Appendix A

VISCOELASTIC MODELS

In the literature on viscoelasticity, it is common to describe the behavior of materials through networks of springs and dashpots, often characterized by either relaxation or retardation spectra. It has been claimed that only attenuation models given in terms of such networks are physically realizable, and models derived by other means have been termed "ad hoc" [e.g. Minster, 1978a].

While it is possible to give physical models for attenuation that can not be modelled by spring-dashpot networks, [e.g. Nur and Mavko, 1979], the formulation of viscoelastic models in terms of relaxation spectra is often useful. Gross [1953] has summarized the relationships between the various functions that have been used to characterize viscoelastic materials. In his notation the retardation frequency density function, N(s), is related to the creep function according to

$$\Psi(t) = -\int_0^\infty N(s)e^{-ts}\,ds \qquad \text{(A-1)}$$

and the relaxation frequency density function, $\bar{N}(s)$, is related to the relaxation function according to

$$\bar{\Psi}(t) = \int_0^\infty \bar{N}(s)e^{-ts}\,ds \qquad \text{(A-2)}$$

Kanamori and Anderson [1977] used a a relaxation function of the form

$$\bar{N}(s) = As^{-1} \qquad s_1 < s < s_2 \qquad \text{(A-3)}$$

$$\bar{N}(s) = 0 \qquad \text{elsewhere}$$

to derive an absorption band NCQ model. The constant Q model may be specified

by

$$\bar{N}(s) = \frac{M_o \sin(2\pi\gamma)}{\pi} (st_o)^{2\gamma} s^{-1} \qquad \text{(A-4)}$$

Using the definition of the gamma function and the identity

$$\Gamma(z)\Gamma(1-z) = \frac{\pi}{\sin(\pi z)} \qquad \text{(A-5)}$$

the constant Q relaxation function (2.20) is readily obtained. Since the constant Q model is mathematically a special case of the power law models of Strick [1967] and Azimi et al. [1968], it follows that those models also have spring-dashpot representations.

Appendix B

LISTING OF FINITE-DIFFERENCE PROGRAMS

```
c       The programs listed here were used to obtain the results
c       shown in figure 6.8. These programs should be portable,
c     except for the input-output routines.
c
c     Finite-difference modeling program, that
c     uses the monochromatic wave equation:
c
c        1
c      ---- Q     +    Q     +     2 m i  Q        =   0
c      2 m    xxz        xx                 z
c
c     Velocity, anelasticity and reflectivity may be
c     arbitrary functions of x and z.
c     An improved approximation for the second derivative
c     is used (variable beta), see FGDP, p. 222.
c     A zero-offset time section is obtained by inversely
c     Fourier transforming the output of this program.
c     Dip filtering is included (see FGDP, p. 225).
c
c        Einar Kjartansson, September 1978.
c
      complex wave(64,64),t(64),d(64),a(64),b(64),e(64),f(64)
      complex aa(64),bb(64)
      complex cv0(64), cexp,cmplx
      complex m,shift,cc3,cc1,rr3,rr1,bab,ra,dipflt
      complex abp(64),cbp(64)
      real q1(64),vel(64),ref(64),gam(64)
      equivalence (a(2),abp(1))  ,  (a(1),cbp(2))
c
c     Read in parameters and set constants.
c
      call rdparm(nom,nx,nz,dom,dx,dz,vis)
      rr1 = (0.,.5)/dz
      rr3 = (0.,2.)*dx*dx/dz
      dipflt = (0.,1.)*vis
      beta = .14
c
c     Clear upgoing wave field.
c
      do 20 iom = 1,nom
         do 20 ix = 1,nx
20          wave (ix,iom) = (0.,0.)
c
c     Take the wave field up through the structure.
c
      do 100 izinv = 1,nz
         iz = nz - izinv + 1
c
```

```
c       Get velocity, 1/Q and reflectivity.
c
        call rdvst(iz,nx,vel)
        call rdqst(iz,nx,ql)
        call rdrst(iz,nx,ref)
        do 40 ix = 1,nx
           gampi =  atan(ql(ix))
           cv0(ix) = cexp((0.,-.5)*gampi)/vel(ix)
40         gam(ix) = gampi/3.141592654
        do 100 iom = 2,nom
           om = (iom-1)*dom
c
c          Apply time shift and
c          compute coefficients.
c
           do 50 ix = 1,nx
              m = -om**(1.-gam(ix))*cv0(ix)
              shift = cexp((0.,1.)*m*dz)
              t(ix) = shift*(wave(ix,iom)+ref(ix))
           m = m + dipflt/vel(ix)
              cc3 = rr3*m
              cc1 = rr1/m + beta*cc3
              aa(ix)= (.5,0.) - cc1
              a(ix) = aa(ix)- (1.,0.)
              bb(ix)  = cc1 + cc1 - (1.,0.) - cc3
50            b(ix) = bb(ix) + (2.,0.)
c
c          Absorbing side condition.
c
           bab = m*cmplx(0.,dx*.25)
           ra = ((1.,0.)+bab) / ((1.,0.)-bab)
           b(1) = b(1) + ra*a(1)
           bb(1) = bb(1) + ra*aa(1)
           b(nx) = b(nx) + ra*a(nx)
           bb(nx) = bb(nx) + ra*aa(nx)
c
c          Solve Crank-Nicolson matrix equation.
c
           d(1) = bb(1)*t(1) + aa(2)*t(2)
              d(nx) = bb(nx)*t(nx) + aa(nx-1)*t(nx-1)
           do 70 ix = 2, nx-1
70             d(ix) = bb(ix)*t(ix)+aa(ix-1)*t(ix-1)+aa(ix+1)*t(ix+1)
           call cvtri(abp,b,cbp,nx,t,d,e,f)
           do 100 ix = 1,nx
100           wave(ix,iom) = t(ix)
c
c     Output the result.
c
      call wrwave(nx,nom,wave)
      stop
      end
```

```
c
c
c     Finite-difference migration program, that
c     uses the monochromatic wave equation:
c
c
c        i
c      ---- Q      +     Q      +      2 m i  Q         =    0
c      2 m     xxz          xx                    z
c
c
c     Velocity may be an arbitrary function of x and z.
c     Anelasticity is not included in this program.
c     An improved approximation for the second derivative
c     is used (variable beta), see FGDP, p. 222.
c     The input to this program is the Fourier tranform of a
c     zero-offset section.
c     Dip filtering is included (see FGDP, p. 225).
c
c        Einar Kjartansson, September 1978.
c
c     Bullet proof version, E.K. april 1979.
c
      complex wave(64,64),t(64),d(64),a(64),b(64),e(64),f(64)
      complex aa(64),bb(64),ref(64)
      complex  cexp,cmplx
      complex shift,cc3,cc1,rr3,rr1,bab,ra,dipflt
      complex abp(64),cbp(64)
      equivalence (a(2),abp(1)) , (a(1),cbp(2))
      real m,vel(64)
c
c     Read in parameters and set constants.
c
      call rdparm(nom,nx,nz,dom,dx,dz,vis)
      rr1 = (0.,.5)/dz
      rr3 = (0.,2.)*dx*dx/dz
      dipflt = (0.,1.)*vis
      beta = .14
c
c     Read the Fourier transform of the surface wave field.
c
      call rdwave(nx,nom,wave)
c
c     Continue the wave field down.
c
      do 150 iz = 1,nz
c
c        Get the velocity and clear the reflector sum.
c        The velocity is taken to be negative in migration.
c
         call rdvst(iz,nx,vel)
         do 40 ix = 1,nx
40          ref(ix) = (0.,0.)
         do 100 iom = 2,nom
```

```
            om = (iom-1)*dom
c
c           Apply time shift and
c           compute coefficients.
c
            do 50 ix = 1,nx
               m = om/vel(ix)
               shift = cexp((0.,1.)*m*dz)
               t(ix) = shift*wave(ix,iom)
                  m = m + dipflt/vel(ix)
               cc3 = rr3*m
               cc1 = rr1/m + beta*cc3
               aa(ix)= (.5,0.) - cc1
               a(ix) = aa(ix)- (1.,0.)
               bb(ix)  = cc1 + cc1 - (1.,0.) - cc3
50             b(ix) = bb(ix) + (2.,0.)
c
c           Absorbing side condition.
c
            bab = m*cmplx(0.,dx*.25)
            ra = ((1.,0.)+bab) / ((1.,0.)-bab)
            b(1) = b(1) + ra*a(1)
            bb(1) = bb(1) + ra*aa(1)
            b(nx) = b(nx) + ra*a(nx)
            bb(nx) = bb(nx) + ra*aa(nx)
c
c           Solve Crank-Nicolson matrix equation.
c
            d(1) = bb(1)*t(1) + aa(2)*t(2)
            d(nx) = bb(nx)*t(nx) + aa(nx-1)*t(nx-1)
            do 70 ix = 2, nx-1
70          d(ix) = bb(ix)*t(ix) + aa(ix-1)*t(ix-1) + aa(ix+1)*t(ix+1)
            call cvtri(abp,b,cbp,nx,t,d,e,f)
            do 100 ix = 1,nx
c
c              Sum to get wave field at t = 0.
c
               ref(ix) = ref(ix) + t(ix)
100            wave(ix,iom) = t(ix)
         do 110 ix = 1,nx
c
c           Subtract wave field at t = 0 to remove wraparound.
c
            ref(ix) = ref(ix)/nom
            do 110 iom = 1,nom
110            wave(ix,iom) = wave(ix,iom) - ref(ix)
150      call wrref(iz,nx,ref)
      stop
      end
```

```
      subroutine rdparm(nom,nx,nz,dom,dx,dz,vis)
c           Suboutine to generate parameters.
      nom = 64
      nx = 64
      nz = 64
      dt = .06
      dom = 2.*3.141592654/(nom*dt)
      dx = .1
      dz = .06
      vis = dom
      return
      end
      subroutine rdvst(iz,nx,vel)
c           Subroutine to generate velocity model
      real vel(nx)
      do 10 ix = 1,nx
10    vel(ix) = 1.
      do 20 ix = 1,iz
20    vel(ix) = 2.
      return
      end
      subroutine rdqst(iz,nx,ql)
c           Subroutine to generate Q model
      real ql(nx)
      do 10 ix = 1,nx
10    ql(ix) = 1./20.
      return
      end
      subroutine rdrst(iz,nx,ref)
c           Subroutine to generate reflector structure.
      real ref(nx)
      if (iz .ne. 48 ) goto 20
      do 10 ix = 1,nx
      xx = (nx + 1.)*.5 - ix
10    ref(ix) = exp(-1.*xx*xx)
      return
20    do 30 ix = 1,nx
30    ref(ix) = 0.
      return
      end
      subroutine rdwave(nx,nom,wave)
c           Subroutine to read in the Fourier transformed wave field.
      complex wave(64,64)
      integer uopen, uread
      logical*1 fn(100)
      call fname('.frq',fn)
      if = uopen(fn,0)
      do 10 iom = 1,nom
10    ir = uread(if,wave(1,iom),512)
      return
      end
      subroutine wrwave(nx,nom,wave)
c           Subroutine to write on disk the wave field.
      complex wave(64,80)
```

```
      integer uwrite,ucreat
      logical*1 fn(100)
      call fname('.frq',fn)
      if = ucreat(fn,"0664)
      do 10 iom = 1,nom
10    ir = uwrite(if,wave(1,iom),512)
      return
      end
      subroutine wrref(iz,nx,ref)
c          Subroutine to write reflector structure on disk.
      complex ref(nx)
      real rref(64)
      logical*1 fn(100)
      integer ucreat,uwrite
      if (iflag .eq. 1) goto 20
      iflag = 1
      call fname('.rst',fn)
      if = ucreat(fn,"0644)
20    do 30 ix = 1,nx
30    rref(ix) = ref(ix)
      nw = uwrite(if,rref,nx*4)
      return
      end
      subroutine cvtri(a,b,c,n,t,d,e,f)
c     Solve a tridiagonal matrix equation with
c     complex and variable coefficients
      implicit complex ( a-h,o-z)
      dimension t(n),d(n),f(n),e(n),a(n),b(n),c(n)
      n1 = n-1
      e(1) = -a(1)/b(1)
      f(1) = d(1)/b(1)
      do 10 i = 2,n1
      den = b(i)+c(i)*e(i-1)
      e(i) = -a(i)/den
10    f(i) = (d(i) - c(i)*f(i-1))/den
      t(n) = (d(n)- c(n)*f(n1))/(b(n)+c(n)*e(n1))
      do 20 j = 1,n1
      i = n-j
20    t(i) = e(i) *t(i+1) + f(i)
      return
      end
```

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