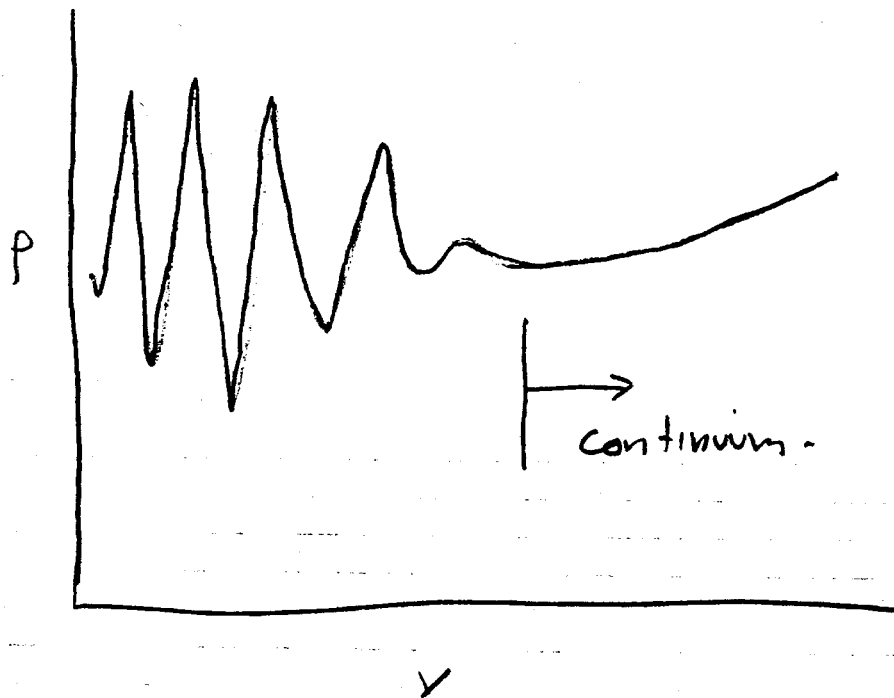


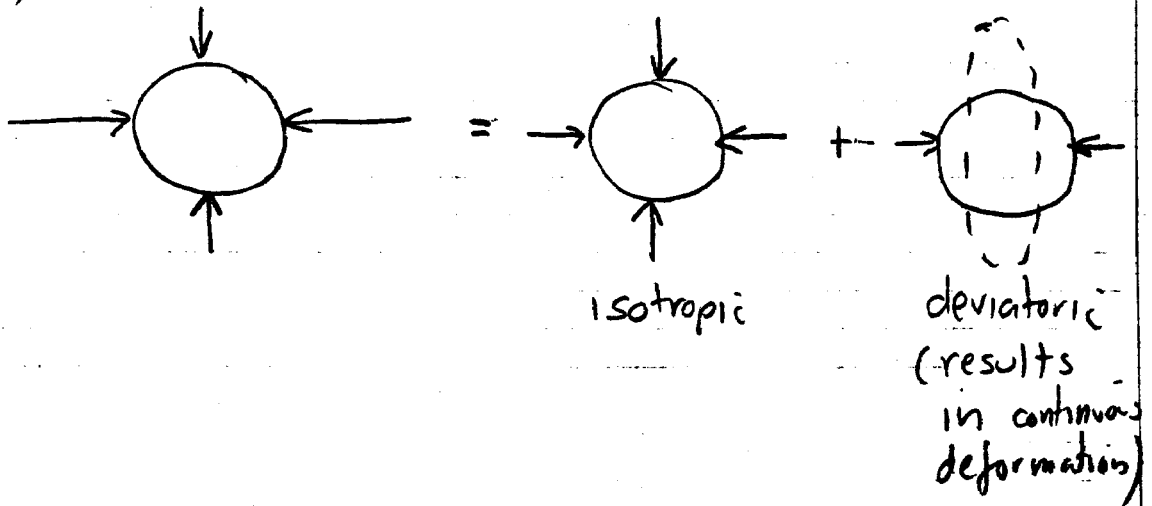
Figure 1



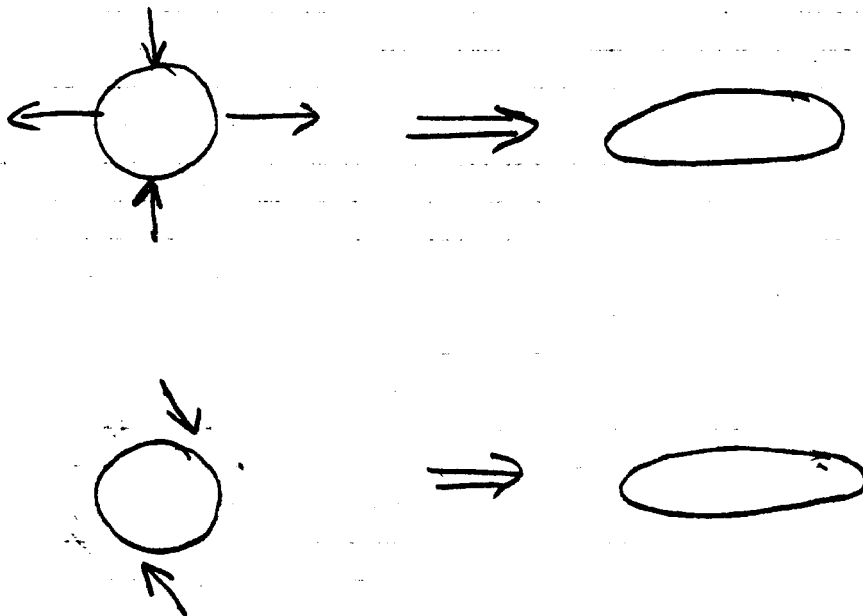
density  $\rho \equiv \text{mass} / \text{Volume}$

# FIGURE 2

(a)

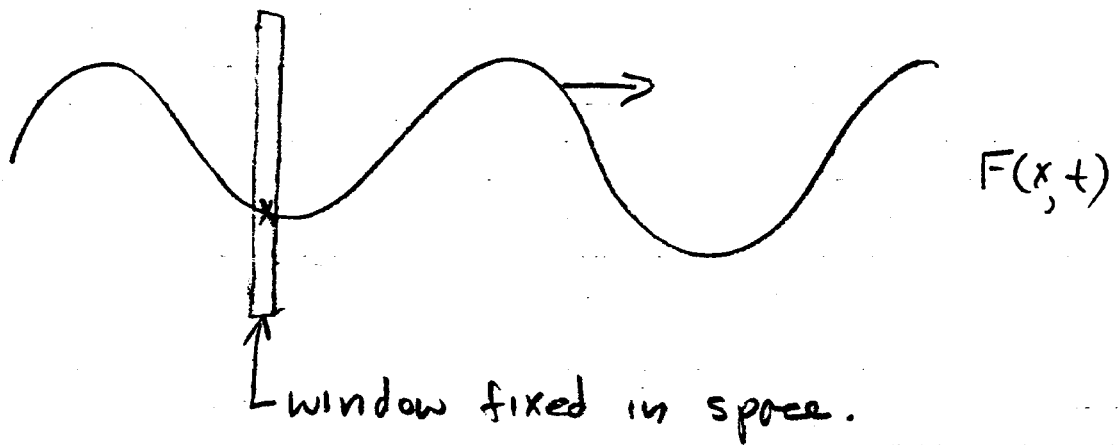


(b)



Non-isotropic normal and shear forces are equivalent.

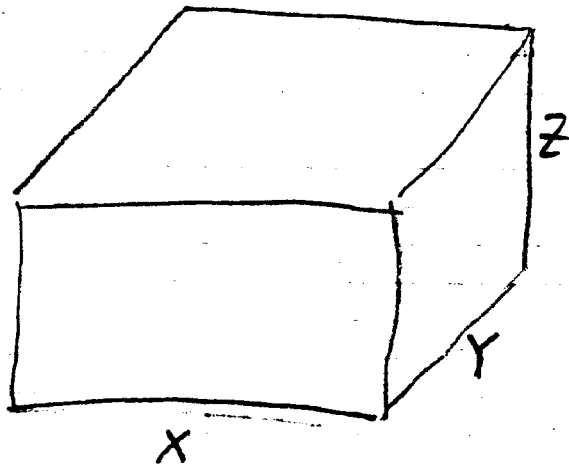
Figure 3.



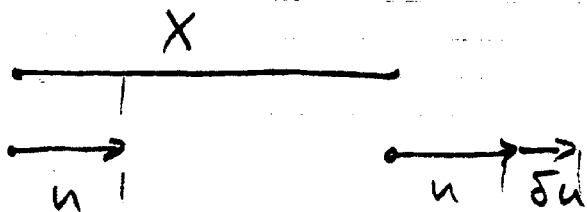
$F(x, t)$  is a sinusoid moving to the right:

- (a) An observer who moves with  $F$  and looks at one point will see a constant.
- (b) An observer fixed in space who observes  $F$  through a slit which is also fixed will see a value that oscillates up and down.

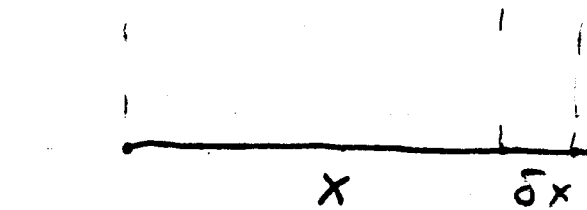
Figure 4



$t=0$

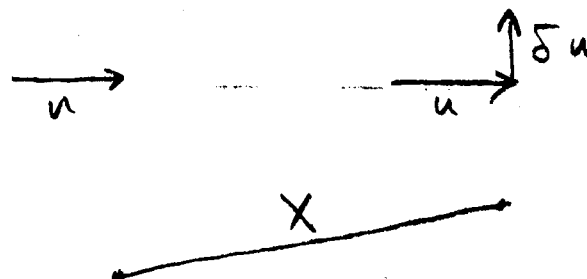


(a)  $t = \delta t$



side is stretched

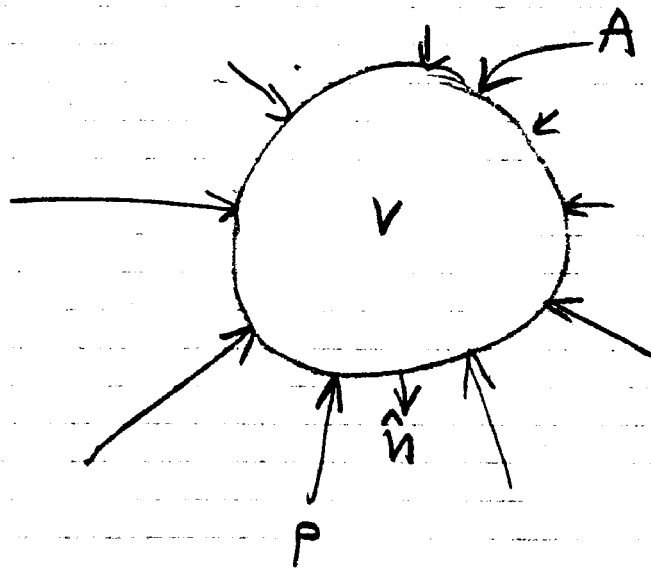
(b)  $t = \delta t$



side is rotated.

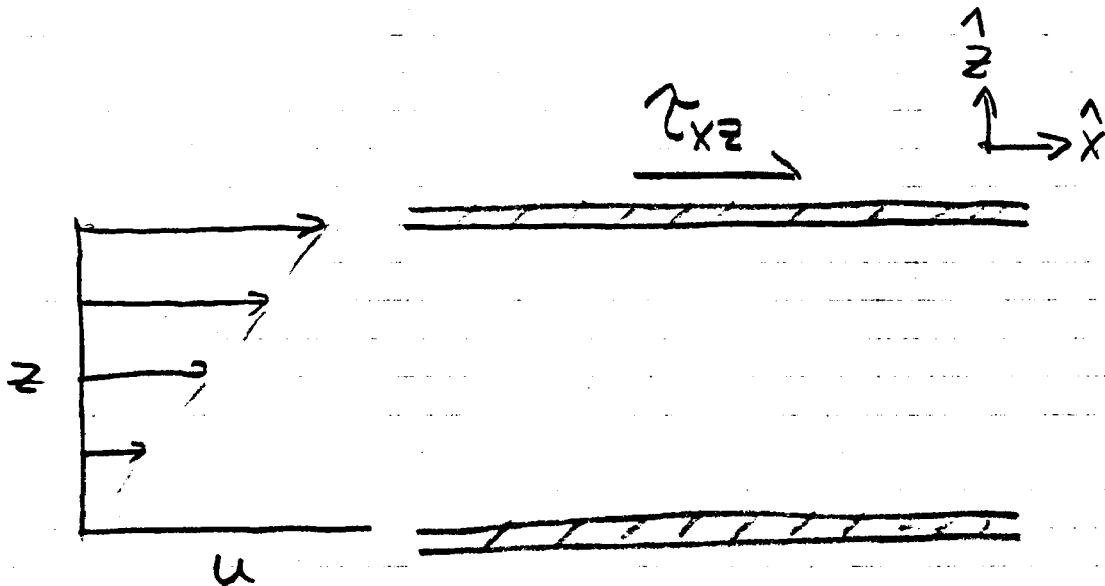
## FIGURE 5

Non-Uniform normal forces acting on a small volume of fluid.



$$\text{normal force/unit area} = -p\hat{n}$$

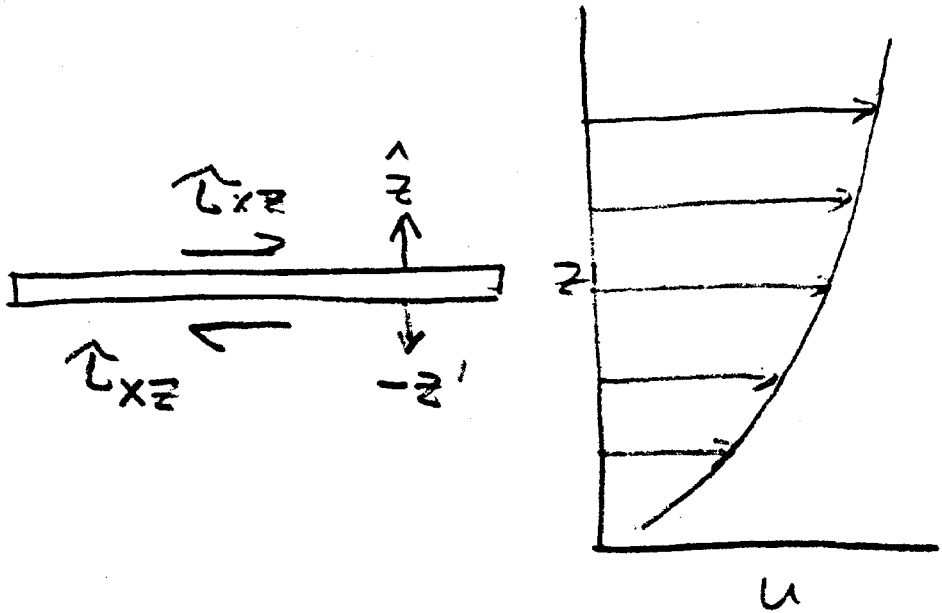
FIGURE 6



$$\tau_{xz} = \mu \frac{\partial u}{\partial z}$$

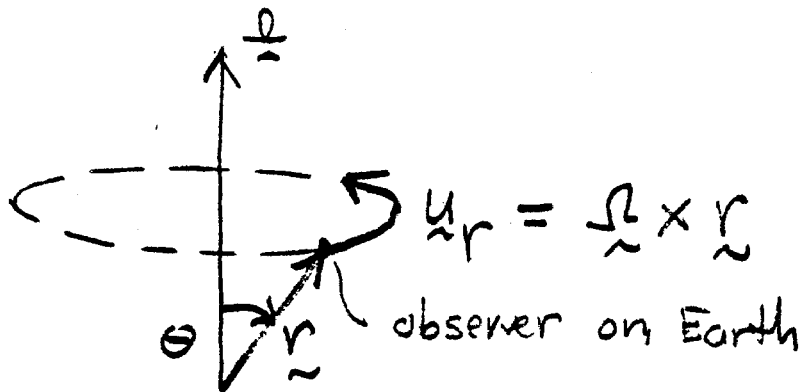
Couette Flow

# FIGURE 7

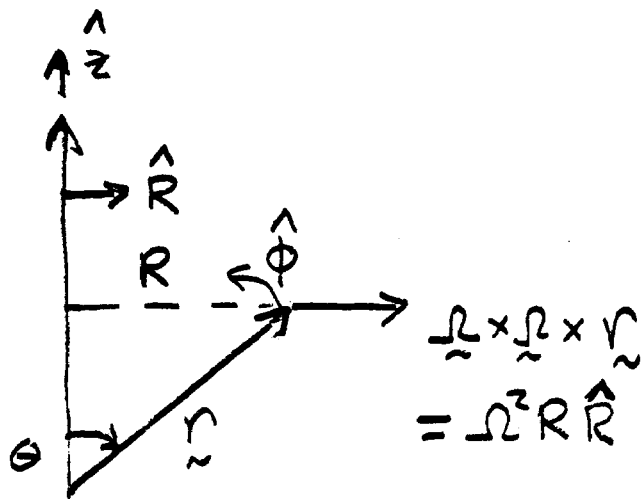


# FIGURE 8

(a)



(b)





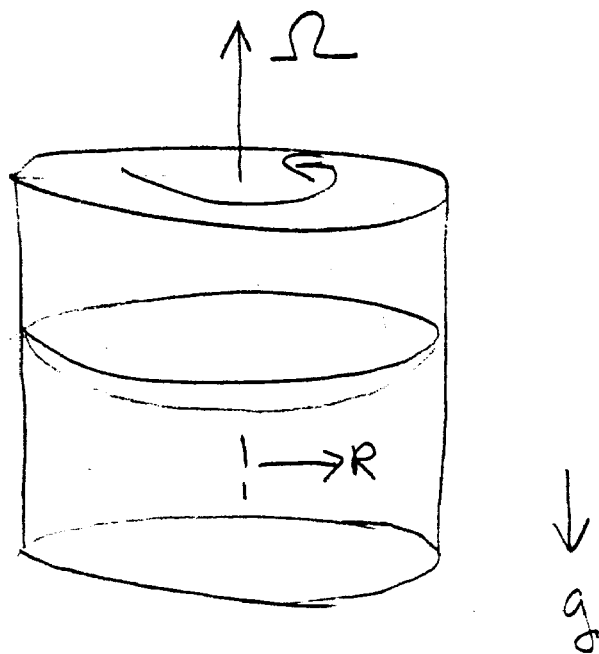
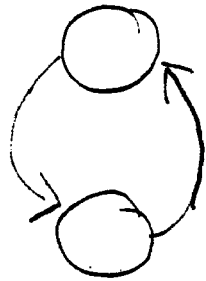


FIGURE 9

# FIGURE 10

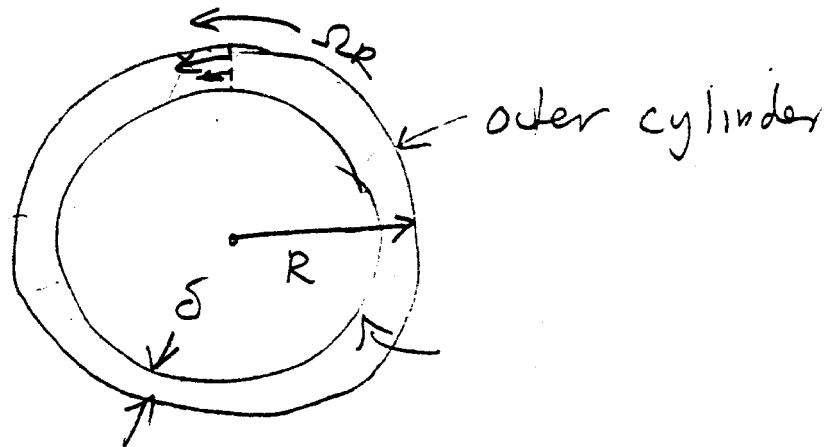
————— surface  
 $P = P_{atm}$



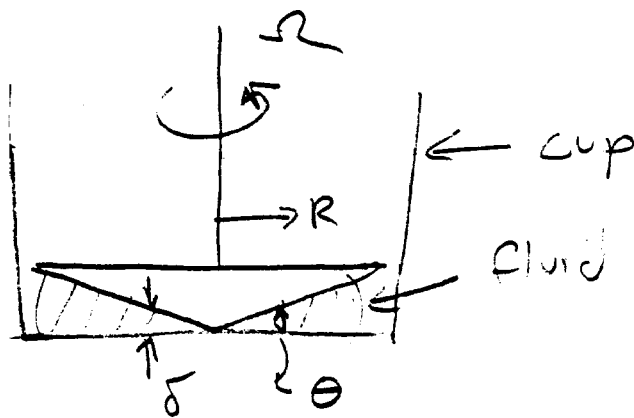
————— bottom

## FIGURE 11

(a) Rotating "Couette" Flow (Top View)



(b) Cone-Plate "Couette" Flow (side view)



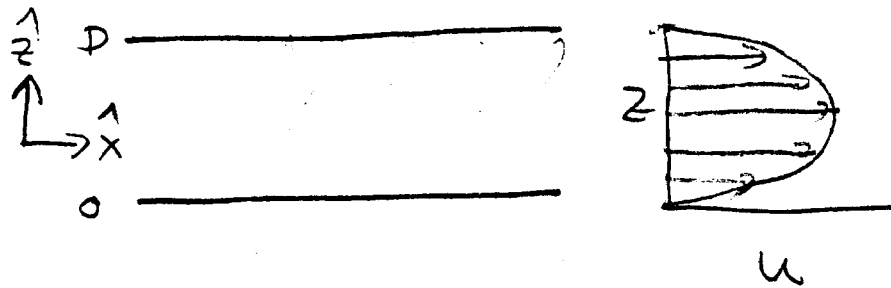
$$u(R) = \Omega R$$

$$\delta(R) = R \tan \theta \approx R \theta$$

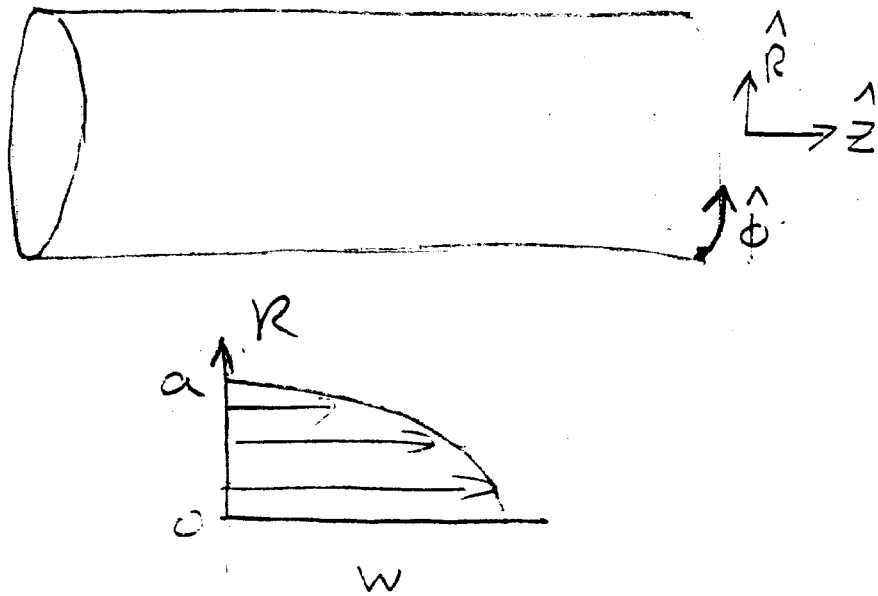
$$\frac{\partial u}{\partial z} = \frac{u}{\delta} = \frac{\Omega}{\theta} = \text{constant}$$

# FIGURE 12

(a) Plane Poiseuille Flow

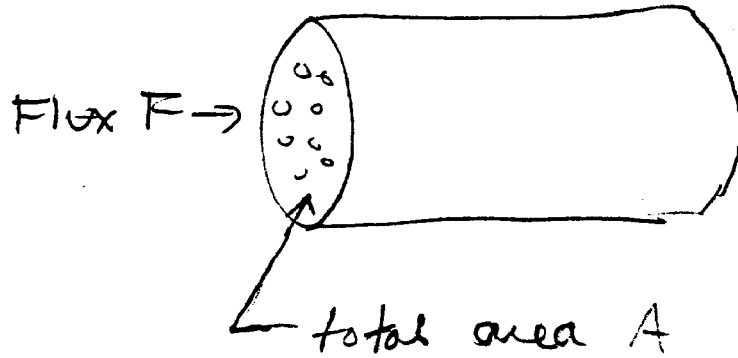


(b) Cylindrical Poiseuille Flow  
(Pipe Flow)



# FIGURE 13

(a) Porous medium



$$u_{avg} = F/A$$

(b) Hele-Shaw Cell

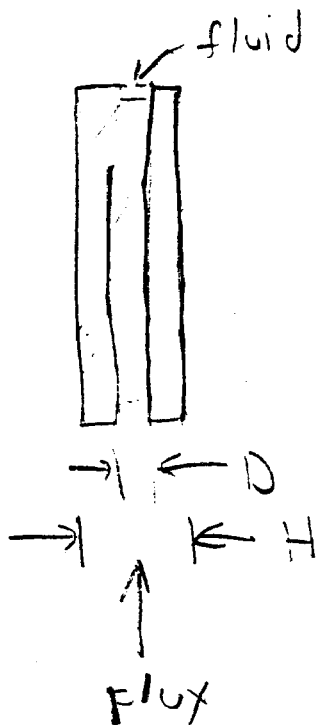


FIGURE 14

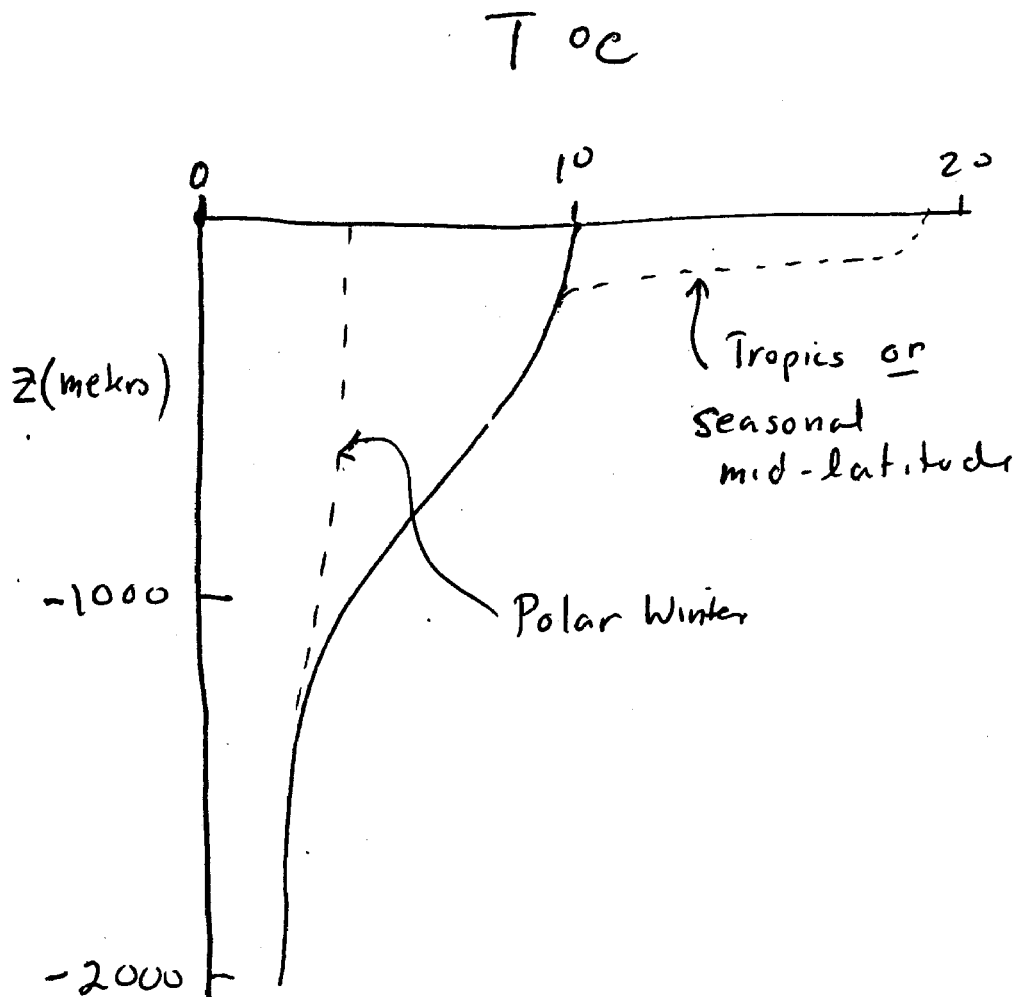
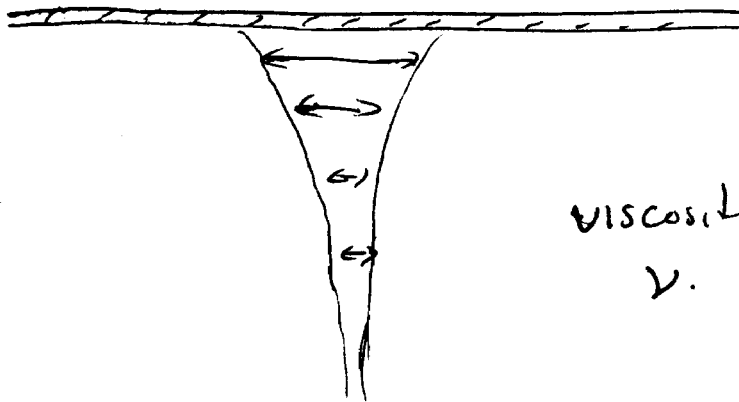
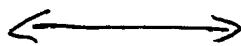


FIGURE 15

$$u = U \cos(\omega t)$$



viscosity  
 $\nu$ .

# FIGURE 16

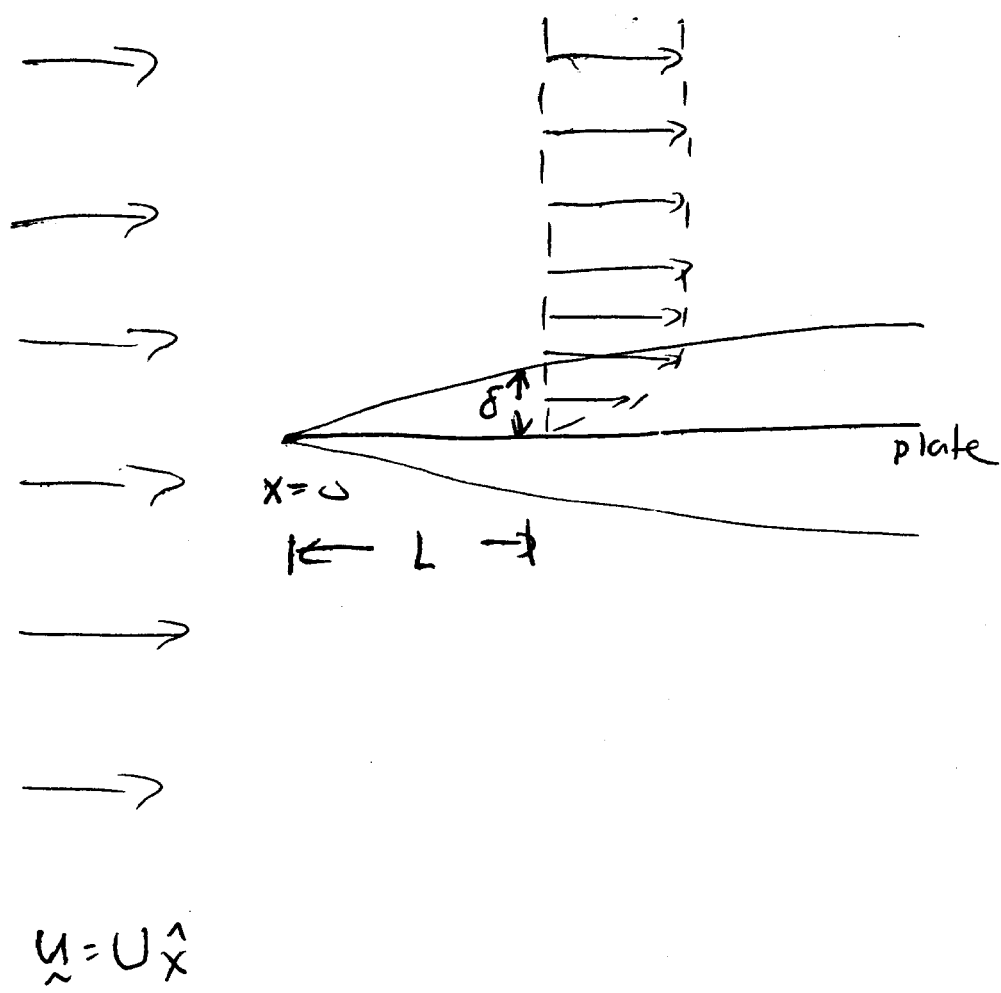
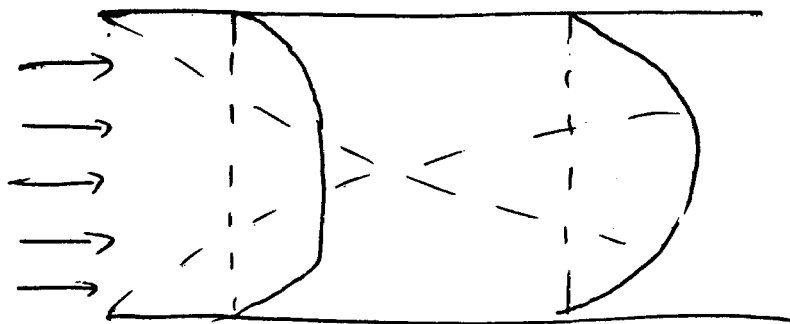




FIGURE 17



also see figure 2.5 in Tritton

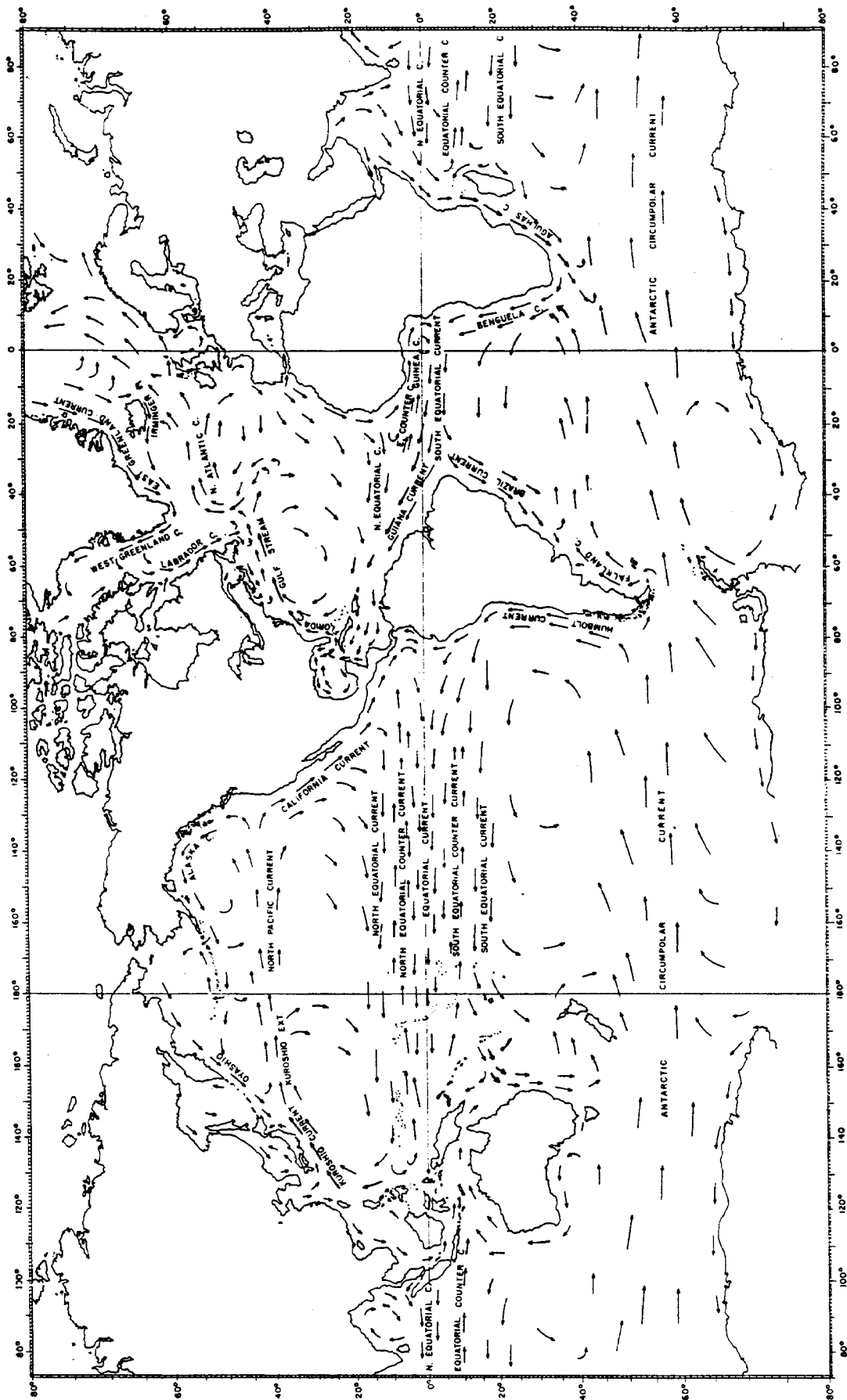
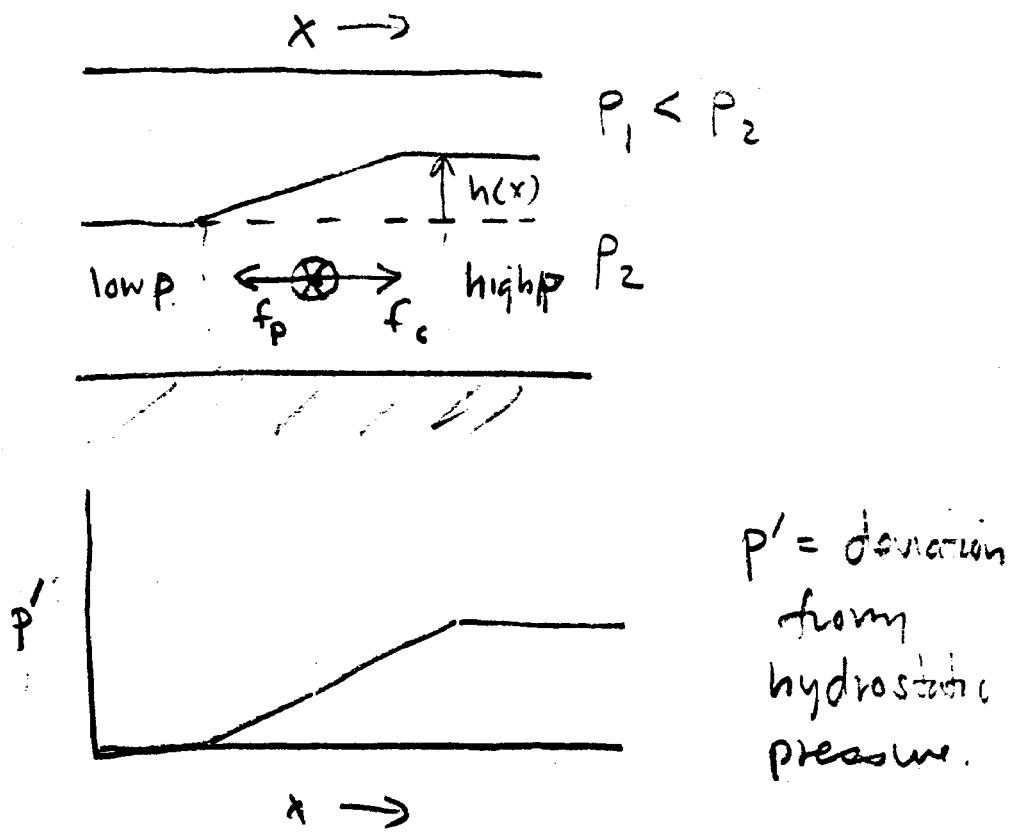


FIGURE 18

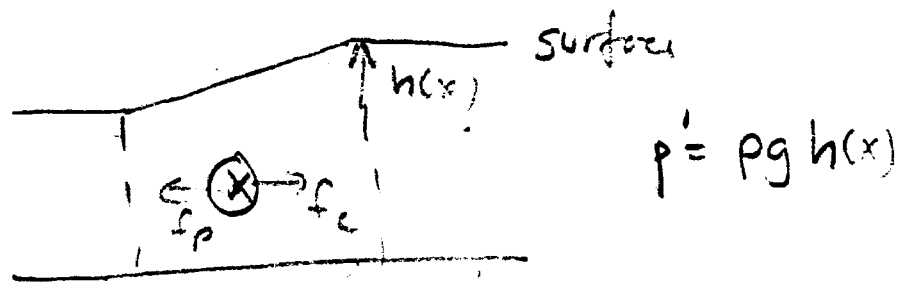
FIGURE 19

(a)



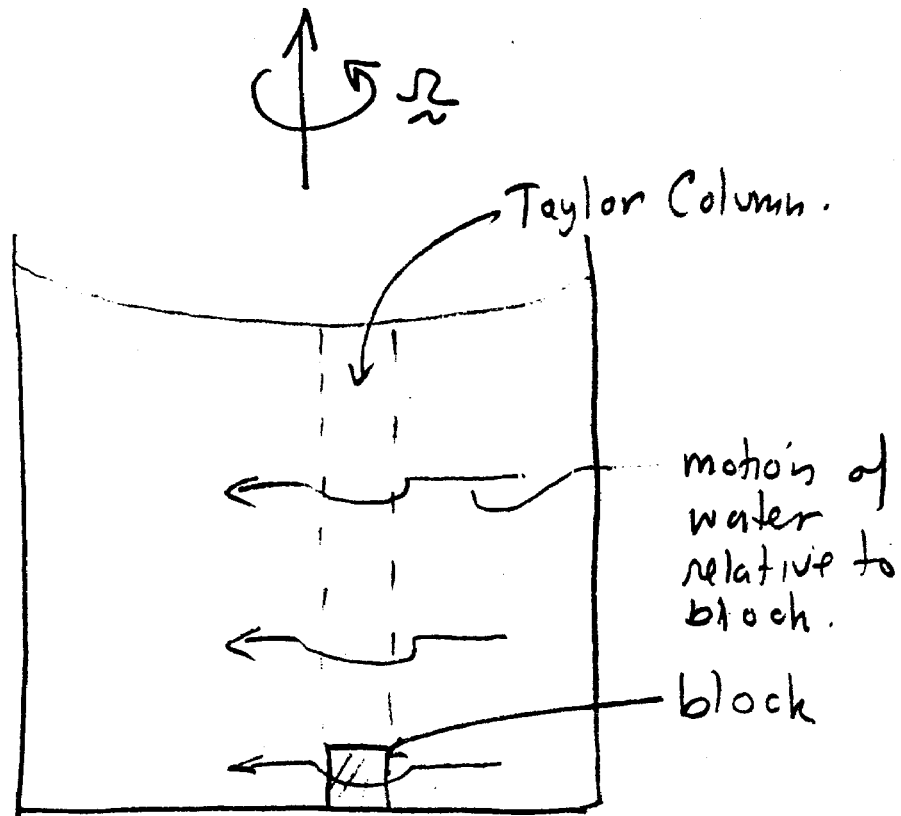
There is a baroclinic geostrophic current northward (in N. hem.) in lower layer.

(b)



The pressure gradient force  $\nabla p'$  is independent of depth. There is a barotropic geostrophic current at all depths.

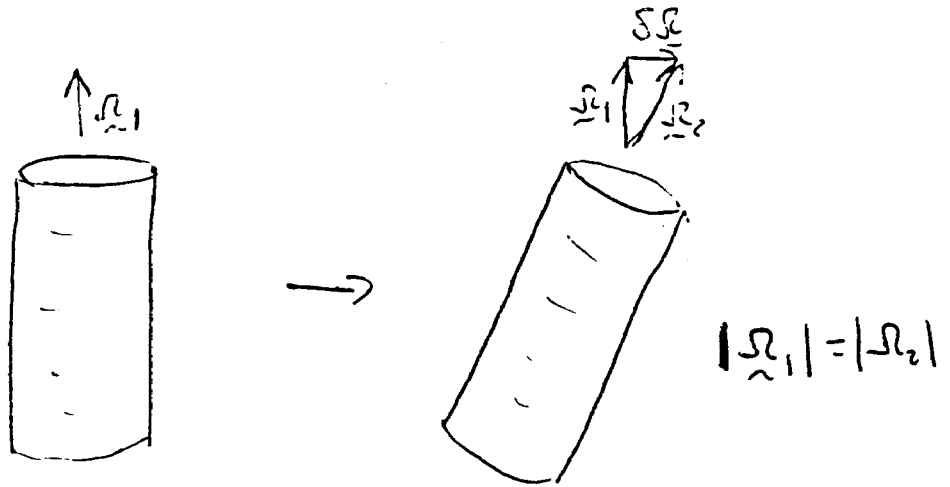
# FIGURE 20



Block moves very slowly relative to rotating tank.

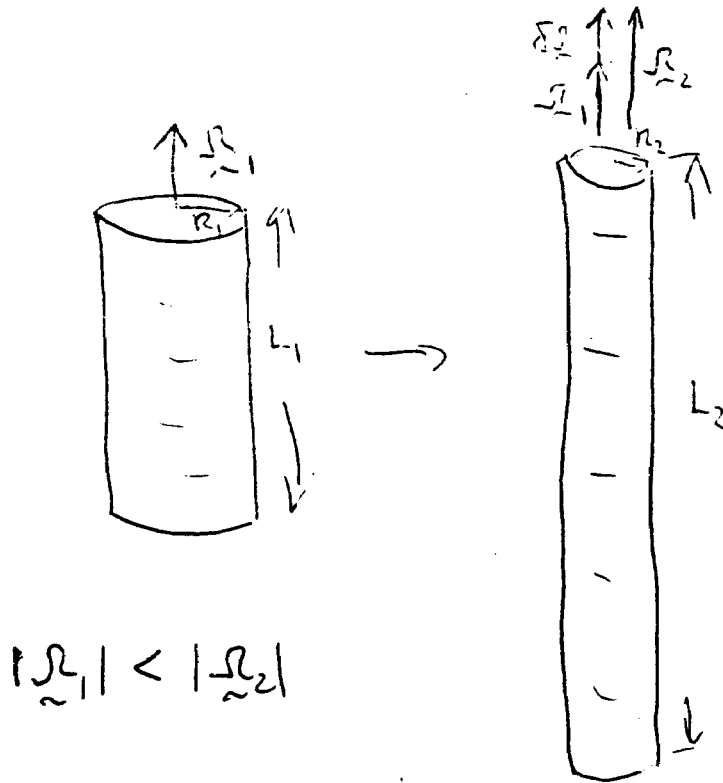
# FIGURE 21

(a)



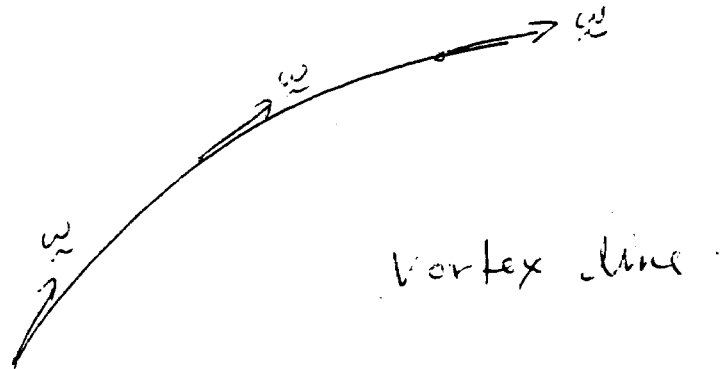
Twisting (or tilting)

(b)



stretching

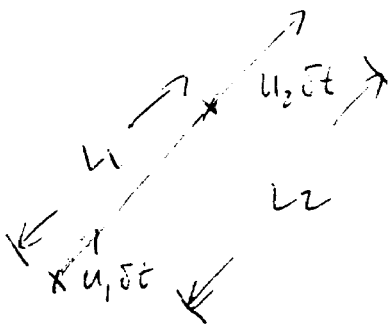
FIGURE 22



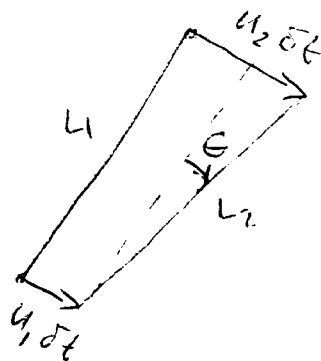
$$\underline{\omega} = \nabla \times \underline{u}$$

$$\underline{u} \parallel \underline{\omega}$$

$$\underline{u} \perp \underline{\omega}$$



$$u_2 > u_1 \Rightarrow L_2 > L_1$$



$$u_2 > u_1 \Rightarrow \theta > 0$$

If small,  $L_1 \approx L_2$

# FIGURE 23

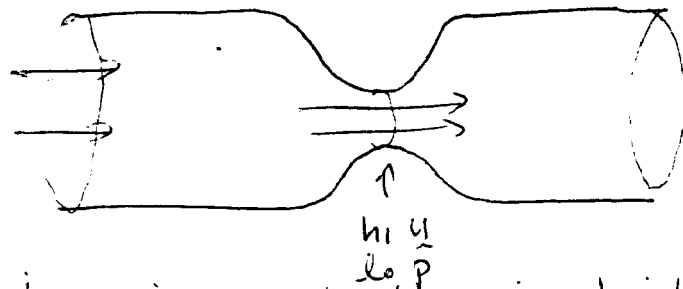
Bernoulli's Theorem  $\Rightarrow$   $P$  inversely proportional to  $u^2$ .

(a) Air foil



velocity above air foil higher due to longer path.

(b) Venturi



velocity in constriction is high due to small cross section.

(c) Corrugation

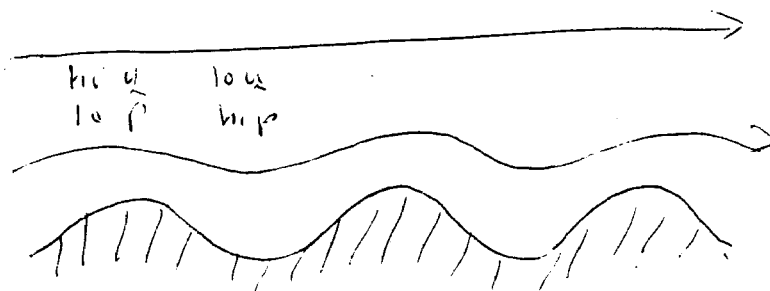
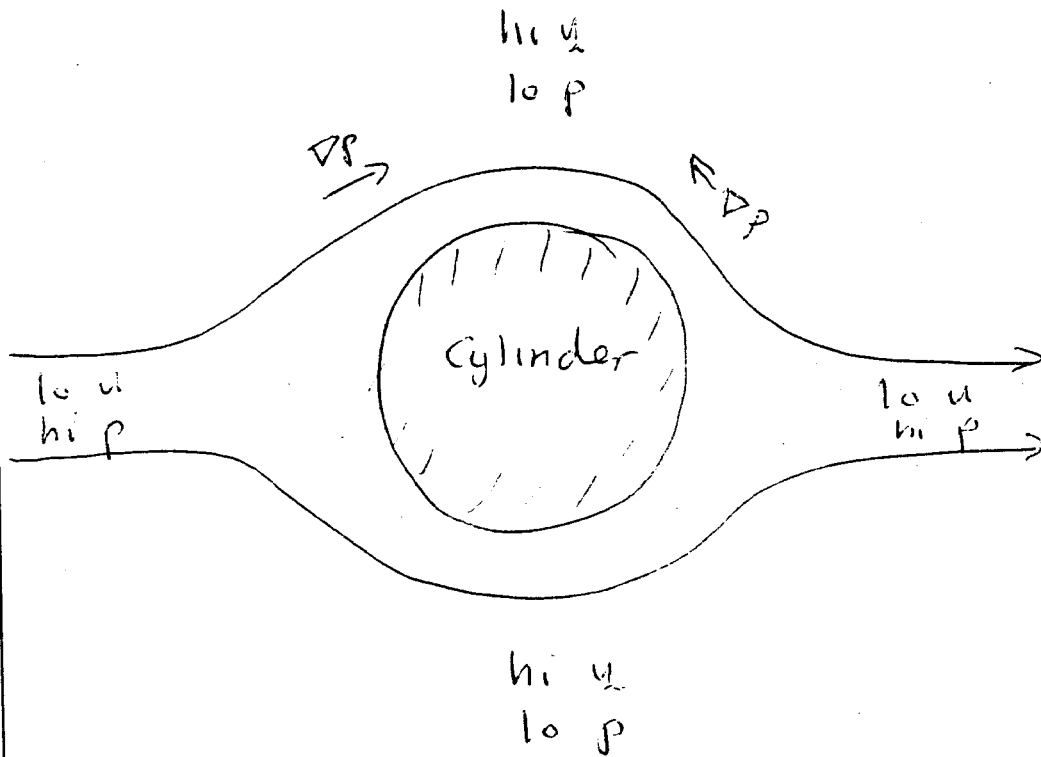
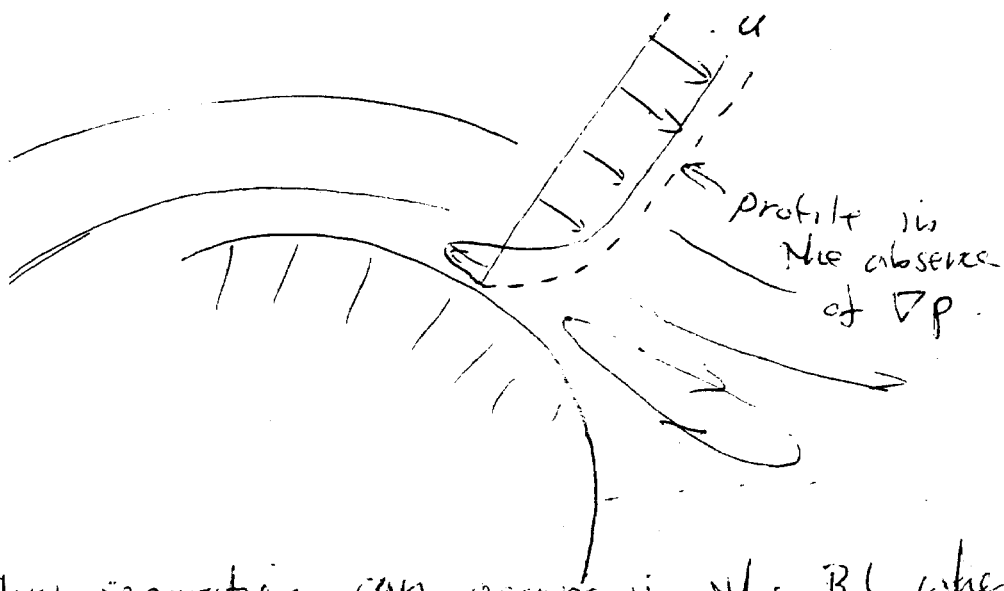


FIGURE 24



Note that  $\nabla p$  is in direction needed to accelerate fluid.

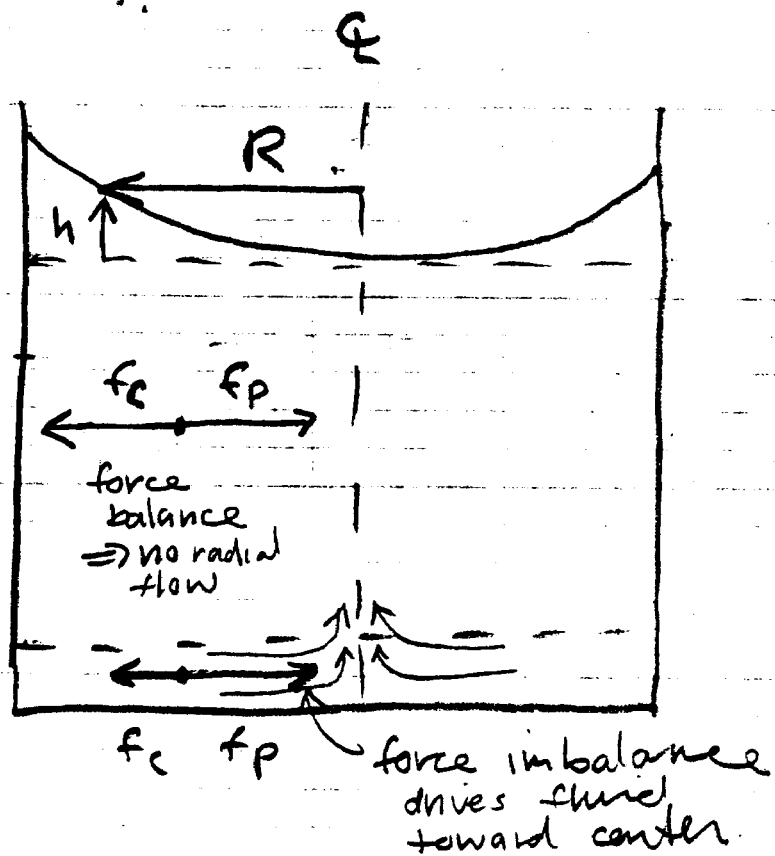


Flow separation can occur in the B.L. when  $\nabla p$  reverses local flow.



## FIGURE 25

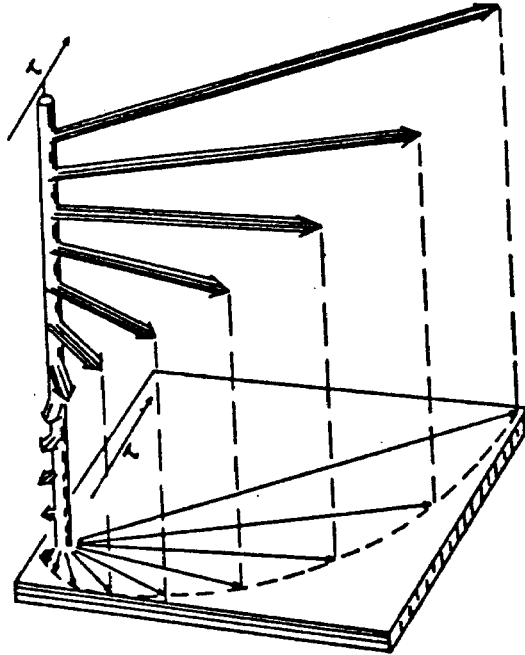
$f_c$  = centrifugal force  
due to rotation  
(decreases in  
boundary layer)



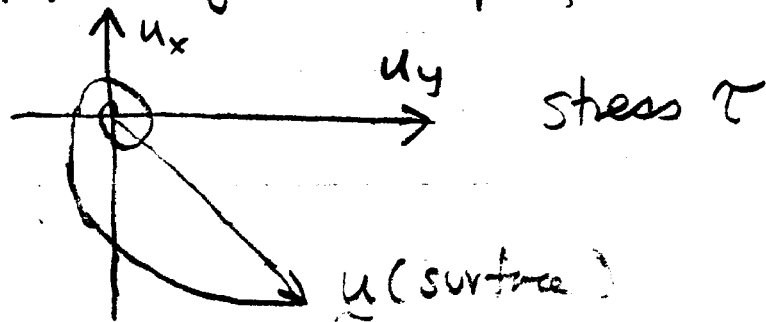
$f_p$  = pressure gradient force  
due to tilt of surface  
(increases linearly with  
 $R \Rightarrow$  slope increases  
with  $R$ ).

# FIGURE 26

(a) Ekman Spiral (side view)



(b) Ekman layer on top of stationary fluid



(c) Ekman layer on fixed lower boundary

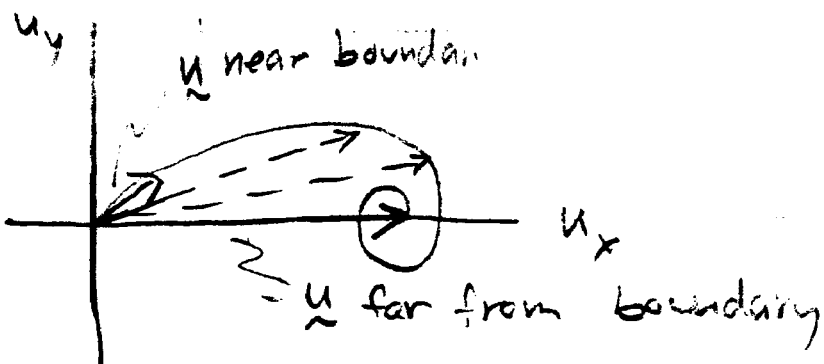
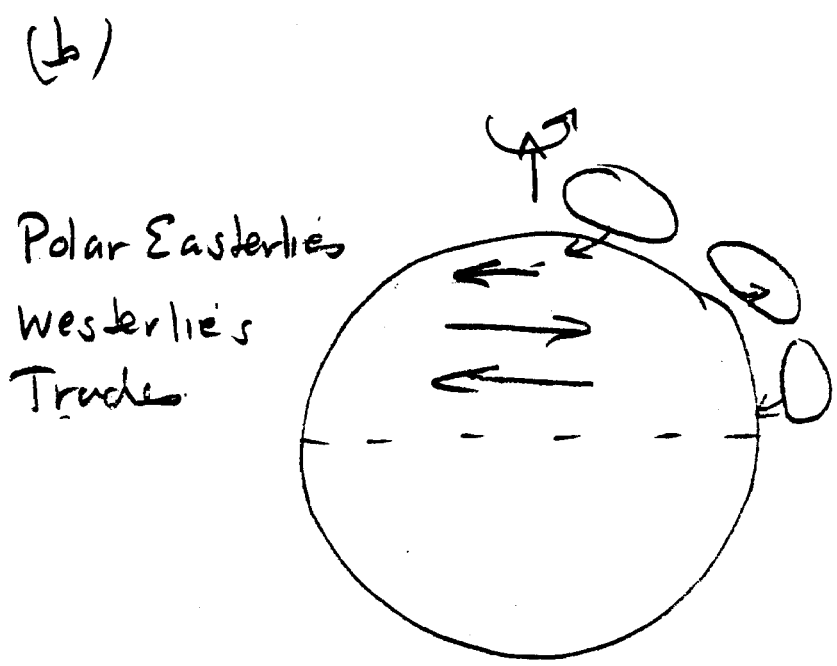
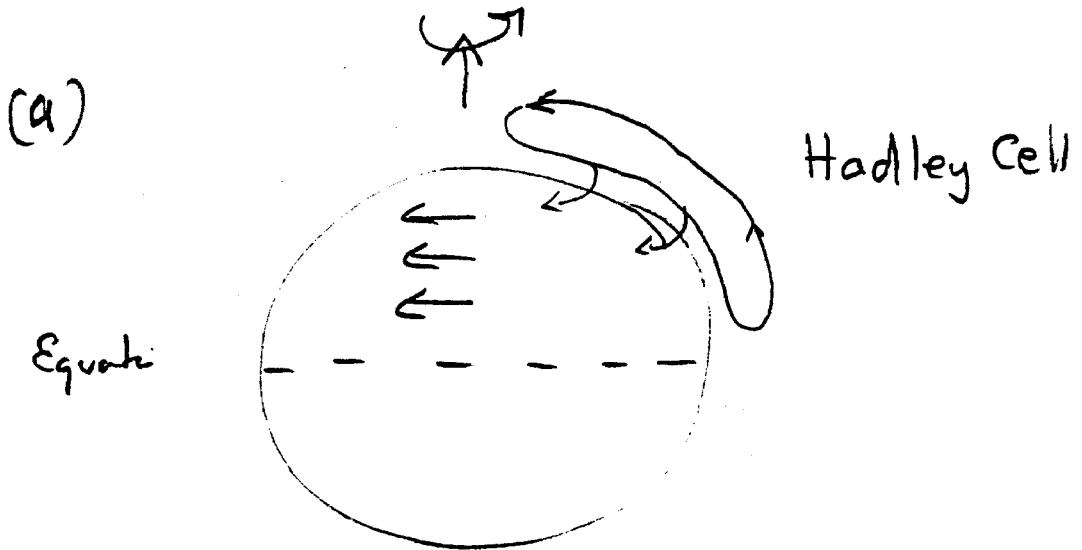
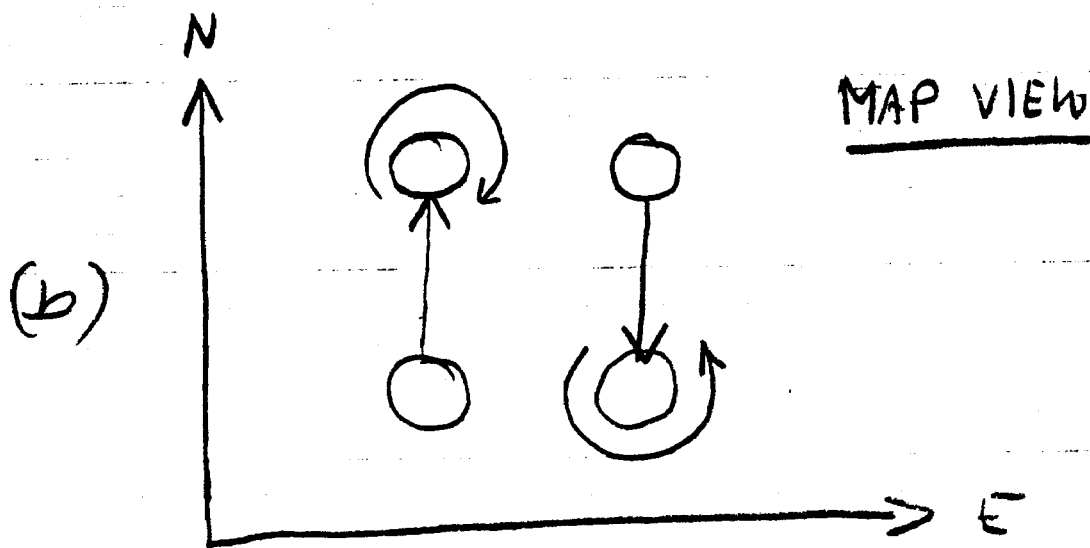
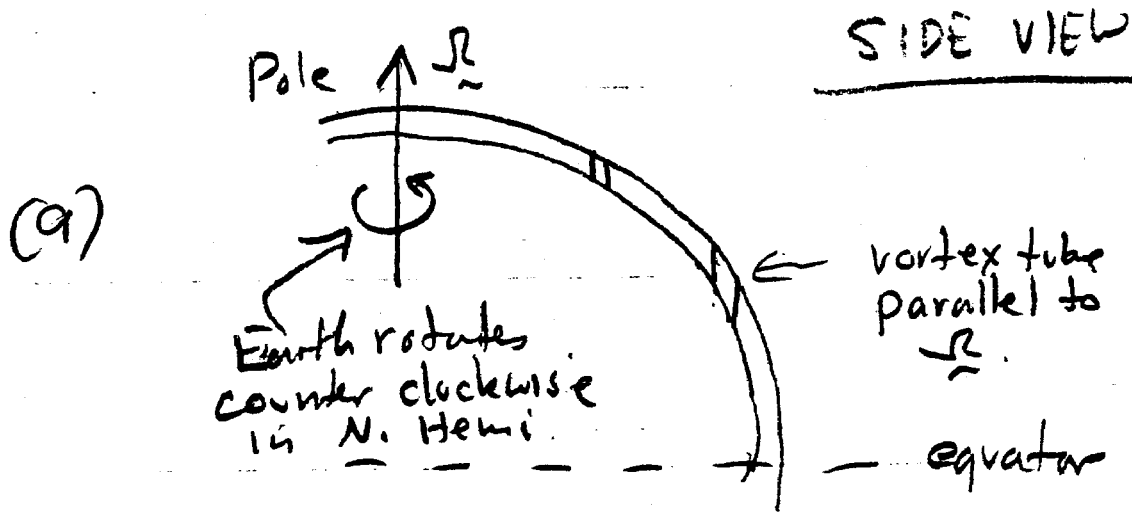


FIGURE 27



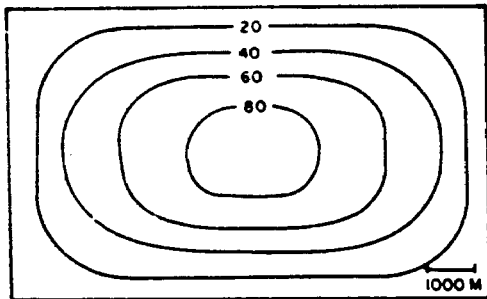
# FIGURE 28



Northward displacement creates clockwise rotation [shortens vortex tube]

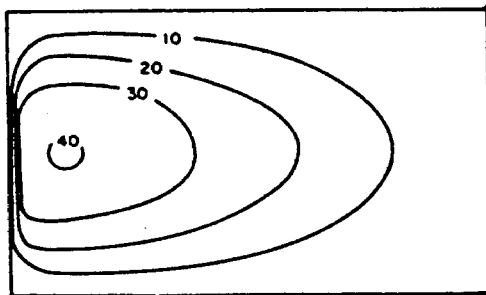
Southward displacement creates counter clockwise rotation [stretches vortex tube]

# FIGURE 29



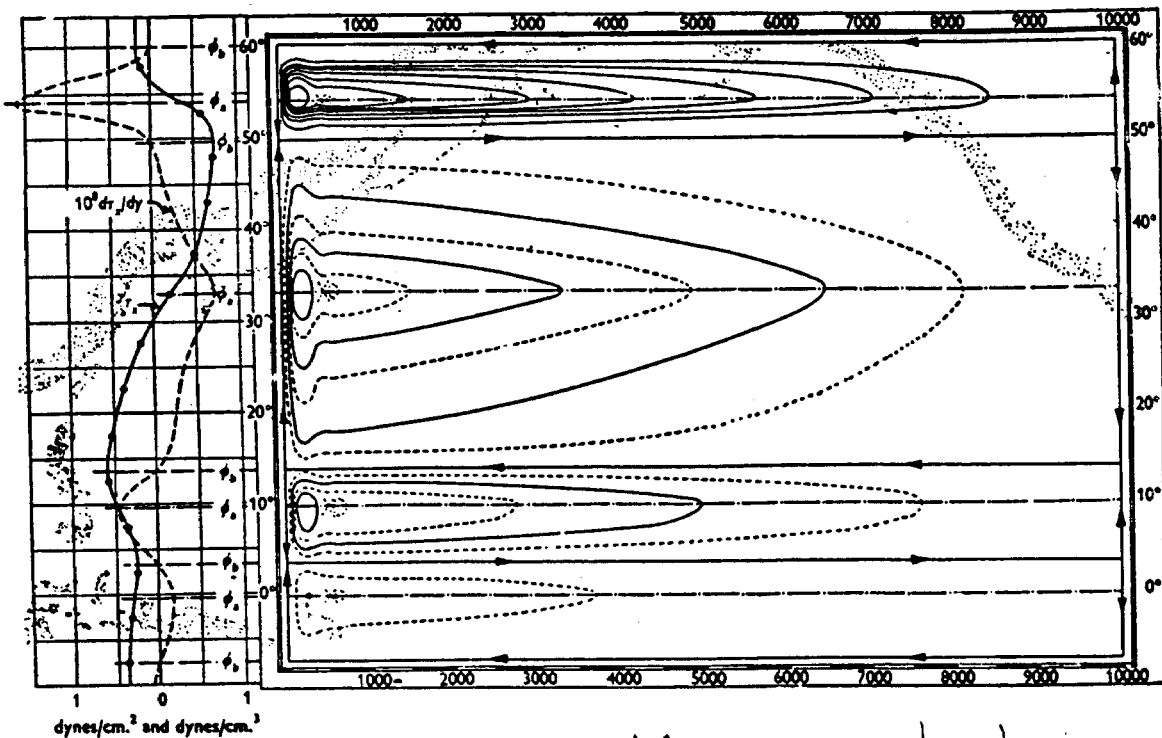
A. NON ROTATING OR UNIFORMLY ROTATING OCEAN (STOMMEL 1948 FIG. 2)

No stretching  
of vortex  
tubes



B. CORIOLIS PARAMETER A LINEAR FUNCTION OF LATITUDE (STOMMEL 1948 FIG. 5)

Stretching  
linearly  
proportional  
to latitude

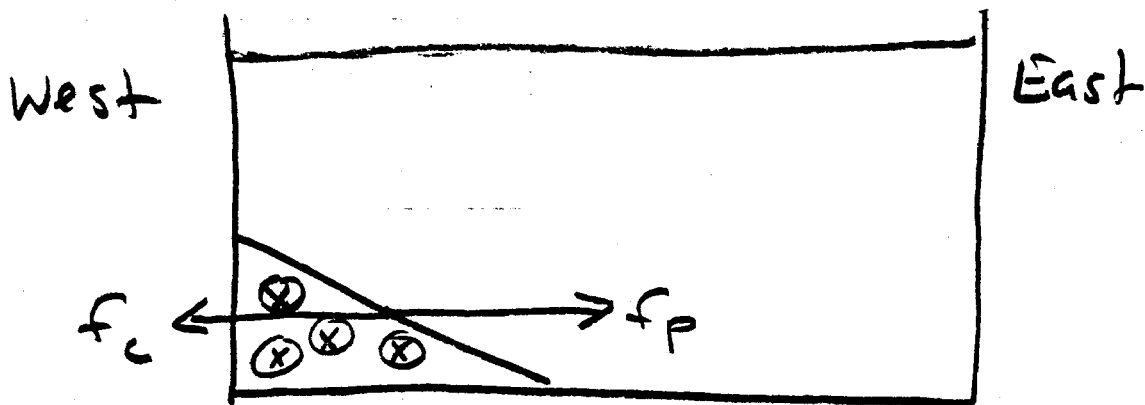


dynes/cm.<sup>2</sup> and dynes/cm.<sup>3</sup>

— wind  
- - - wind stress

More realistic  
picture

Figure 30(a)

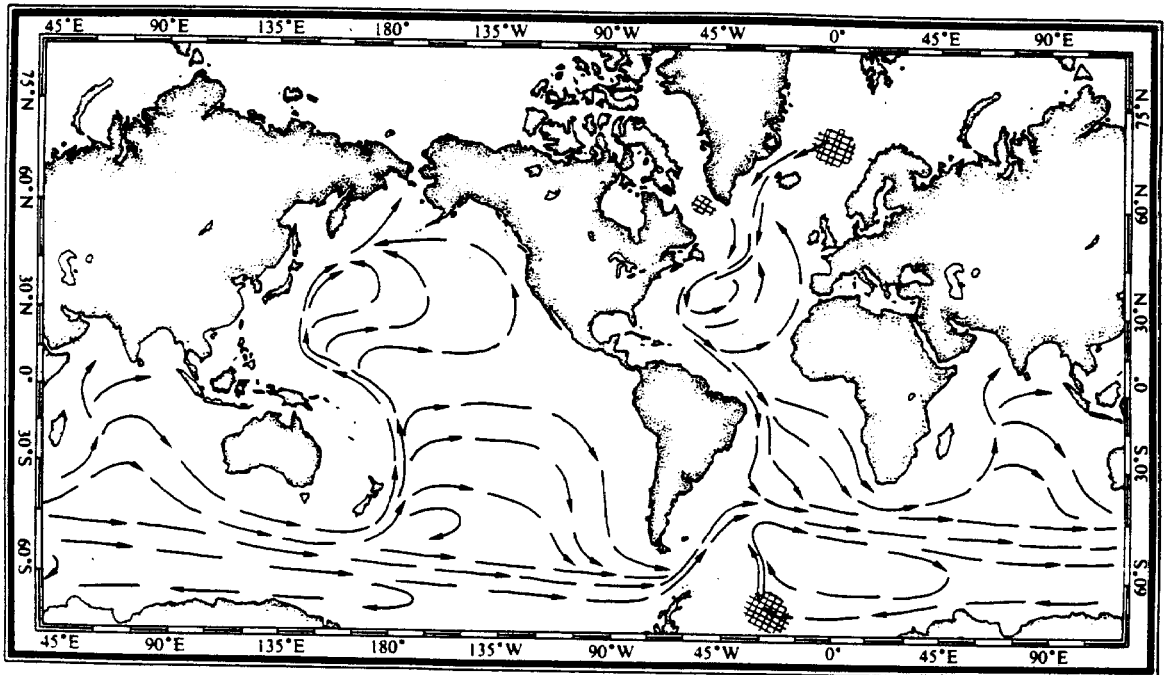


Schematic cross section  
of South Atlantic

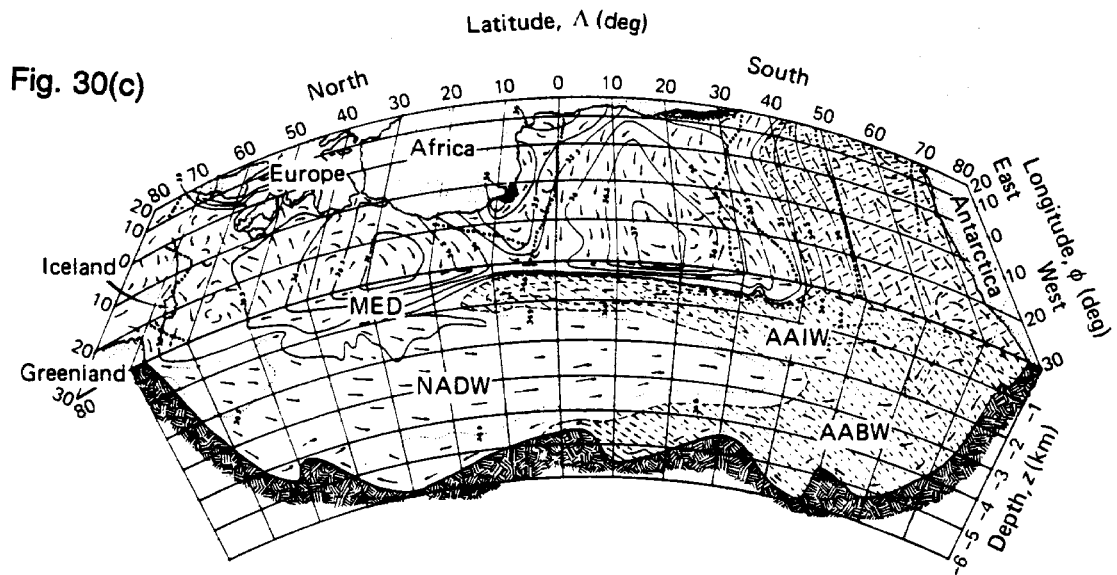
13/82 500 SHEETS, FILLER, 5 SQUARE  
42/81 50 SHEETS, EYE-EASE, 5 SQUARE  
42/82 100 SHEETS, EYE-EASE, 5 SQUARE  
42/83 100 SHEETS, EYE-EASE, 5 SQUARE  
42/84 100 SHEETS, EYE-EASE, 5 SQUARE  
42/85 100 SHEETS, EYE-EASE, 5 SQUARE  
42/86 100 SHEETS, EYE-EASE, 5 SQUARE  
42/87 100 SHEETS, EYE-EASE, 5 SQUARE  
42/88 100 SHEETS, EYE-EASE, 5 SQUARE  
42/89 100 SHEETS, EYE-EASE, 5 SQUARE  
42/90 100 SHEETS, EYE-EASE, 5 SQUARE  
42/91 100 SHEETS, EYE-EASE, 5 SQUARE  
42/92 100 SHEETS, EYE-EASE, 5 SQUARE  
42/93 100 SHEETS, EYE-EASE, 5 SQUARE  
42/94 100 SHEETS, EYE-EASE, 5 SQUARE  
42/95 100 SHEETS, EYE-EASE, 5 SQUARE  
42/96 100 SHEETS, EYE-EASE, 5 SQUARE  
42/97 100 SHEETS, EYE-EASE, 5 SQUARE  
42/98 100 SHEETS, EYE-EASE, 5 SQUARE  
42/99 100 SHEETS, EYE-EASE, 5 SQUARE  
42/100 100 SHEETS, EYE-EASE, 5 SQUARE  
MADE IN U.S.A.



Fig. 30(b)



Schematic flow lines for abyssal circulation. The cross-hatched areas indicate regions of production of bottom water. [Adapted from Stommel, H., *Deep Sea Research* (1958).]



Schematic cross section of surface and subsurface currents in the North and South Atlantic. [Adapted from Wüst, G., *Kieler Meeresforschungen* (1950).]

Figure 31

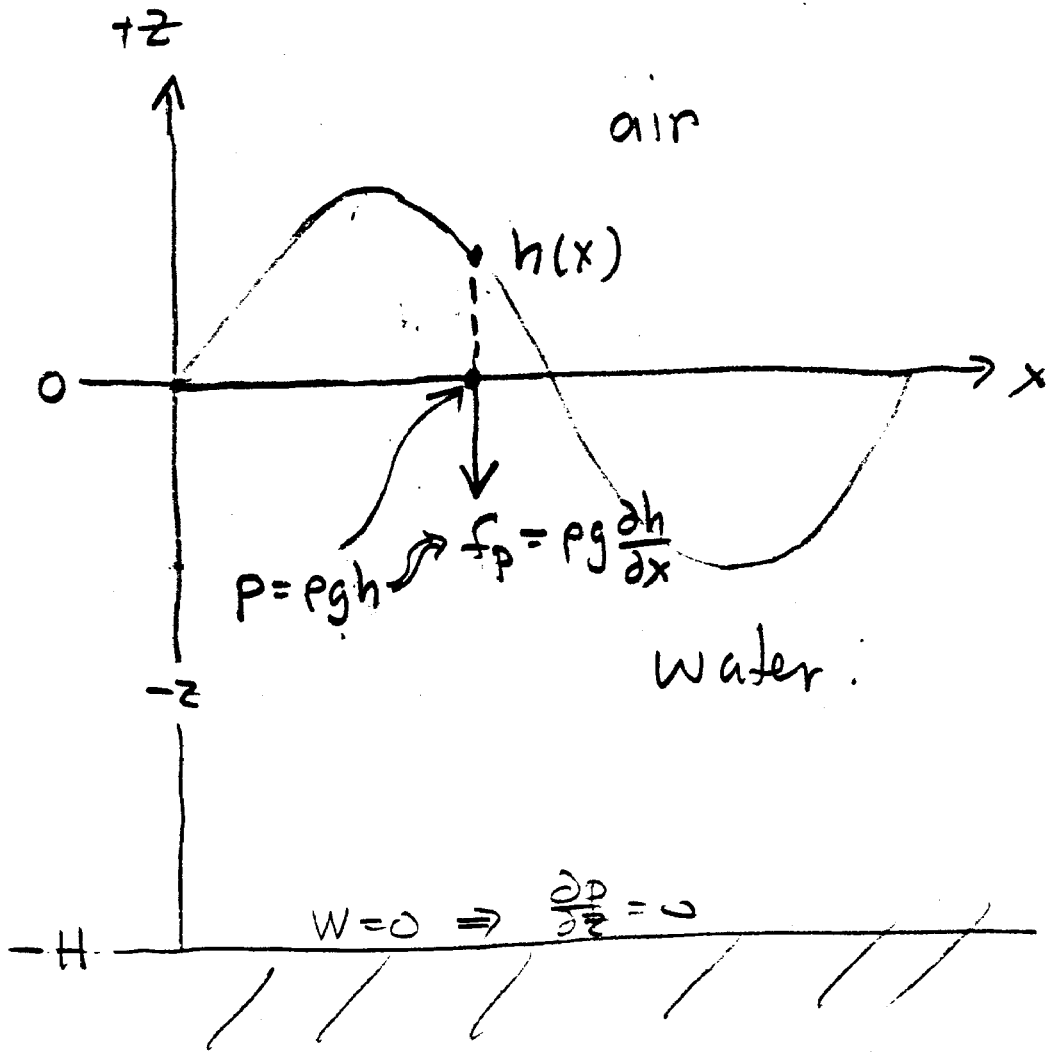
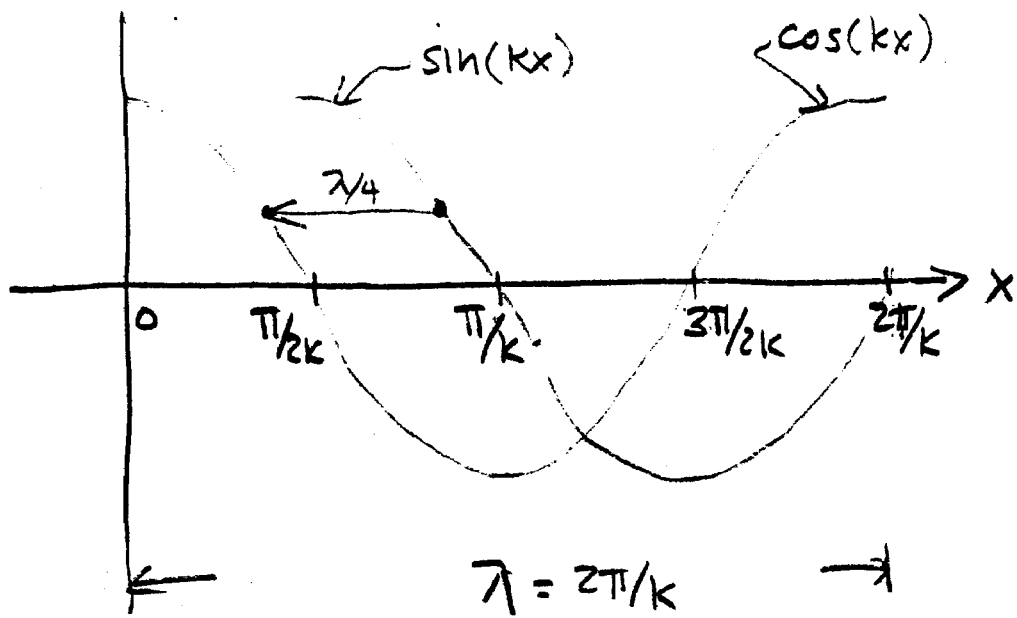




Figure 32

(a)



(b)

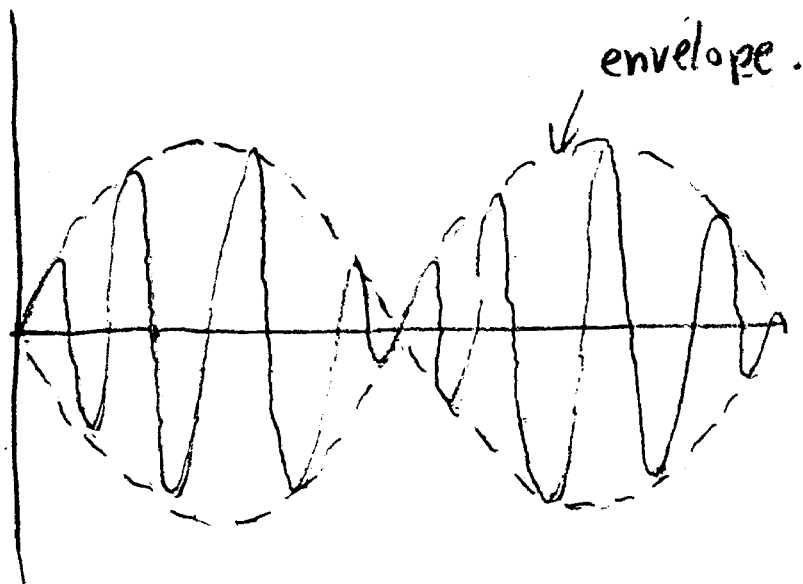
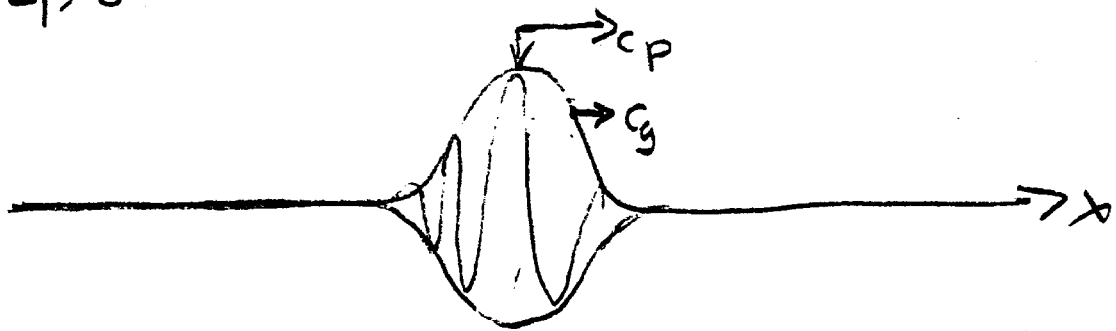


Figure 33

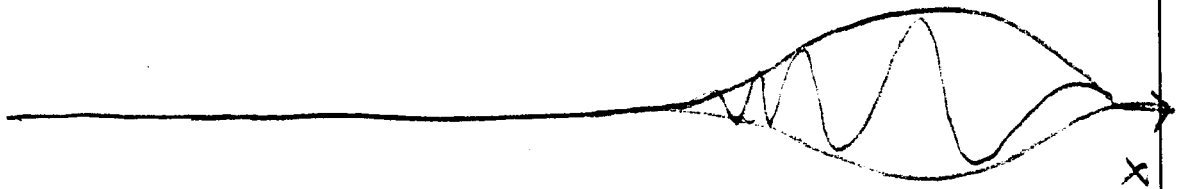
$t \approx 0$



$t_1 > 0$



$t_2 > t_1$



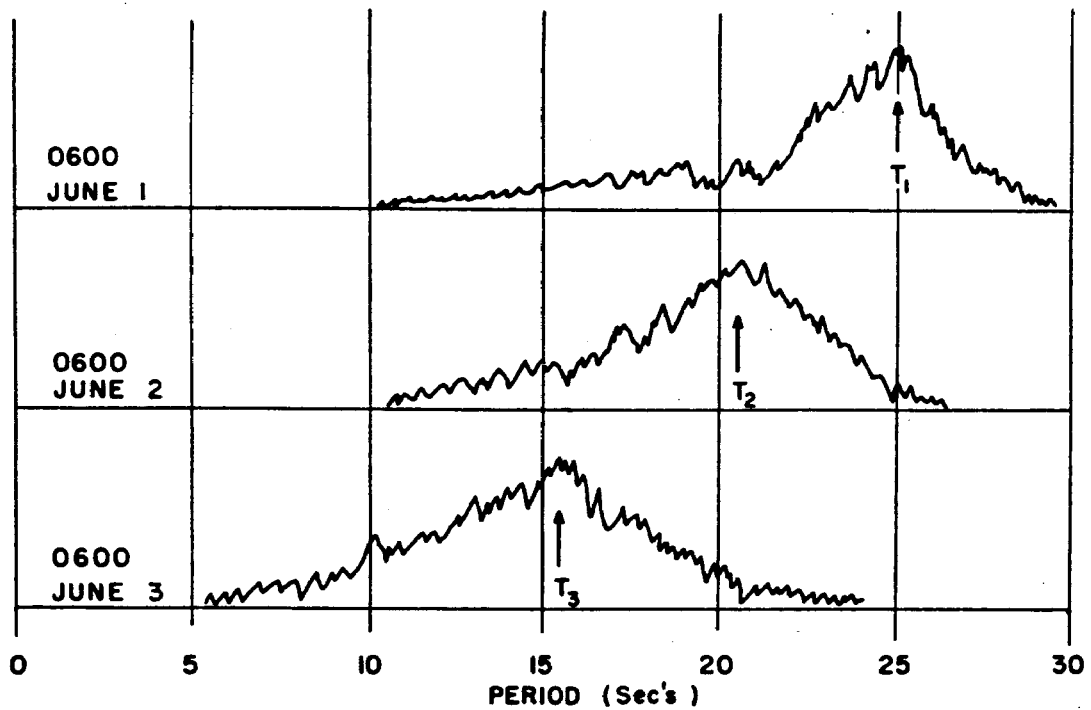
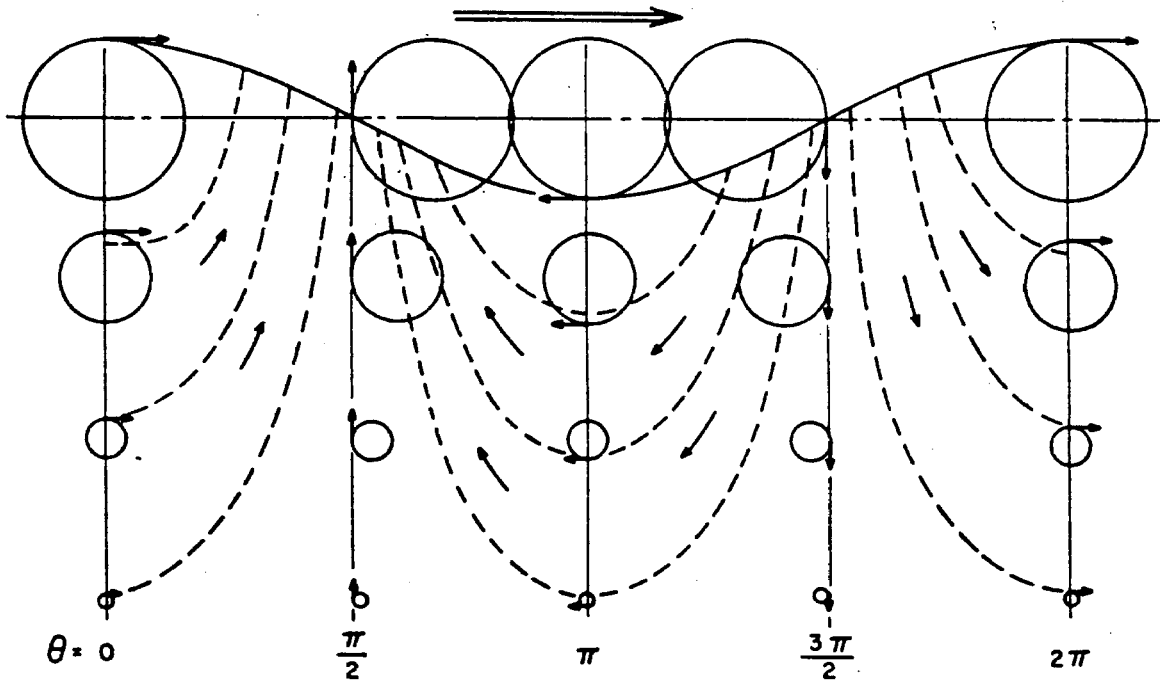


Fig. 34. Wave energy spectra on successive days at a coastal site

FIGURE 35

Fluid motion in surface gravity waves

(a) Deep water.



(b) Shallow water.

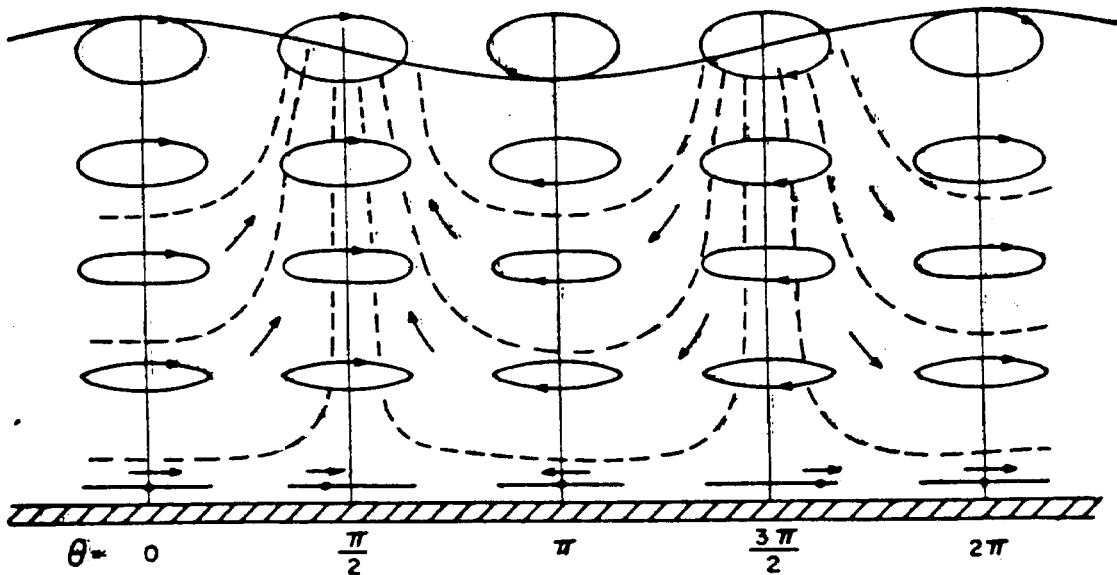
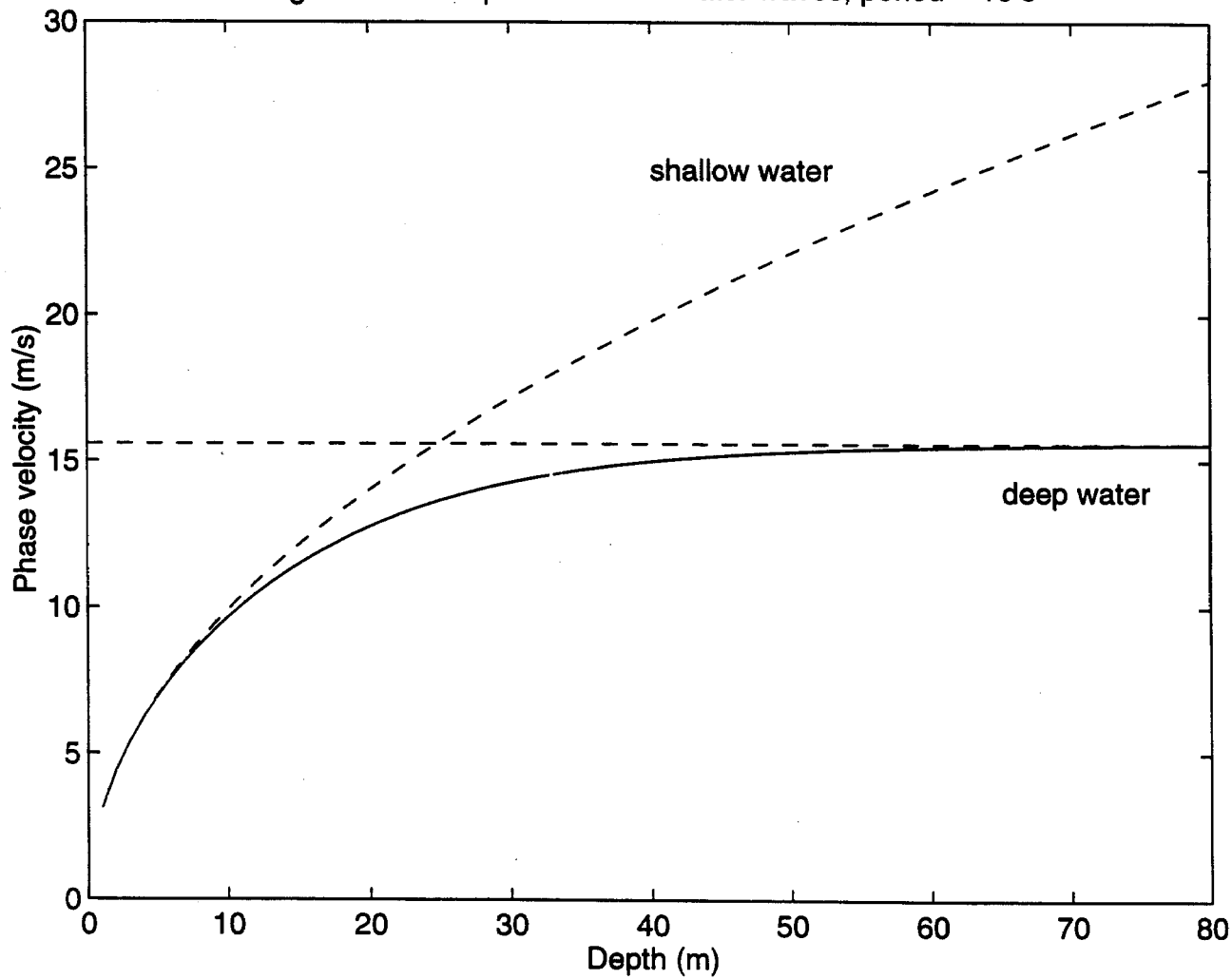
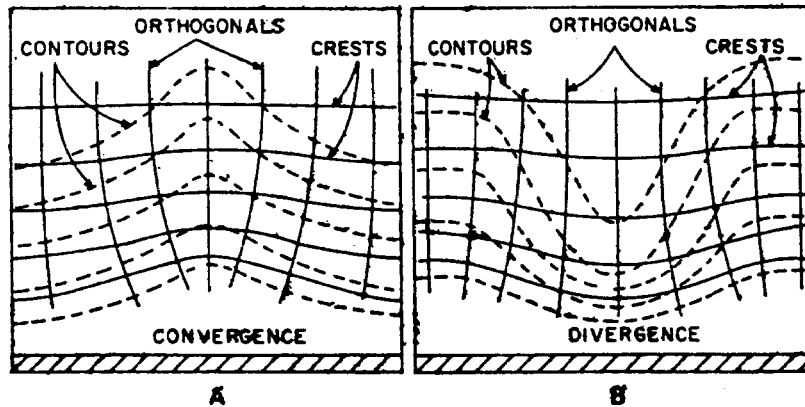


Figure 36 – Deep and shallow water waves; period = 10 s



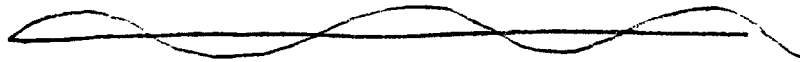
# FIGURE 37



Wave crest convergence (focussing) and divergence (de-focussing) due to bottom contours. Wave energy is focussed on a ridge (which would erode the ridge).

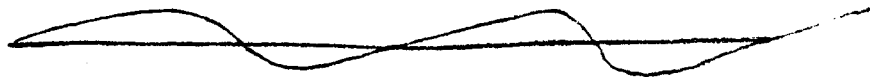
Figure. 38

Linear wave



Weakly non-linear wave

→  $c_p$



Strongly non-linear wave

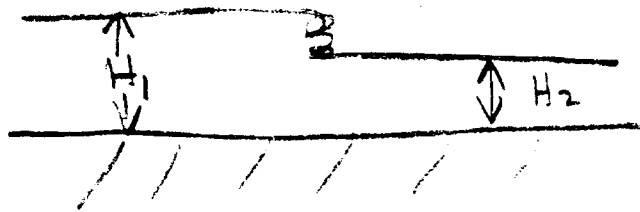
120°

→  $c_p$



Bore (shock wave)

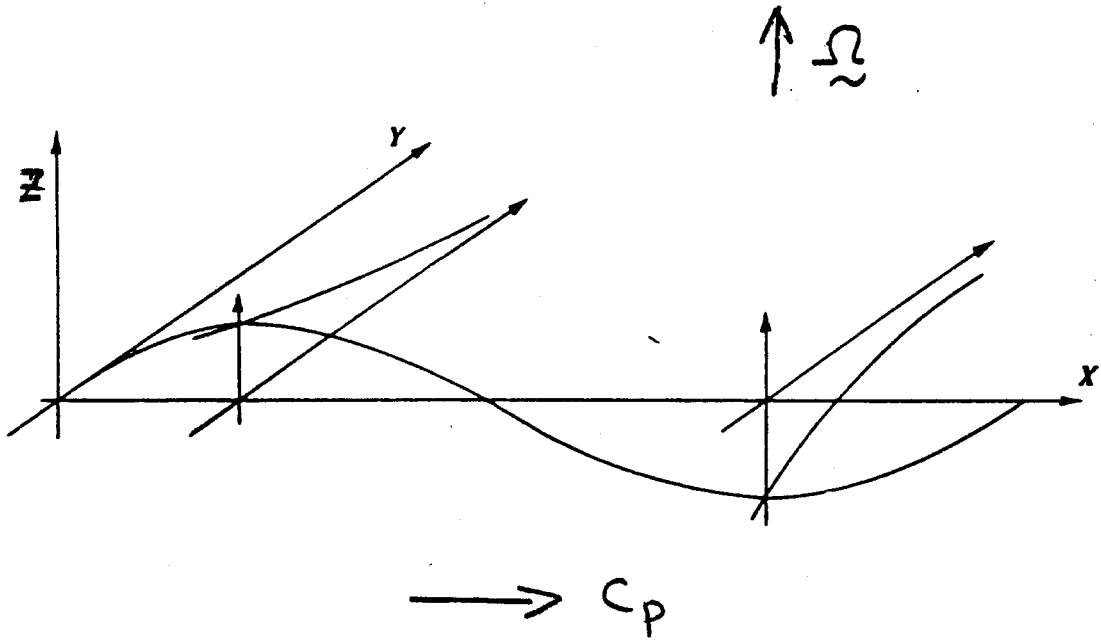
→  $c$



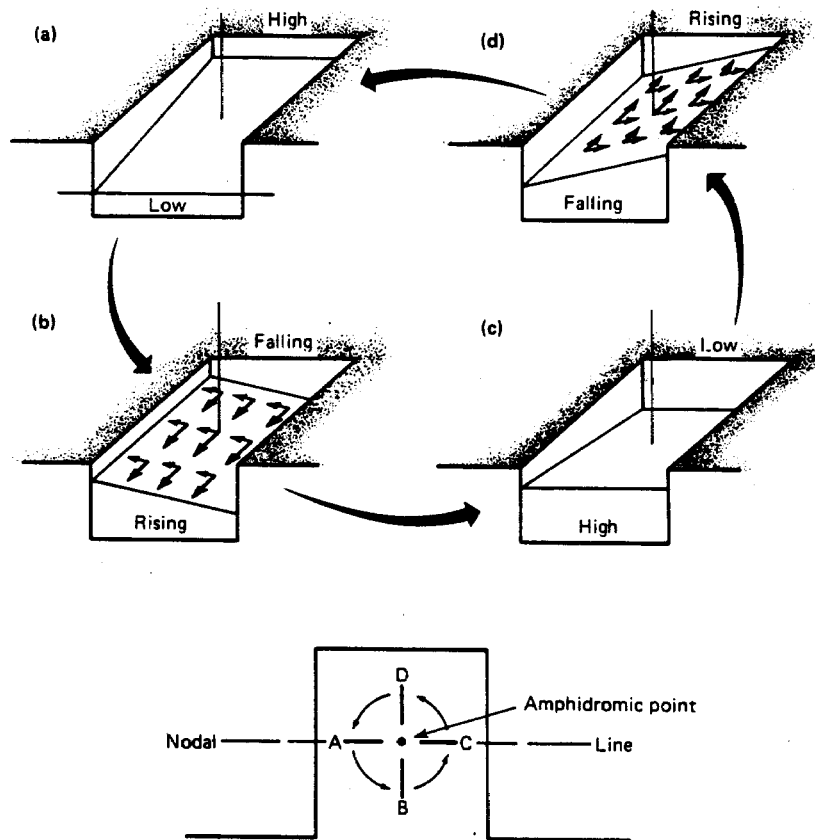
$$\sqrt{gH_1} > c > \sqrt{gH_2}$$

FIGURE 39

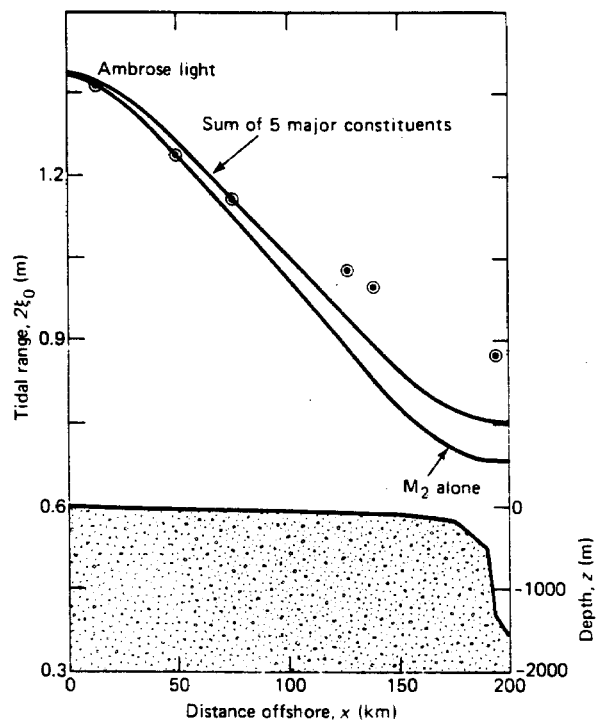
Kelvin Wave







**Fig. 40(a)** Schematic of rise and fall of tides in an embayment in the Northern Hemisphere. Tidal elevations appear to rotate counterclockwise about the amphidromic point. [Adapted from von Arx, W. S., *An Introduction to Physical Oceanography* (1962).]



**Fig. 40(b)** Transition of tidal amplitude from New York harbor across the continental shelf to the shelf break. [Adapted from Schwiderski, E. W., *Rev. Geophys. and Space Phys.* (1980).]

CHART 6  
of Tides and Tidal Forms in  
the World Ocean  
Semi-diurnal(after G. Dietrich, 1911)

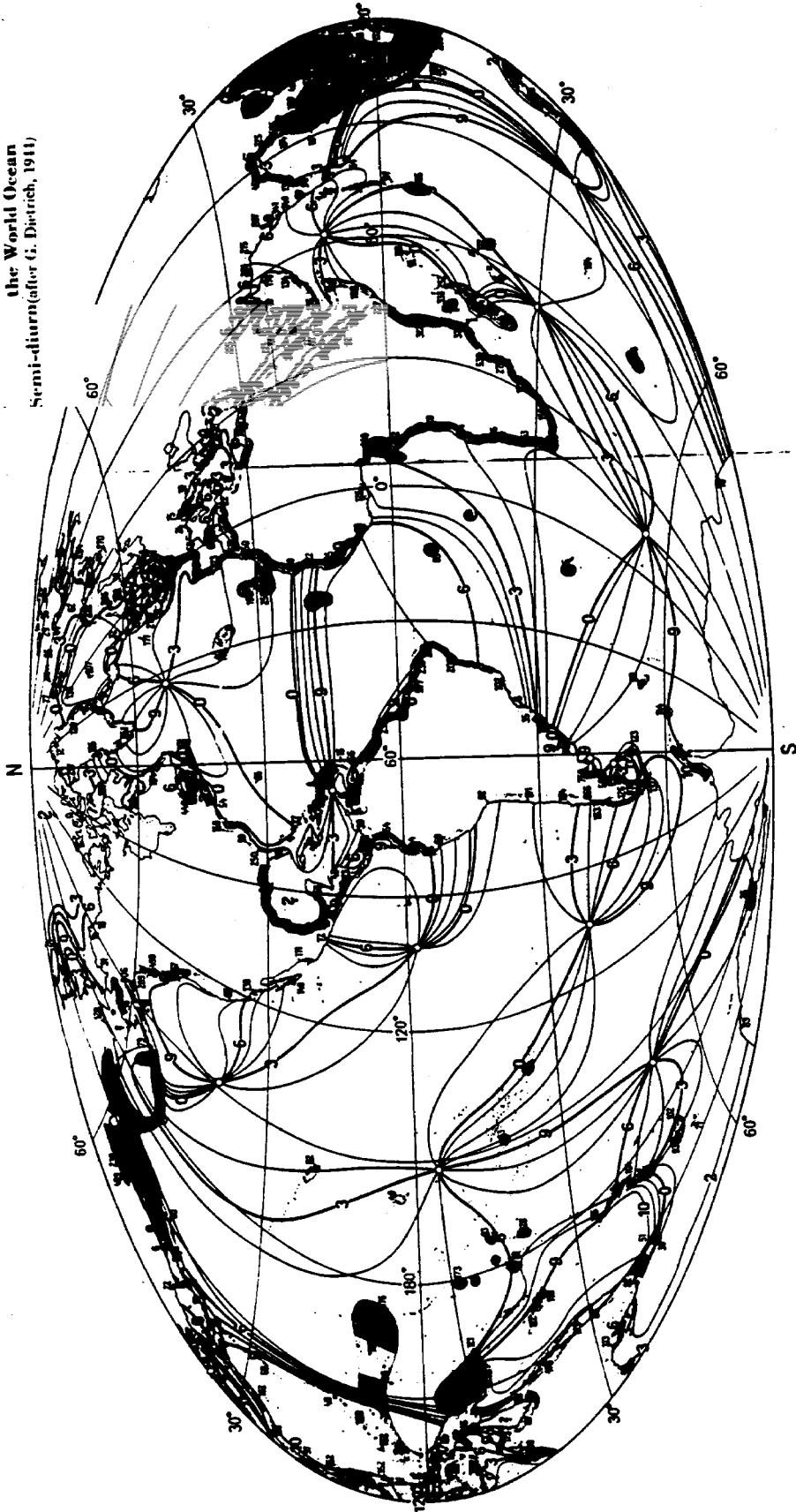


Figure 40(c). Positions of crests as a function of time for the M2 (Lunar Diurnal) tide. This is the largest tide. The next largest is the S2 (Solar Diurnal). Note that the time is labeled in units of the period/12 and is not exactly hours, because the lunar day (time from moon overhead to moon overhead) is not 24 hours. Note that the wave circulates around single nodes (amphidromes) in the North and South Atlantic, but that there are four amphidromes in the Pacific south of the equator.

Figure 41 - Deep water capillary and gravity waves

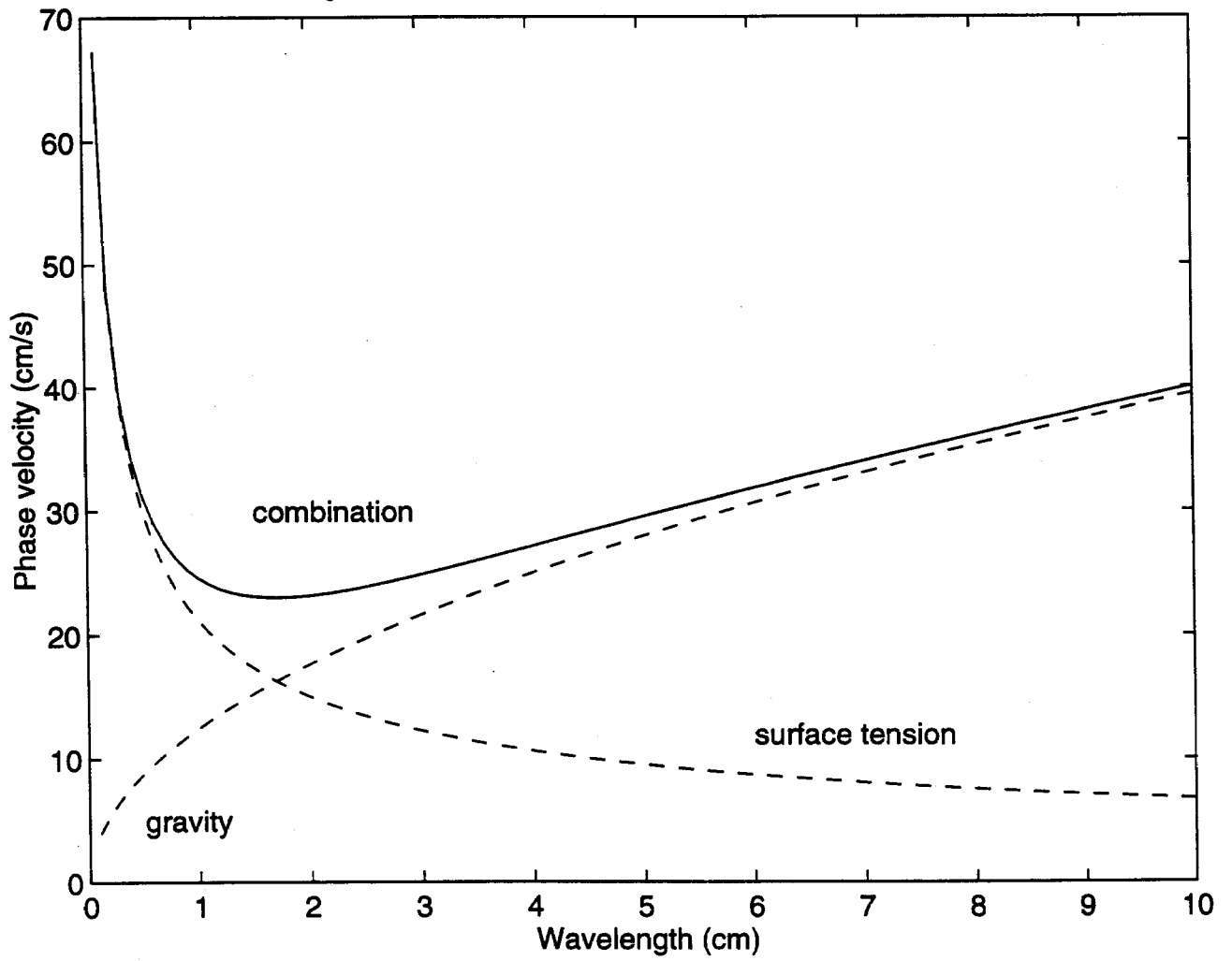
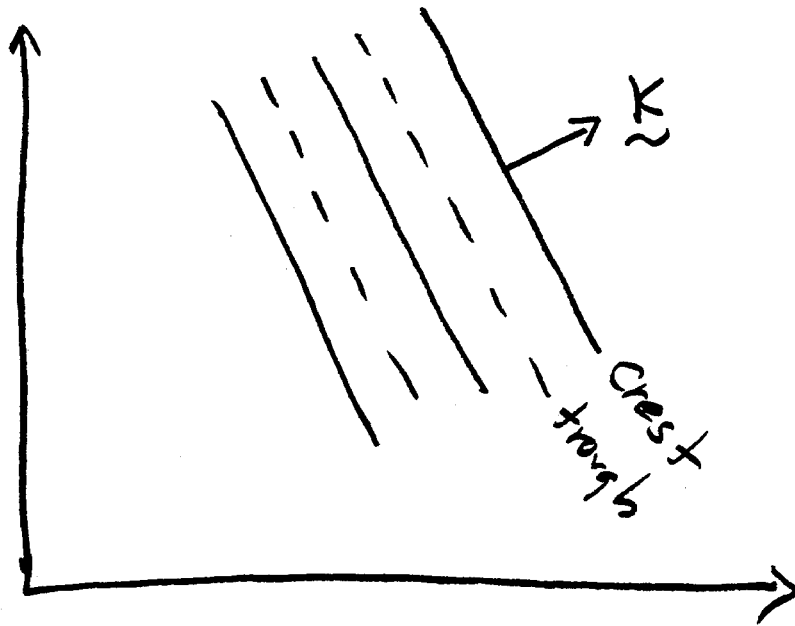


Figure 42



$$\text{Phase } \phi = \vec{k} \cdot \vec{x} - \sigma t$$

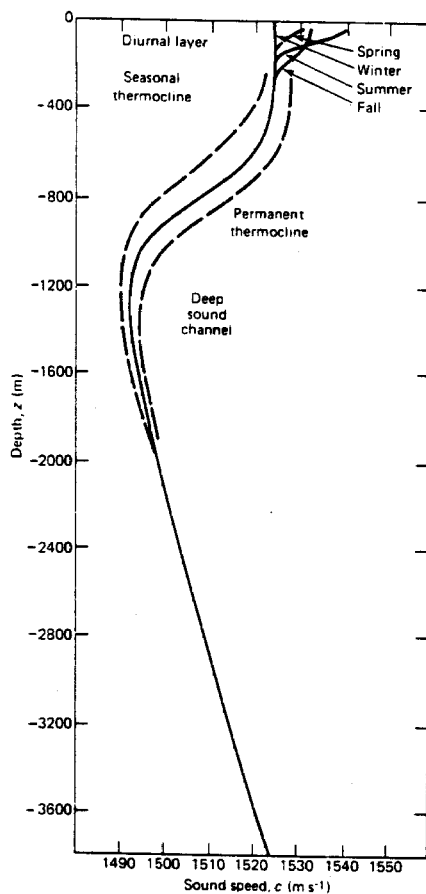
$$\vec{k} = k\hat{x} + l\hat{y} + m\hat{z}$$

is  $\perp$  to  $\phi = \text{const}$   
surfaces (ie  $\perp$  to  
crest + troughs)

$\therefore$  To keep  $\phi$  constant, observer  
must move  $\perp$  to crest (|| to  $\vec{k}$ )  
at speed  $\frac{\sigma}{|\vec{k}|}$ , which we call  
phase velocity.

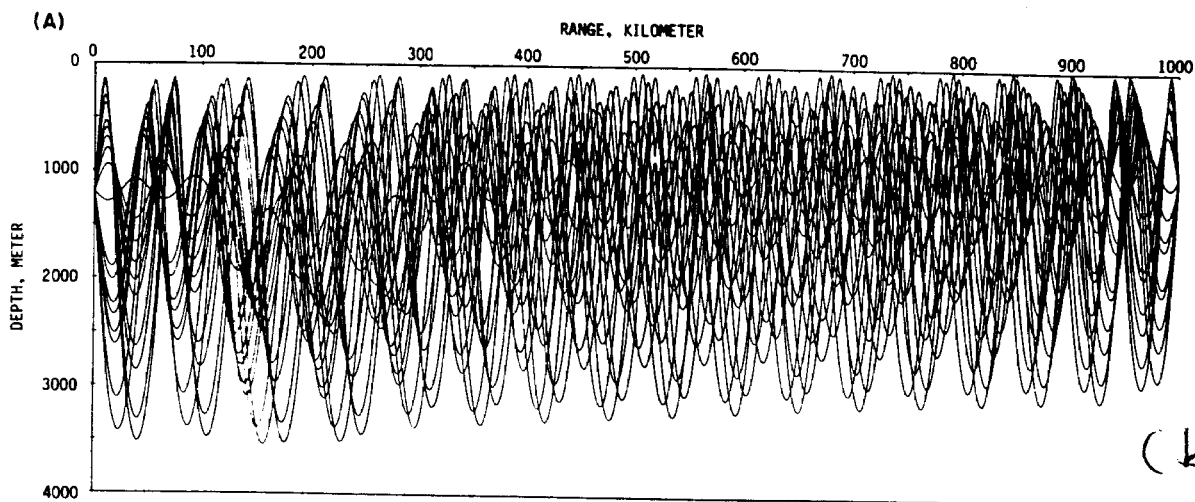
FIGURE

43



(a)

Sound speed profile from a station near Bermuda as averaged over nine years. [Adapted from Jones, L. M., and W. A. Von Winkle, *USN Underwater Sound Laboratory Report 632* (1965).]

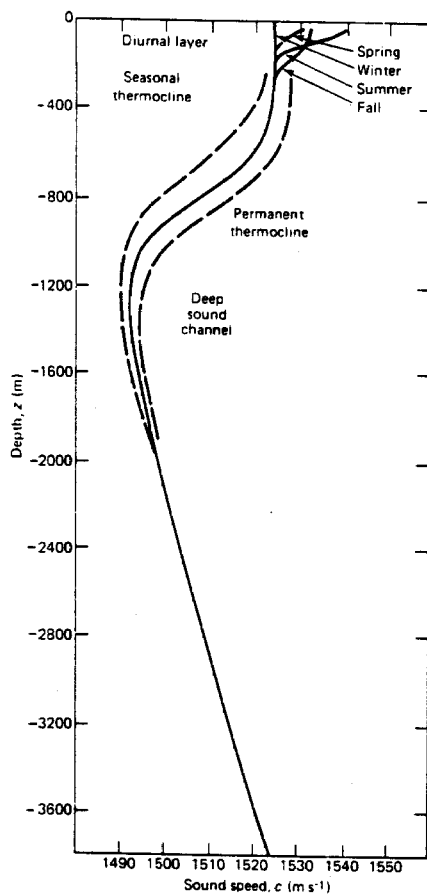


(b)

All the acoustic rays between a source (at 1200 m) and a receiver (at 1000 m) through a realistic ocean that includes a mesoscale warm eddy centered at 200 km downrange. From Mercer and Booker (1983).

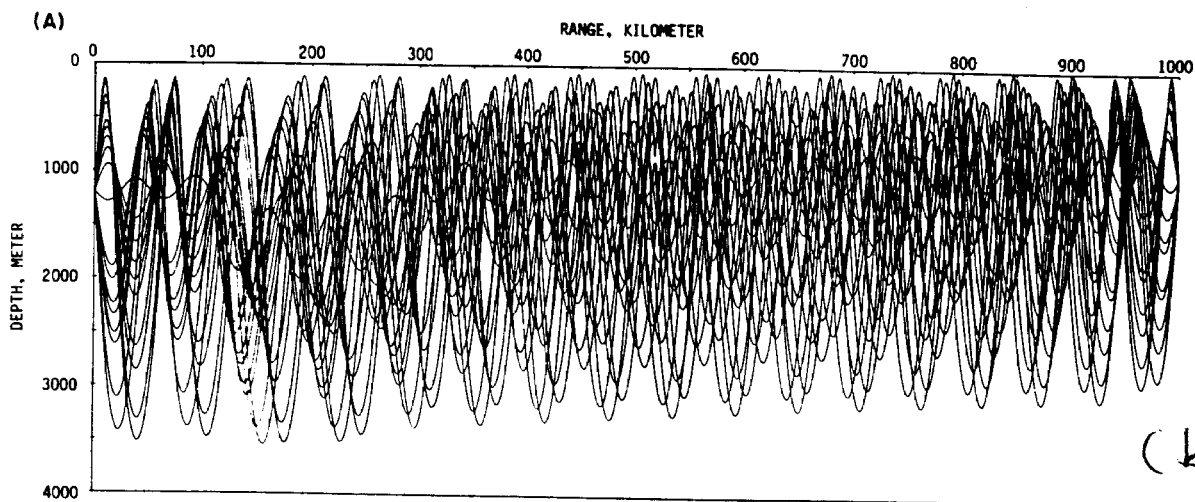
FIGURE

43



(a)

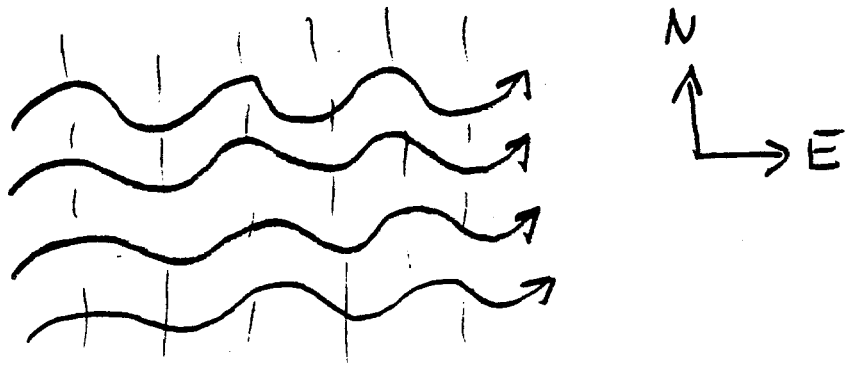
Sound speed profile from a station near Bermuda as averaged over nine years. [Adapted from Jones, L. M., and W. A. Von Winkle, *USN Underwater Sound Laboratory Report 632* (1965).]



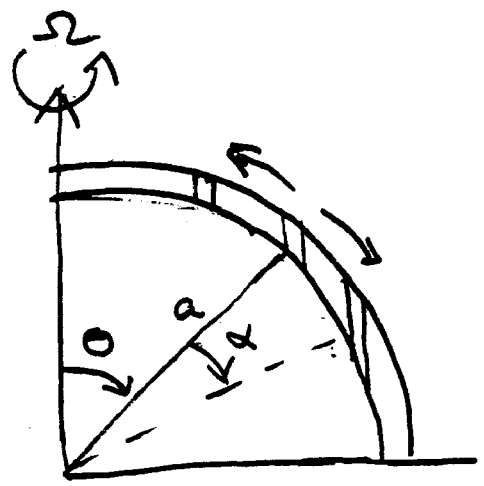
All the acoustic rays between a source (at 1200 m) and a receiver (at 1000 m) through a realistic ocean that includes a mesoscale warm eddy centered at 200 km downrange. From Mercer and Booker (1983).

# Figure 47

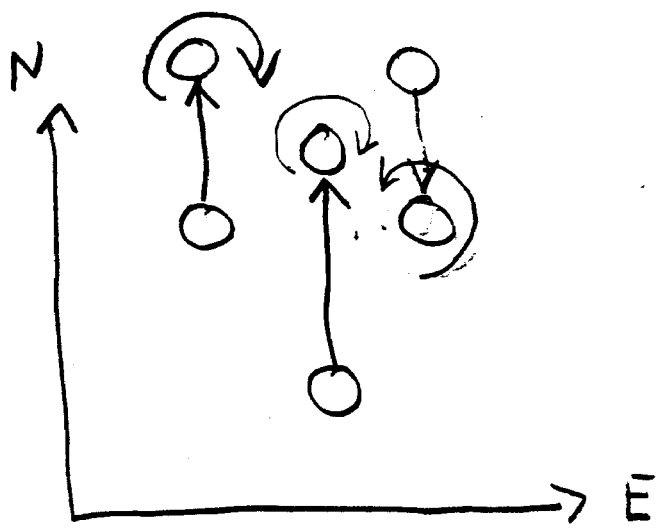
(a)



(b)



(c)



12 107  
42 381  
42 382  
42 383  
42 384  
42 385  
42 386  
42 387  
42 388  
42 389  
42 390  
42 391  
42 392  
42 393  
42 394  
42 395  
42 396  
42 397  
42 398  
42 399  
42 400  
42 401  
42 402  
42 403  
42 404  
42 405  
42 406  
42 407  
42 408  
42 409  
42 410  
42 411  
42 412  
42 413  
42 414  
42 415  
42 416  
42 417  
42 418  
42 419  
42 420  
42 421  
42 422  
42 423  
42 424  
42 425  
42 426  
42 427  
42 428  
42 429  
42 430  
42 431  
42 432  
42 433  
42 434  
42 435  
42 436  
42 437  
42 438  
42 439  
42 440  
42 441  
42 442  
42 443  
42 444  
42 445  
42 446  
42 447  
42 448  
42 449  
42 450  
42 451  
42 452  
42 453  
42 454  
42 455  
42 456  
42 457  
42 458  
42 459  
42 460  
42 461  
42 462  
42 463  
42 464  
42 465  
42 466  
42 467  
42 468  
42 469  
42 470  
42 471  
42 472  
42 473  
42 474  
42 475  
42 476  
42 477  
42 478  
42 479  
42 480  
42 481  
42 482  
42 483  
42 484  
42 485  
42 486  
42 487  
42 488  
42 489  
42 490  
42 491  
42 492  
42 493  
42 494  
42 495  
42 496  
42 497  
42 498  
42 499  
42 500  
42 501  
42 502  
42 503  
42 504  
42 505  
42 506  
42 507  
42 508  
42 509  
42 510  
42 511  
42 512  
42 513  
42 514  
42 515  
42 516  
42 517  
42 518  
42 519  
42 520  
42 521  
42 522  
42 523  
42 524  
42 525  
42 526  
42 527  
42 528  
42 529  
42 530  
42 531  
42 532  
42 533  
42 534  
42 535  
42 536  
42 537  
42 538  
42 539  
42 540  
42 541  
42 542  
42 543  
42 544  
42 545  
42 546  
42 547  
42 548  
42 549  
42 550  
42 551  
42 552  
42 553  
42 554  
42 555  
42 556  
42 557  
42 558  
42 559  
42 560  
42 561  
42 562  
42 563  
42 564  
42 565  
42 566  
42 567  
42 568  
42 569  
42 570  
42 571  
42 572  
42 573  
42 574  
42 575  
42 576  
42 577  
42 578  
42 579  
42 580  
42 581  
42 582  
42 583  
42 584  
42 585  
42 586  
42 587  
42 588  
42 589  
42 590  
42 591  
42 592  
42 593  
42 594  
42 595  
42 596  
42 597  
42 598  
42 599  
42 600  
42 601  
42 602  
42 603  
42 604  
42 605  
42 606  
42 607  
42 608  
42 609  
42 610  
42 611  
42 612  
42 613  
42 614  
42 615  
42 616  
42 617  
42 618  
42 619  
42 620  
42 621  
42 622  
42 623  
42 624  
42 625  
42 626  
42 627  
42 628  
42 629  
42 630  
42 631  
42 632  
42 633  
42 634  
42 635  
42 636  
42 637  
42 638  
42 639  
42 640  
42 641  
42 642  
42 643  
42 644  
42 645  
42 646  
42 647  
42 648  
42 649  
42 650  
42 651  
42 652  
42 653  
42 654  
42 655  
42 656  
42 657  
42 658  
42 659  
42 660  
42 661  
42 662  
42 663  
42 664  
42 665  
42 666  
42 667  
42 668  
42 669  
42 670  
42 671  
42 672  
42 673  
42 674  
42 675  
42 676  
42 677  
42 678  
42 679  
42 680  
42 681  
42 682  
42 683  
42 684  
42 685  
42 686  
42 687  
42 688  
42 689  
42 690  
42 691  
42 692  
42 693  
42 694  
42 695  
42 696  
42 697  
42 698  
42 699  
42 700  
42 701  
42 702  
42 703  
42 704  
42 705  
42 706  
42 707  
42 708  
42 709  
42 710  
42 711  
42 712  
42 713  
42 714  
42 715  
42 716  
42 717  
42 718  
42 719  
42 720  
42 721  
42 722  
42 723  
42 724  
42 725  
42 726  
42 727  
42 728  
42 729  
42 730  
42 731  
42 732  
42 733  
42 734  
42 735  
42 736  
42 737  
42 738  
42 739  
42 740  
42 741  
42 742  
42 743  
42 744  
42 745  
42 746  
42 747  
42 748  
42 749  
42 750  
42 751  
42 752  
42 753  
42 754  
42 755  
42 756  
42 757  
42 758  
42 759  
42 760  
42 761  
42 762  
42 763  
42 764  
42 765  
42 766  
42 767  
42 768  
42 769  
42 770  
42 771  
42 772  
42 773  
42 774  
42 775  
42 776  
42 777  
42 778  
42 779  
42 780  
42 781  
42 782  
42 783  
42 784  
42 785  
42 786  
42 787  
42 788  
42 789  
42 790  
42 791  
42 792  
42 793  
42 794  
42 795  
42 796  
42 797  
42 798  
42 799  
42 800  
42 801  
42 802  
42 803  
42 804  
42 805  
42 806  
42 807  
42 808  
42 809  
42 810  
42 811  
42 812  
42 813  
42 814  
42 815  
42 816  
42 817  
42 818  
42 819  
42 820  
42 821  
42 822  
42 823  
42 824  
42 825  
42 826  
42 827  
42 828  
42 829  
42 830  
42 831  
42 832  
42 833  
42 834  
42 835  
42 836  
42 837  
42 838  
42 839  
42 840  
42 841  
42 842  
42 843  
42 844  
42 845  
42 846  
42 847  
42 848  
42 849  
42 850  
42 851  
42 852  
42 853  
42 854  
42 855  
42 856  
42 857  
42 858  
42 859  
42 860  
42 861  
42 862  
42 863  
42 864  
42 865  
42 866  
42 867  
42 868  
42 869  
42 870  
42 871  
42 872  
42 873  
42 874  
42 875  
42 876  
42 877  
42 878  
42 879  
42 880  
42 881  
42 882  
42 883  
42 884  
42 885  
42 886  
42 887  
42 888  
42 889  
42 890  
42 891  
42 892  
42 893  
42 894  
42 895  
42 896  
42 897  
42 898  
42 899  
42 900  
42 901  
42 902  
42 903  
42 904  
42 905  
42 906  
42 907  
42 908  
42 909  
42 910  
42 911  
42 912  
42 913  
42 914  
42 915  
42 916  
42 917  
42 918  
42 919  
42 920  
42 921  
42 922  
42 923  
42 924  
42 925  
42 926  
42 927  
42 928  
42 929  
42 930  
42 931  
42 932  
42 933  
42 934  
42 935  
42 936  
42 937  
42 938  
42 939  
42 940  
42 941  
42 942  
42 943  
42 944  
42 945  
42 946  
42 947  
42 948  
42 949  
42 950  
42 951  
42 952  
42 953  
42 954  
42 955  
42 956  
42 957  
42 958  
42 959  
42 960  
42 961  
42 962  
42 963  
42 964  
42 965  
42 966  
42 967  
42 968  
42 969  
42 970  
42 971  
42 972  
42 973  
42 974  
42 975  
42 976  
42 977  
42 978  
42 979  
42 980  
42 981  
42 982  
42 983  
42 984  
42 985  
42 986  
42 987  
42 988  
42 989  
42 990  
42 991  
42 992  
42 993  
42 994  
42 995  
42 996  
42 997  
42 998  
42 999  
43 000



Made in U.S.A.

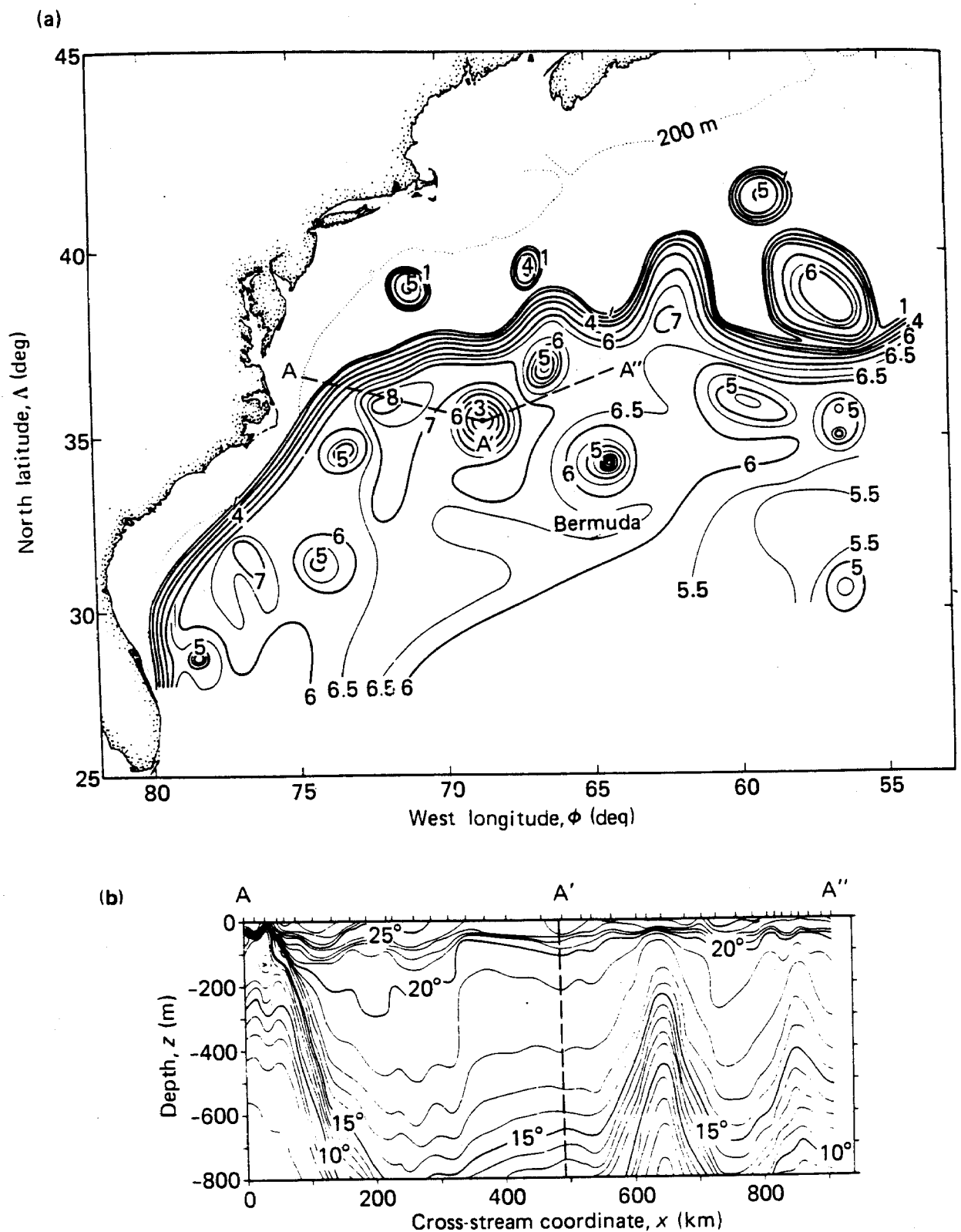


Fig. 4.5 (a) Positions of the 15°C isotherm at depths between 100 and 700 m, showing the Gulf Stream, nine cyclonic, and three anticyclonic eddies. Data were taken by subsurface drifting floats and other means. (b) Subsurface profile along a line segment A-A'-A'' in Fig. 6.42a, showing the Gulf Stream boundary at left, and cold-core rings at 650 and 850 km. [From Richardson, P., et al., *J. Geophys. Res.* (1978)].



FIGURE 46

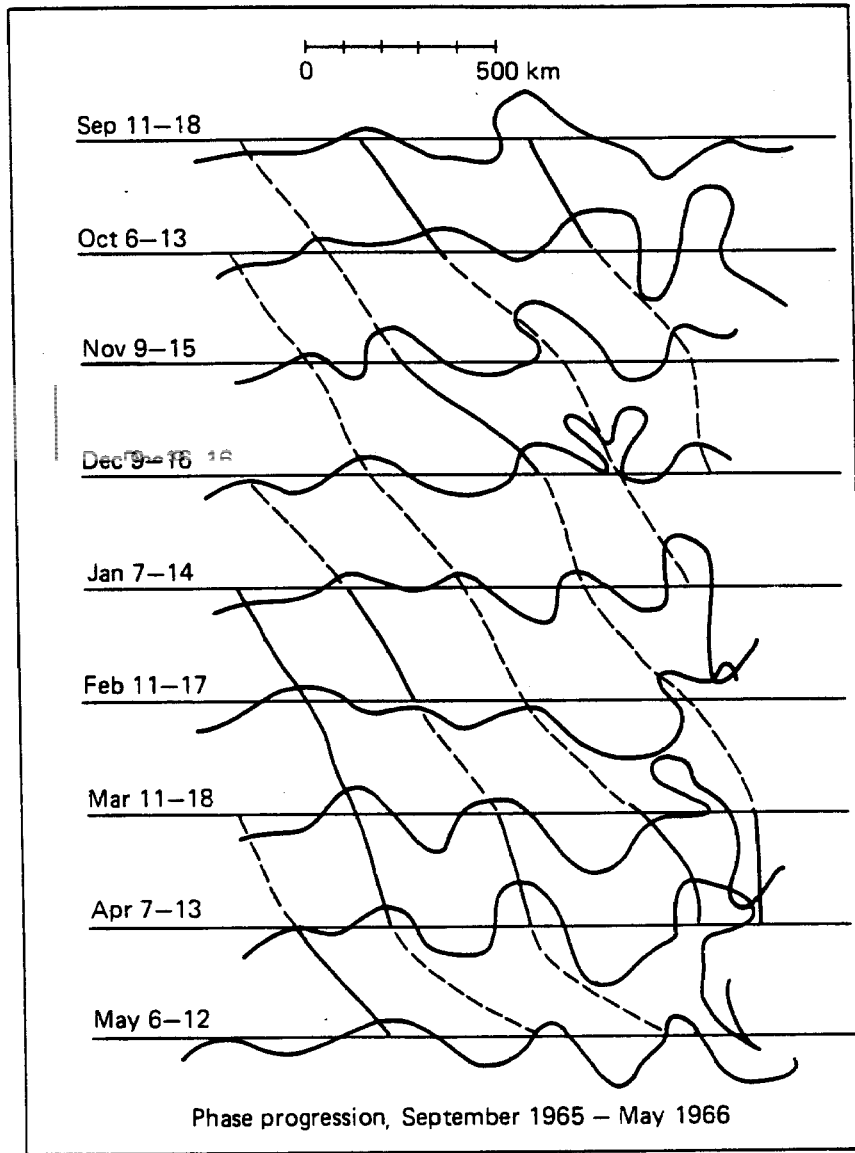
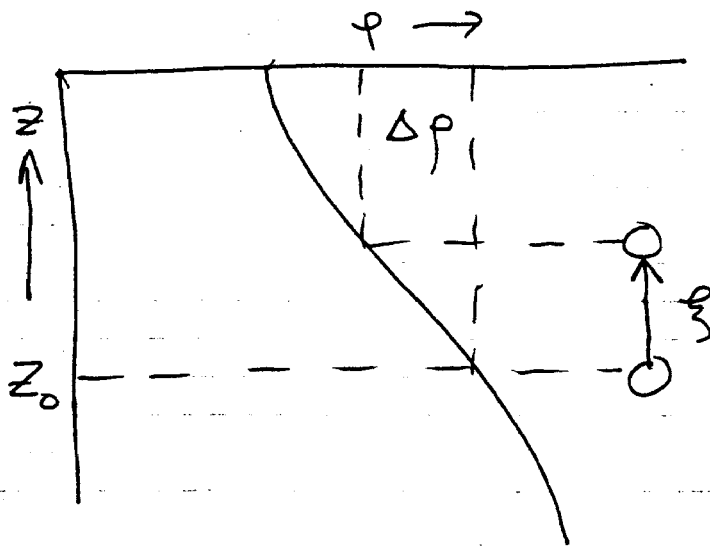
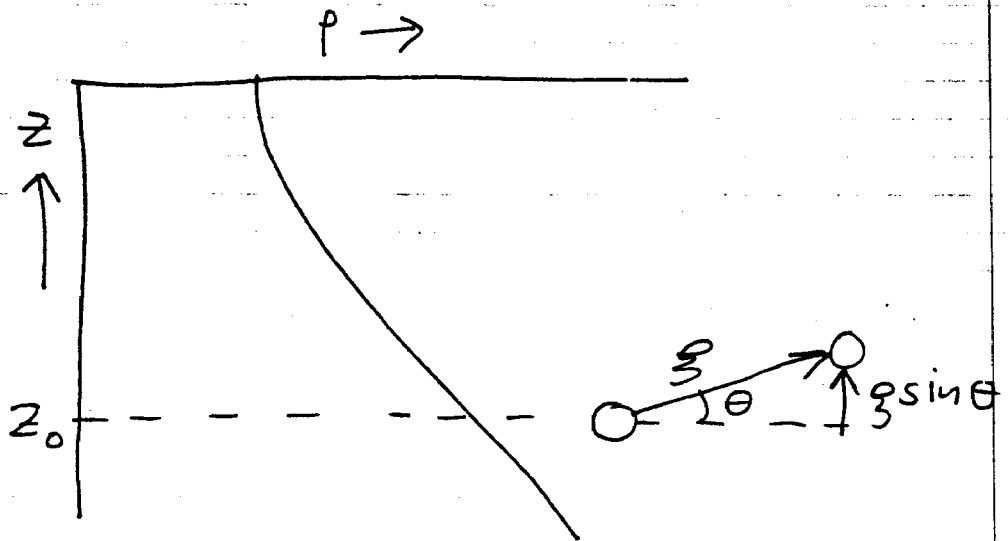


FIGURE 47

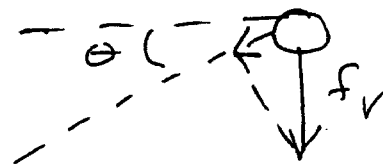
(a)



(b)

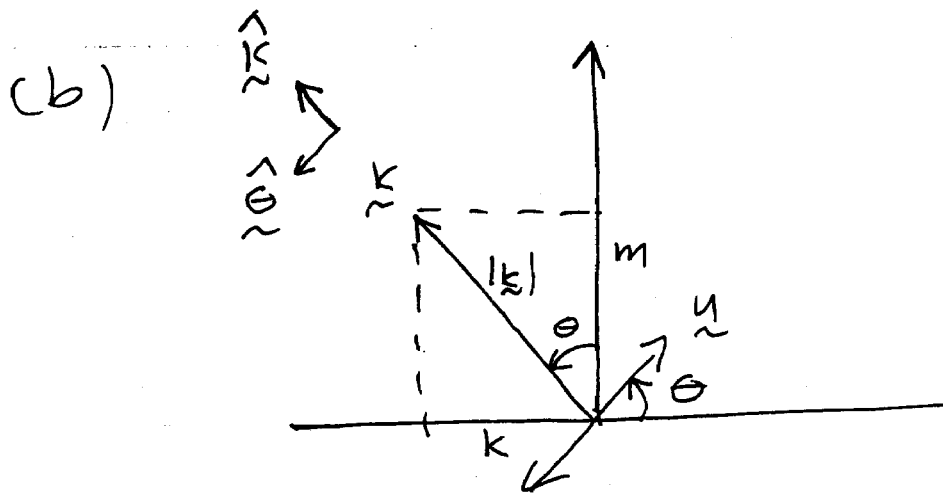
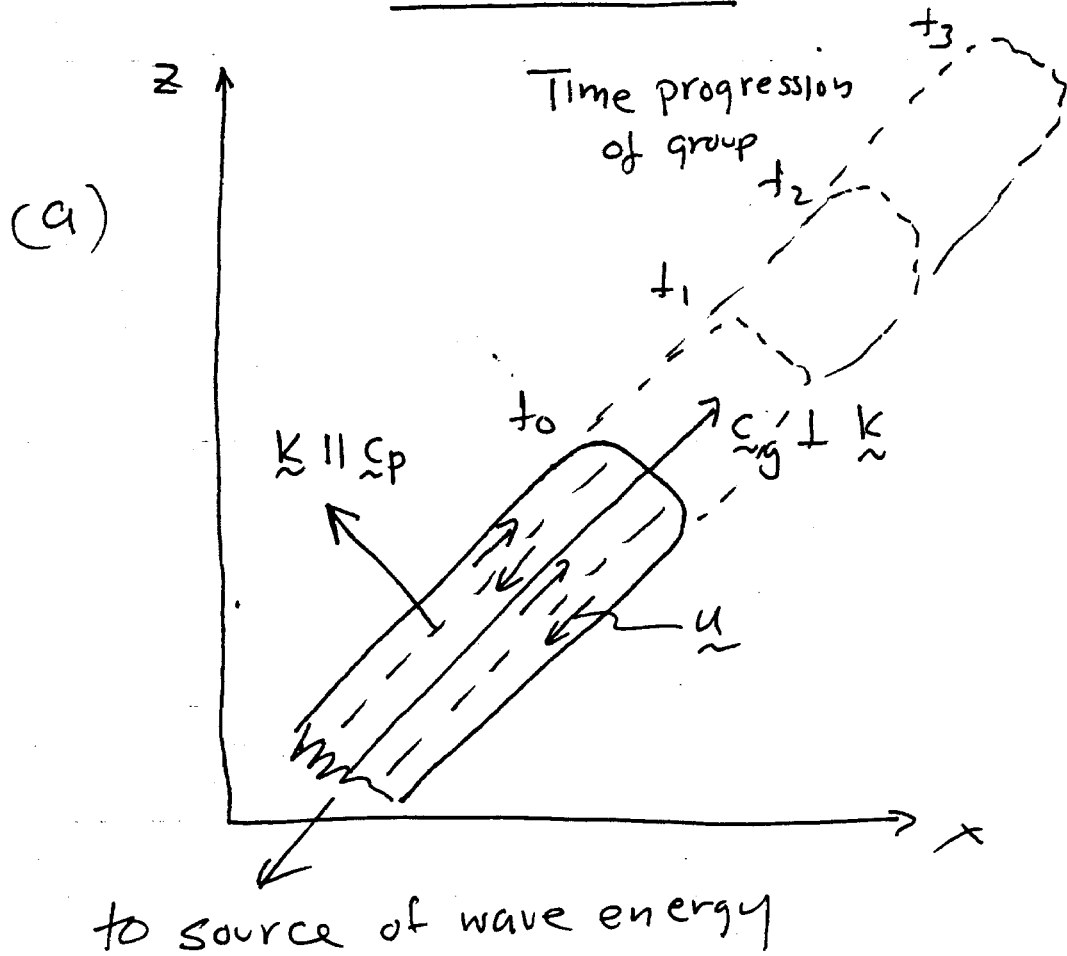


Restoring force in  $\hat{z}$  direction  $\propto g \sin \theta$



Restoring force directed towards original position  $\propto g \sin^2 \theta$

FIGURE 48



$$\sin \theta = \frac{k}{|k_{\sim}|} ; \cos \theta = \frac{m}{|k_{\sim}|}$$

FIGURE 49 (From Triffon)

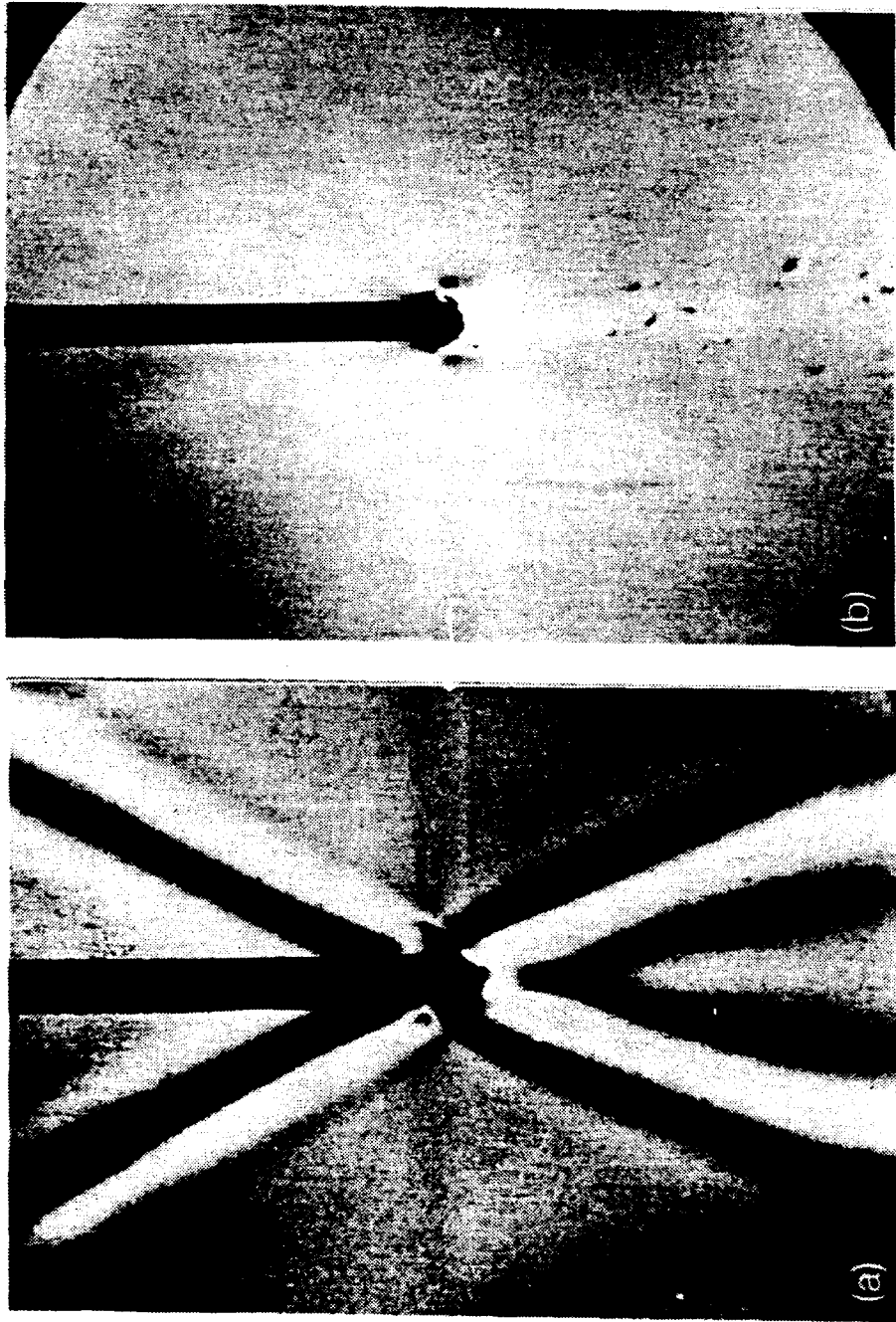
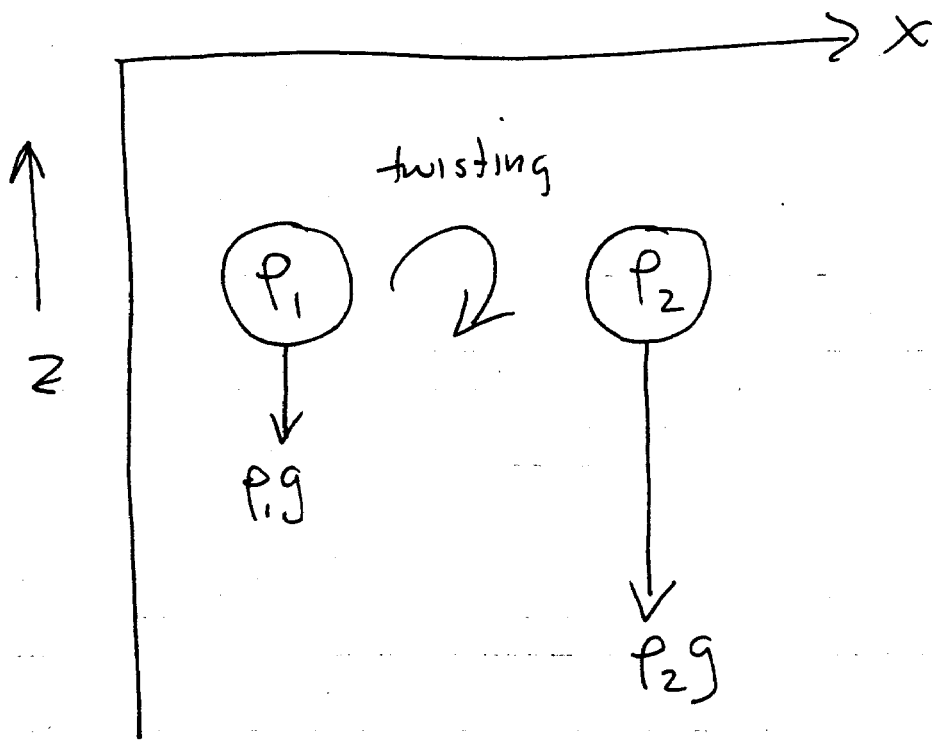


Fig. 15.11 Waves produced by vibrating cylinder in a stratified fluid (dark vertical line is cylinder support). (a)  $\omega/N = 0.90$ ; (b)  $\omega/N = 1.11$ . Ref. [282].

FIGURE 50



Generation of vorticity by  
lateral density variations

FIGURE 51

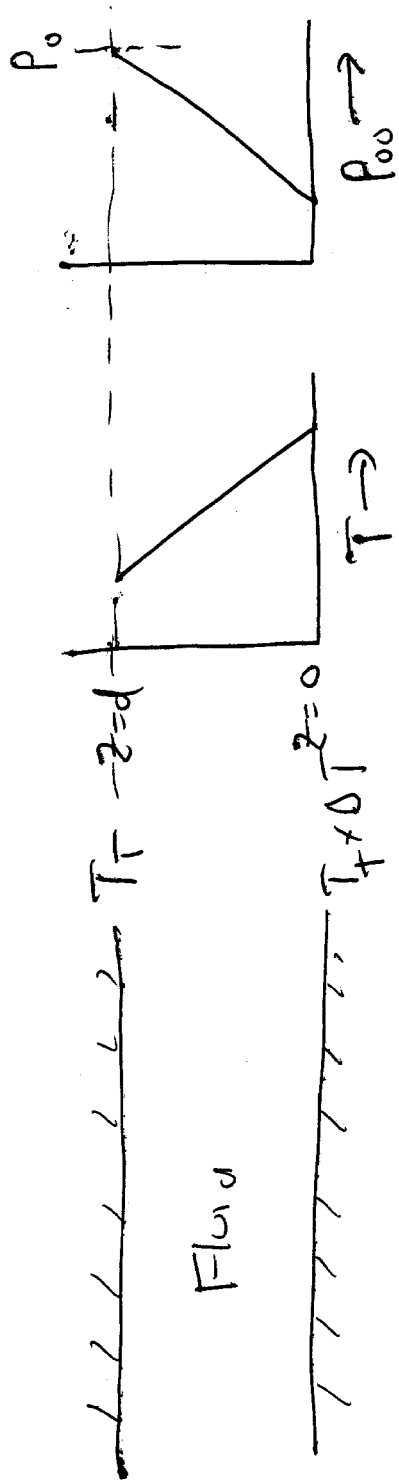
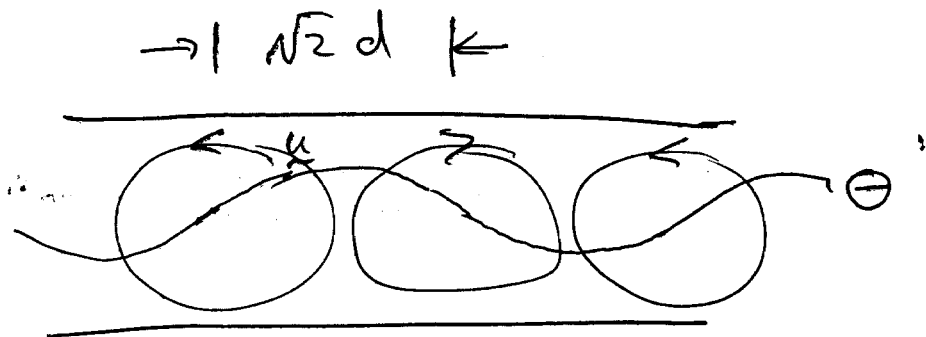
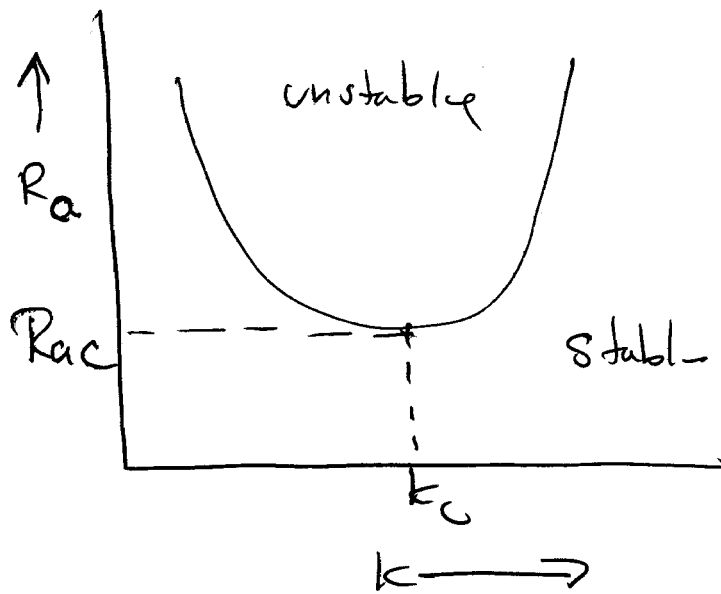


FIGURE 52

(a)



(b)



# FIGURE 53

