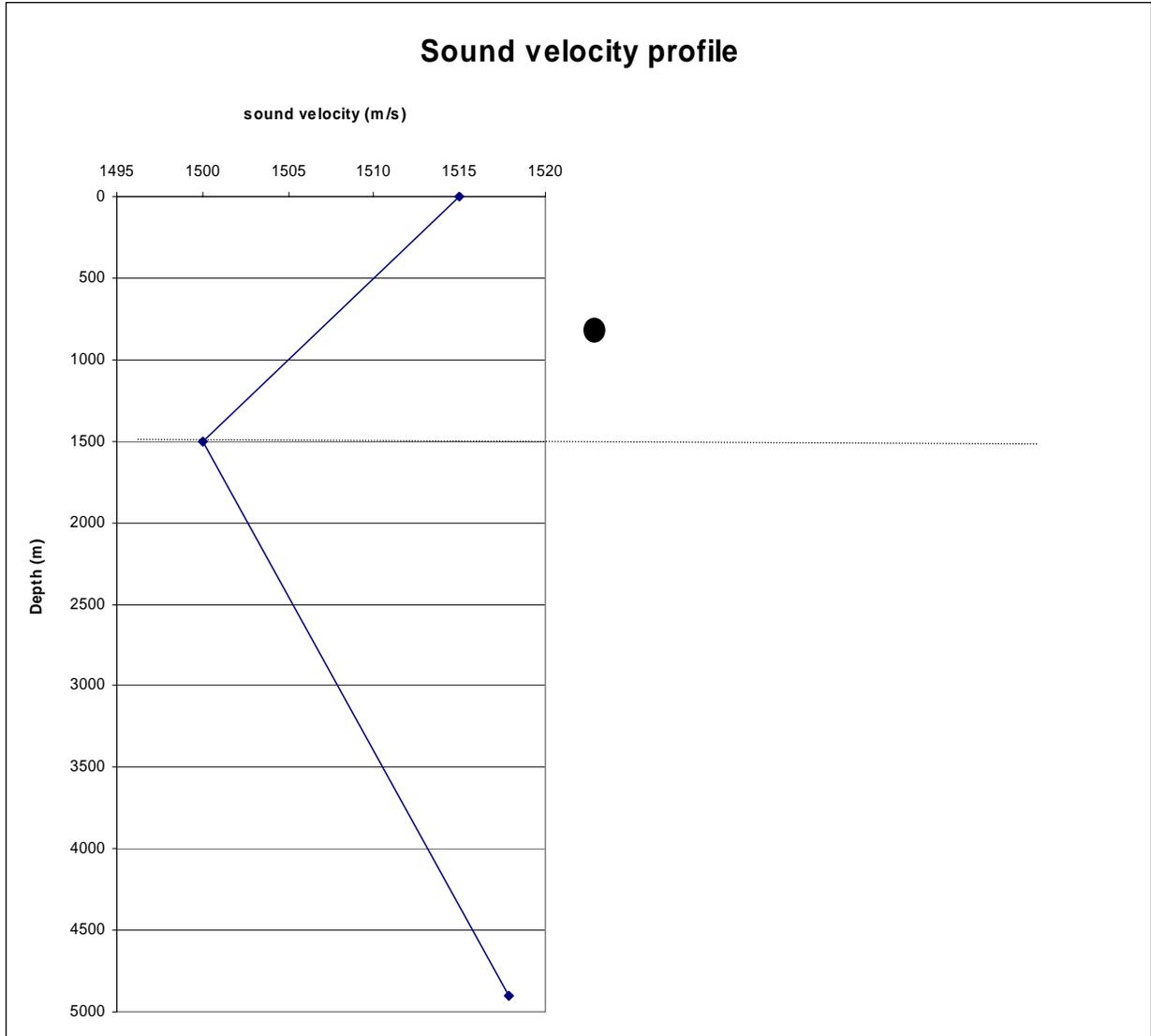
Sound velocity profile

sound velocity (m/s)
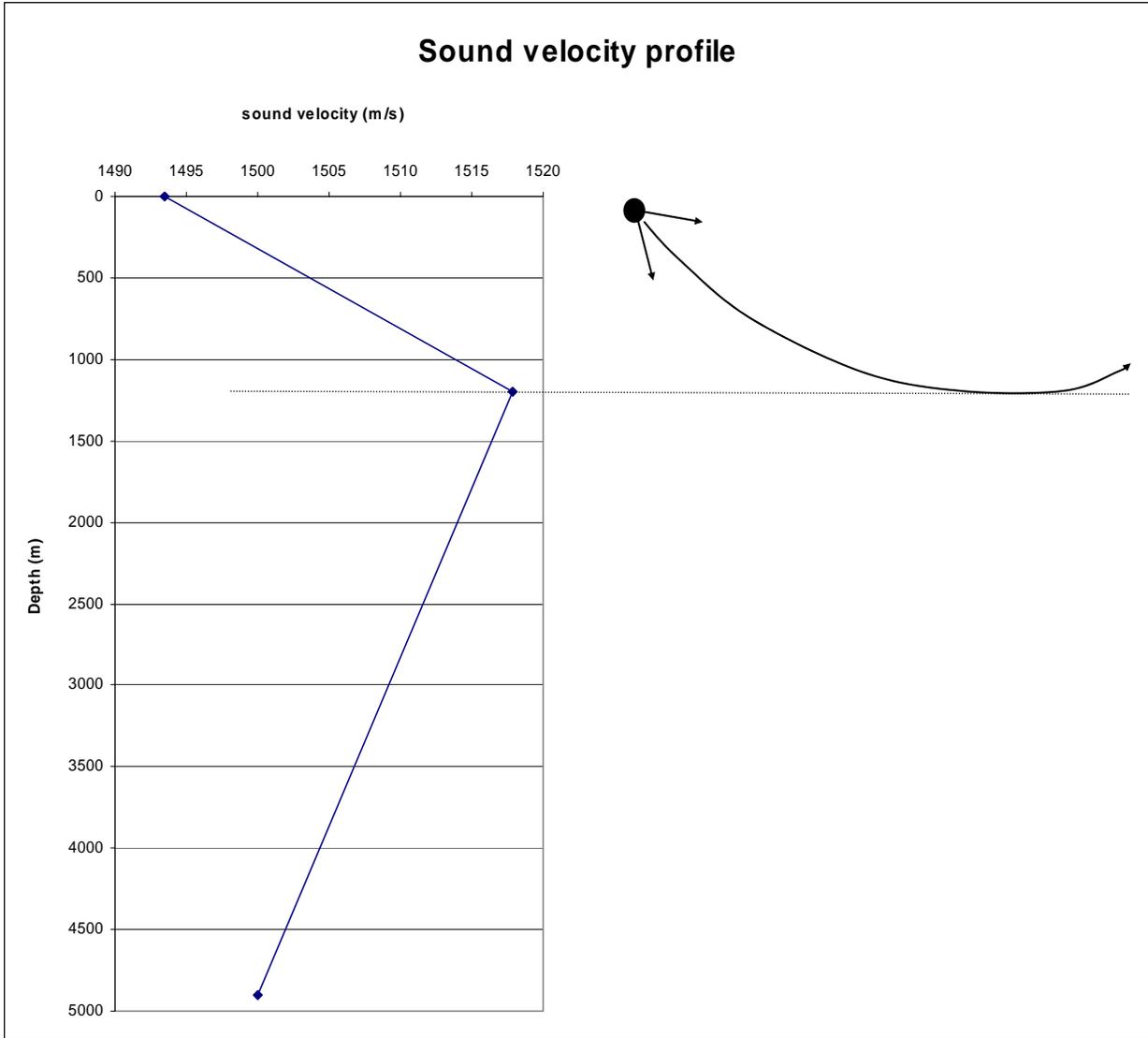
6. Continue these rays until they hit the surface, the bottom or reach the right hand side of the page. Draw other rays to show how a sound channel is formed.
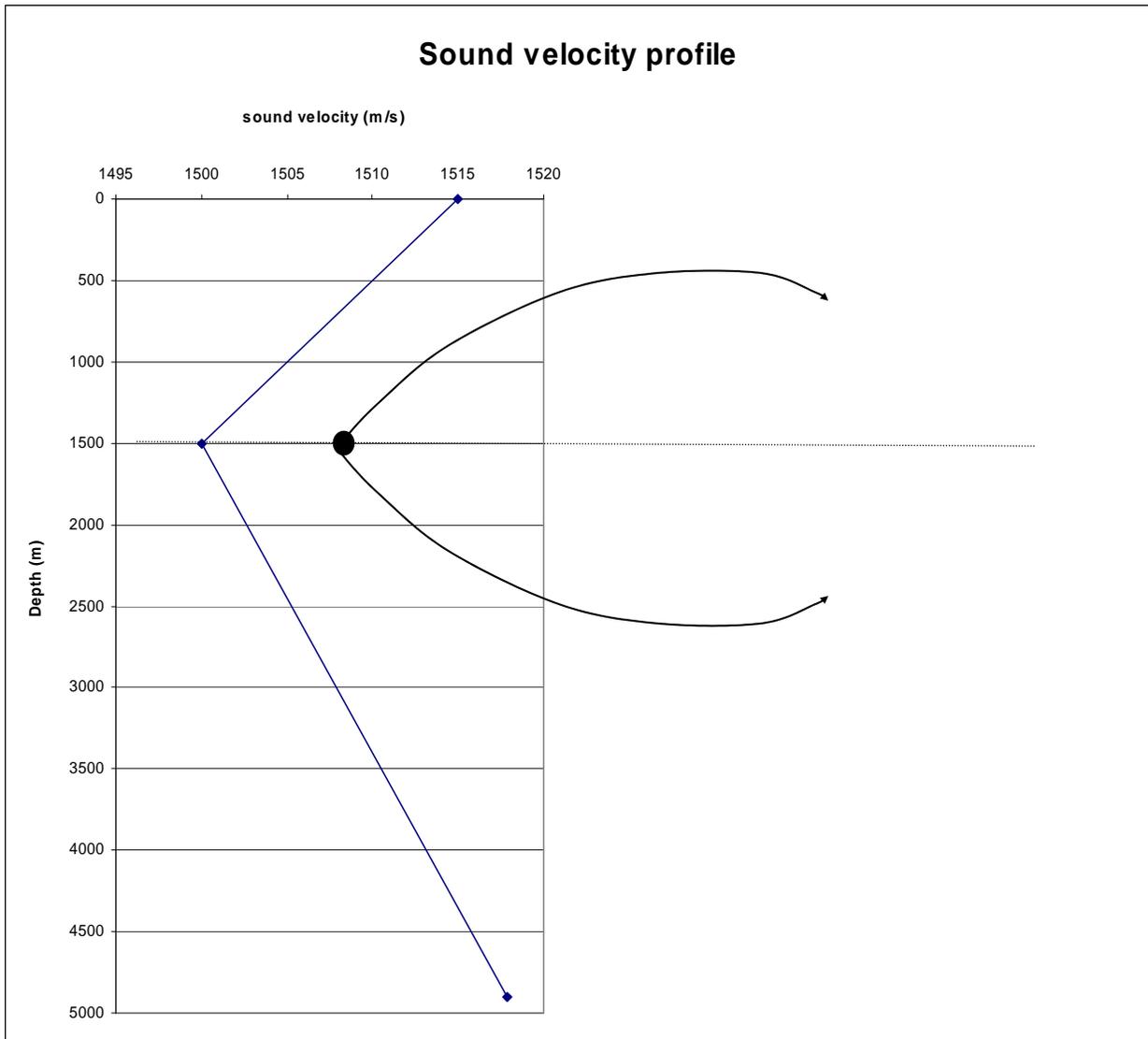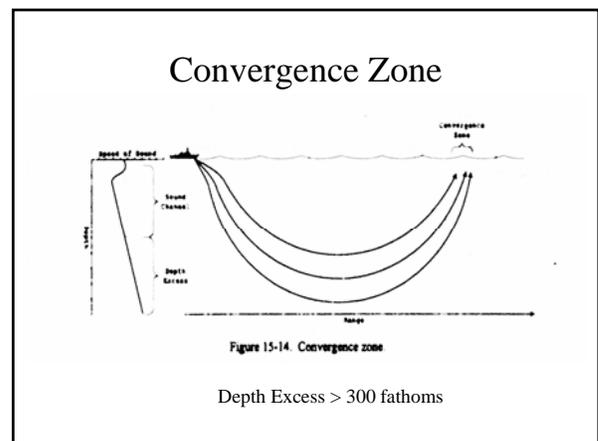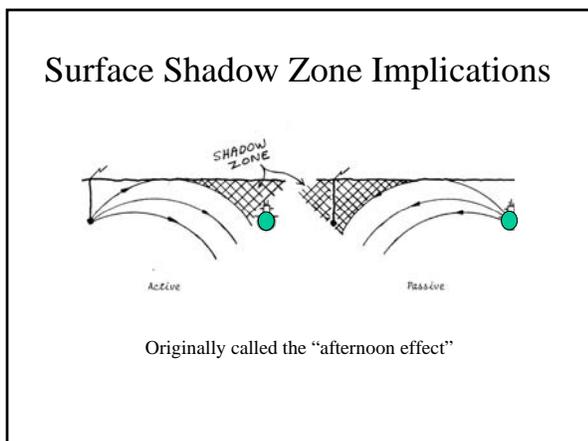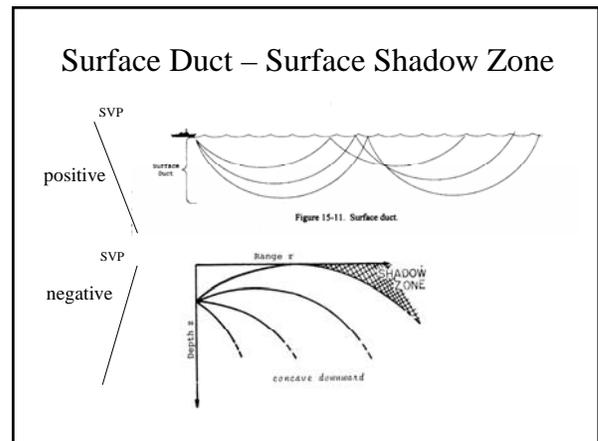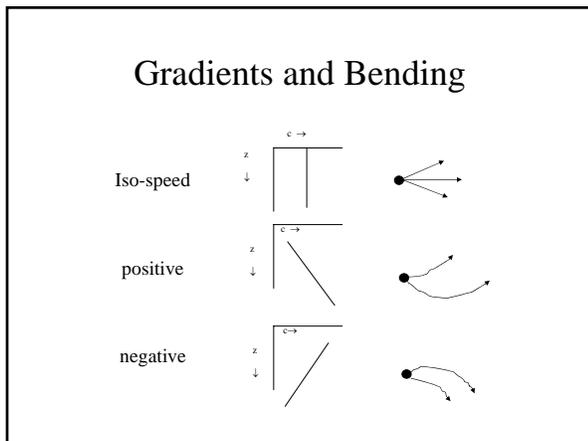
Sound velocity profile

sound velocity (m/s)
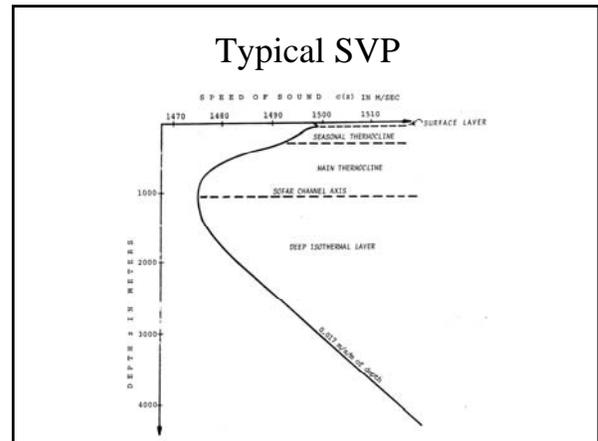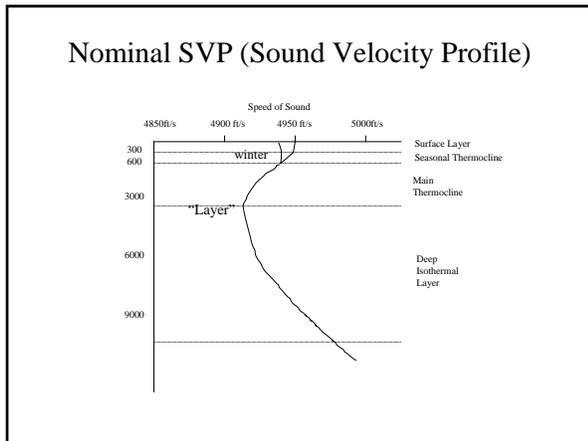
7. Continue these rays until they hit the surface, the bottom or reach the right hand side of the page.

Sound velocity profile
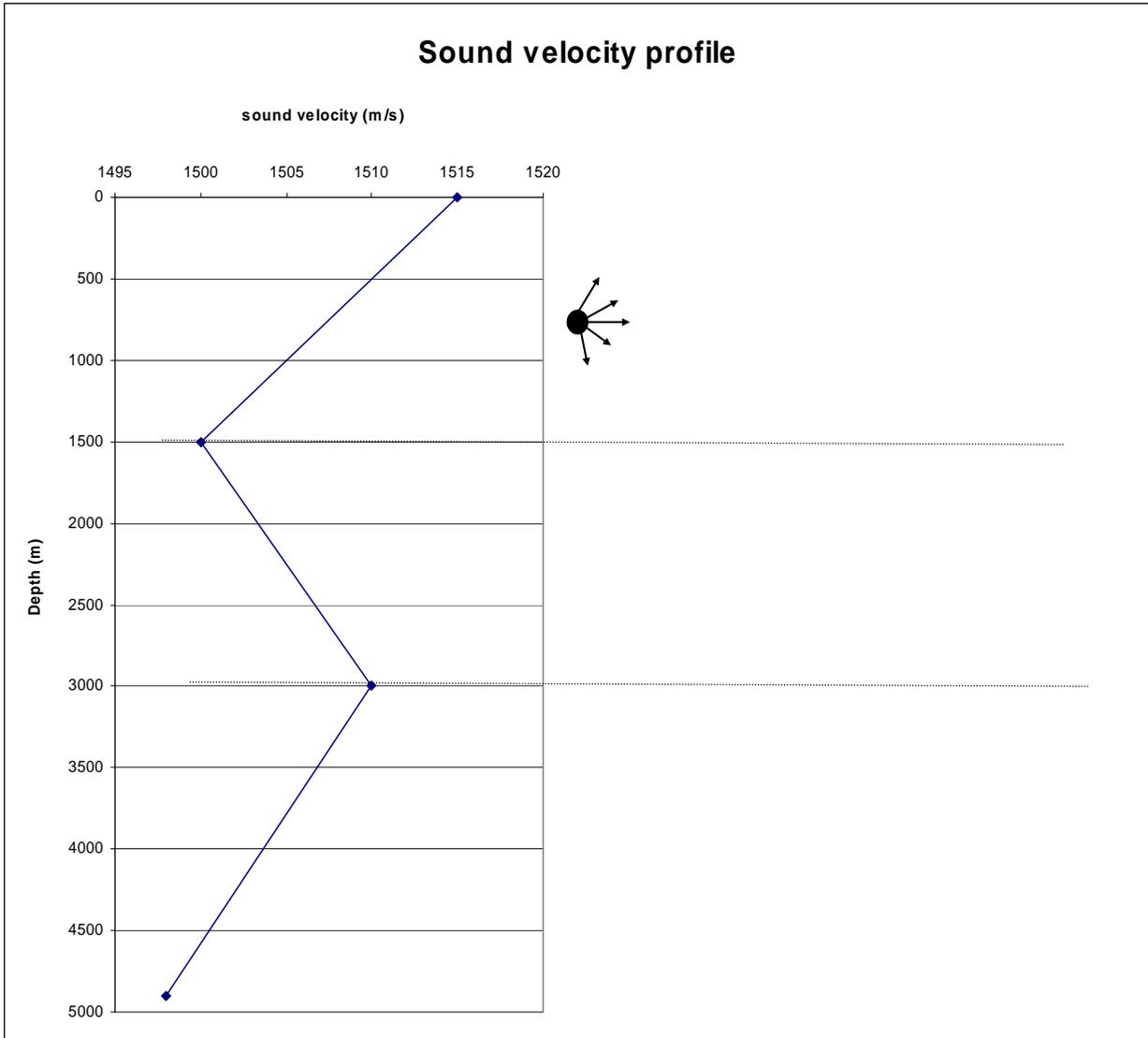
sound velocity (m/s)

8. In the following sound velocity profile draw rays leaving the source towards the right hand side of the page at a large variety of angles with respect to the horizontal to show any:
Surface duct ray paths
Bottom bounce ray paths
Shadow zones
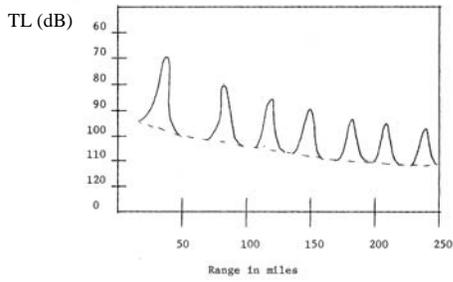Convergence zones
Limiting rays
The depth excess
Or other phenomena

Sound velocity profile
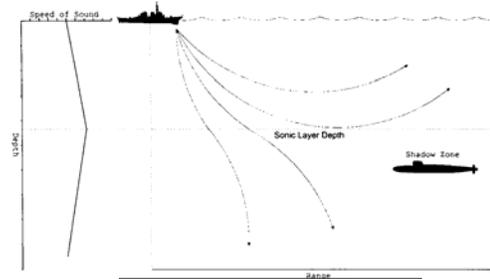
Lesson 5

Nominal SVP (Sound Velocity Profile)

Typical SVP

Gradients and Bending

Surface Duct – Surface Shadow Zone

Surface Shadow Zone Implications

Originally called the "afternoon effect"

Convergence Zone

Depth Excess > 300 fathoms

CZ Effect on Transmission Loss (TL)

TL (dB)

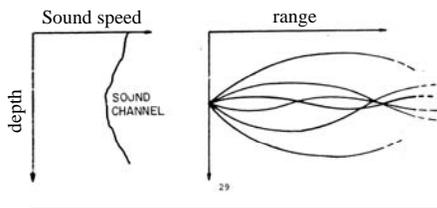

Range in miles

Deep Shadow Zones

$BD = 17(LD)1/2$ if $LD < 60m$.
$BD = LD + 60m$ if $LD > 60m$.

Deep sound channel

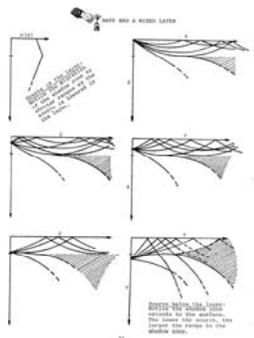## Mixed Layer Example

$D = 40$ m
$L = 100$ m
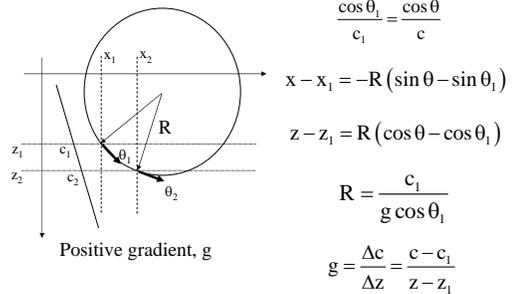$C_1 = 1500$ m/s
$g = 0.017$ s^{-1}
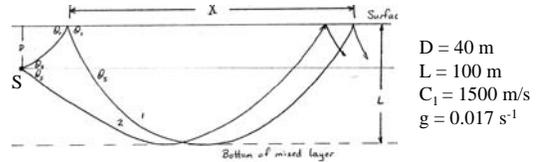
- Find sound speed at S and at bottom of layer
- Angle of the rays at the source
- Angle of the rays at the surface
- Radius of curvature of the ray
- Skip distance , X

Mixed Layer

Summary

Positive gradient, g

$$\frac{\cos \theta_1}{c_1} = \frac{\cos \theta}{c}$$

$$x - x_1 = -R\left(\sin \theta - \sin \theta_1\right)$$

$$z - z_1 = R\left(\cos \theta - \cos \theta_1\right)$$

$$R = \frac{c_1}{g \cos \theta_1}$$

$$g = \frac{\Delta c}{\Delta z} = \frac{c - c_1}{z - z_1}$$

Lesson 5

CONSTRUCTION OF RAY PATHS FOR TWO GRADIENTS