Defense Threat Reduction Agency
8725 John J. Kingman Road, MS 6201
Fort Belvoir, VA 22060-6201

DTRA-TR-03-34

TECHNICAL REPORT

Reducing Systematic Errors for Seismic Event Locations Using a Model Incorporating Anisotropic Regional Structures

March 2006

DTRA01-00-C-0103

Gideon P. Smith and
Douglas A. Wiens

DARE Tracking
73776

Prepared by:
Washington University
One Brookings Drive
St. Louis, MO 63130-4899

DESTRUCTION NOTICE

FOR CLASSIFIED documents, follow the procedures in DoD 5550.22-M, National Industrial Security Program Operating Manual, Chapter 5, Section 7 (NISPOM) or DoD 5200.1-R, Information Security Program Regulation, Chapter 1X.

FOR UNCLASSIFIED limited_documents, destroyed by any method that will prevent disclosure of contents or reconstruction of the document.

Retention of this document by DoD contractors is authorized in accordance with DoD 5220.22M, Industrial Security manual.

PLEASE NOTIFY THE DEFENSE THREAT REDUCTION AGENCY, ATTN: IMMI, 8725 JOHN J. KINGMAN ROAD, MS-6201, FT. BELVOIR, VA 22060-6201. IF YOUR ADDRESS IS INCORRECT, IF YOU WISH IT DELETED FROM THE DISTRIBUTION LIST, OR IF THE ADDRESSEE IS NO LONGER EMPLOYED BY YOUR ORGANIZATION.

DISTRIBUTION LIST UPDATE

<u>This mailer is provided to enable DTRA to maintain current distribution lists for reports. (We would appreciate you providing the requested information.)</u>

- ☐ Add the individual listed to your distribution list.
- ☐ Delete the cited organization/individual.
- ☐ Change of address.

> Note:
> Please return the mailing label from the document so that any additions, changes, corrections or deletions can be made easily. For distribution cancellation or more information call DTRA/BDLMI (703) 767-4725.

NAME: ______________________________

ORGANIZATION: ______________________________

OLD ADDRESS	**NEW ADDRESS**
______________	______________
______________	______________
______________	______________

TELEPHONE NUMBER: (   ) ______________________________

DTRA PUBLICATION NUMBER/TITLE	**CHANGES/DELETIONS/ADDITONS, etc.** *(Attach Sheet if more Space is Required)*
______________	______________
______________	______________
______________	______________

DTRA or other GOVERNMENT CONTRACT NUMBER: ______________

CERTIFICATION of NEED-TO-KNOW BY GOVERNMENT SPONSOR (if other than DTRA):

SPONSORING ORGANIZATION: ______________

CONTRACTING OFFICER or REPRESENTATIVE: ______________

SIGNATURE: ______________

DEFENSE THREAT REDUCTION AGENCY
ATTN: BDLMI
8725 John J Kingman Road, MS 6201
Fort Belvoir, VA 22060-6201

DEFENSE THREAT REDUCTION AGENCY
ATTN: BDLMI
8725 John J Kingman Road, MS 6201
Fort Belvoir, VA 22060-6201

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYY)* 03 May 2006	**2. REPORT TYPE** Technical Report	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITL
Reducing Systematic Errors for Seismic Even Locations Using a Model Incorporating Anisotropic Regional Structures (U)

5a. CONTRACT NUMBER
DTRA 01-00-C-0103

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
132D

6. AUTHOR(S)
Gideon P. Smith and Douglas A. Wiens

5d. PROJECT NUMBER
NS

5e. TASK NUMBER
AA

5f. WORK UNIT NUMBER
DH 01154

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Washington University
One Brookings Drive
St. Louis, MO 63130-4899

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Threat Reduction Agency
8725 John J. Kingman Rd., MS 6201
Fort Belvoir, VA 22060-6201

10. SPONSOR/MONITOR'S ACRONYM(S)
DTRA

11. SPONSOR/MONITOR'S REPORT NOS.
TR-03-34

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We have utilized a mapping of the lateral and anisotropic variations in Pn velocities beneath continents across the globe (Smith & Ekstrom, 1999) to predict travel times of P-wave . propagation at distances of 2-14 degrees. At such distances, the phase Pn is in the seismic phase that is most frequently reported and that thus controls the location accuracy. This is important in CTBT applications as many events of interest are only detected at these distances. We have thus worked on reducing the systematic errors in Pn travel-times and the resulting seismic event location at regional distances using our mapping.

15. SUBJECT TERMS
Pn Anisotropy Regional Phases CTBT Relocation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	SAR	17	**19b. TELEPHONE NUMBER** *(include area code)*

CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY → BY → TO GET
TO GET ← BY ← DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^o f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 ($N\text{-}s/m^2$)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 ($kg\text{-}m^2$)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (GY) is the SI unit of absorbed radiation.

ABSTRACT

We have utilized a mapping of the lateral and anisotropic variations in Pn velocities beneath continents across the globe (Smith and Ekstrom, 1999) to predict travel times of P-wave propagation at distances of 2-14 degrees. At such distances the phase Pn is the seismic phase that is most frequently reported and that thus controls the location accuracy. This is important in CTBT applications as many events of interest are only detected at these distances. We have thus worked on reducing the systematic errors in Pn travel-times and the resulting seismic event location at regional distances using our mapping.

In our investigations we have used a list of ground truth events by which to test locations using our different models. In establishing this list we have endeavored to include a variety of geographic areas and sizes of events. We have also developed a grid-search algorithm to relocate each of these events using isotropic, laterally varying, and full anisotropic models. Ray-path effects were also investigated and proven to be insignificant at current model resolutions. Our results indicate a progressive improvement in the relocation with increased model complexity. However, significant systematic errors remain in locations where heterogenity is accounted for but anisotropy is not. The most significant results appear to be for events with few stations reporting but with reasonable azimuthal distribution. Larger improvements are observed in tectonically active regions where the Pn models are better resolved. For CTBT purposes this improvement could therefore be of significant political importance.

KEY WORDS: Pn, anisotropy, regional phases, CTBT, relocation

OBJECTIVE

Introduction

In CTBT applications many events of interest are only detected at regional distances. Our objective is identification and reduction of systematic errors in the location of events determined using regional seismic data. At such distances (2-14 degrees) the phase Pn is the seismic phase that is most commonly reported and which thus controls the location accuracy. In order to accurately locate seismic events, whether natural or artificial, by traditional travel-time methods one must first be able to accurately predict arrival times. Historically travel-times have been calculated using one-dimensional seismic velocity models (e.g. Jeffreys and Bullen, 1940; Herrin et al., 1968; Herrin and Taggart, 1968; Herrin, 1968; Dziewonski and Anderson, 1981; Kennett and Engdahl, 1991). However, the Earth is composed of rocks which vary laterally at varying length scales (e.g. Crosson, 1976; Engdahl et al., 1977, 1982; Engdahl and Billington, 1986; Dziewonski, 1984; Su and Dziewonski, 1993) and can be anisotropic (e.g. Christensen, 1966; Kumazawa and Anderson, 1969; Hess, 1964; Raitt et al., 1969; Forsyth, 1975; Tanimoto and Anderson, 1984), resulting in travel-times which do not match those predicted by these one-dimensional velocity profiles. In addition, at regional length scales global Earth models, which are largely based on long-period surface waves and vertically arriving body waves, provide poor first arrival travel-time predictions. Providing more accurate prediction of P-wave propagation at regional distances is therefore of particular importance in event location. When attempting to satisfy the location requirements of the CTBT it is essential to obtain the most accurate location possible, with the minimum necessary computing time

The question remains as to whether the current generation of regional models can usefully contribute to relocation problems. While it has already been well established that variations in regional phases such as Pn can lead to large mislocations of the epicenter (Herrin and Taggart, 1962), progress has been slow in routinely applying regional models to locations for global catalogs. This is probably because most of the Pn velocity models produced are of a highly local nature (e.g. Hess, 1964; Raitt et al., 1969; Bamford, 1977; Fuchs, 1977; Hirn, 1977; Vetter and Minster, 1981), and no systematic global mapping of Pn velocities has been attempted. In addition although azimuthal anisotropy is a known feature of Pn propagation (e.g. Beghoul and Barazangi, 1990; Hearn, 1996), most previous studies of Pn anisotropy have not mapped lateral variations in azimuthal anisotropy, but instead produced, if anything, a single estimate for an entire region.

In recent work the P.I. has mapped lateral and anisotropic variations in Pn velocities beneath continents across the globe (Smith and Ekstrom, 1999). This work represents the most comprehensive and possibly the most accurate mapping of anisotropic Pn velocities available to date. This provides the first opportunity to truly test the possibility of applying an anisotropic Pn velocity model to calculation of travel-times to improve regional locations for events distributed in different parts of the world. The question remains whether this new mapping can provide, in a practical application, significant reductions in systematic event location at the regional scale. Our work is aimed at applying this new mapping of Pn anisotropic structure to investigate the possible systematic errors produced by lateral heterogeneity and azimuthal anisotropy

RESEARCH ACCOMPLISHED

Grid Search Relocation Algorithm

We began our study by developing and applying a grid search relocation algorithm to ground truth events. In this study we use travel-time data from the ISC database. The ISC location is used as a first estimate. The fit of travel times is then calculated for this location and for a set of points on a rectangular grid at 10-km spacing. The minimum in the rms of the travel times is then selected as the new location estimate and the travel-time misfits recalculated using a smaller grid spacing. This is repeated until the travel-time misfit appears to converge. This procedure has been performed for a selection of PNE for isotropic, laterally heterogeneous, and anisotropic structures. In this stage of our study great-circle raypaths were used.

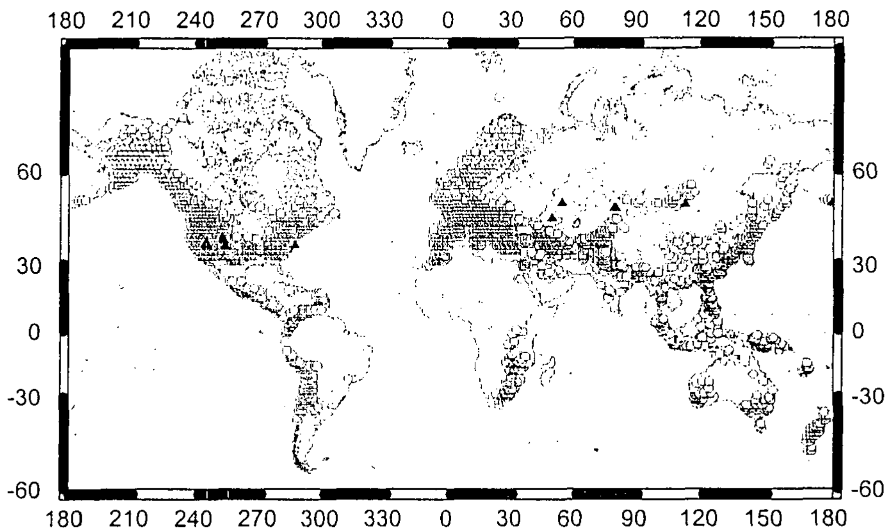

Figure 1 Worldwide distribution of Pn velocity estimates in the model of Smith and Ekstrom (1999). Triangles show the locations of PNEs used in Smith and Ekstrom (1996).

Figure 1 shows the worldwide distribution of Pn velocity estimates in the model of Smith and Ekstrom (1999). Triangles show the locations of PNEs used in Smith and Ekstrom (1996). We have used this same list of PNEs as a starting list of ground truth events for the current study. Clearly the geographic area with the best coincident coverage of PNEs and Pn velocity estimates is the United States. Although we are continuing to expand our list of test events the events in this region provide useful insight into effects of our model and algorithm (see Figure 2). Pn anisotropy for this region is shown in Figure 3.

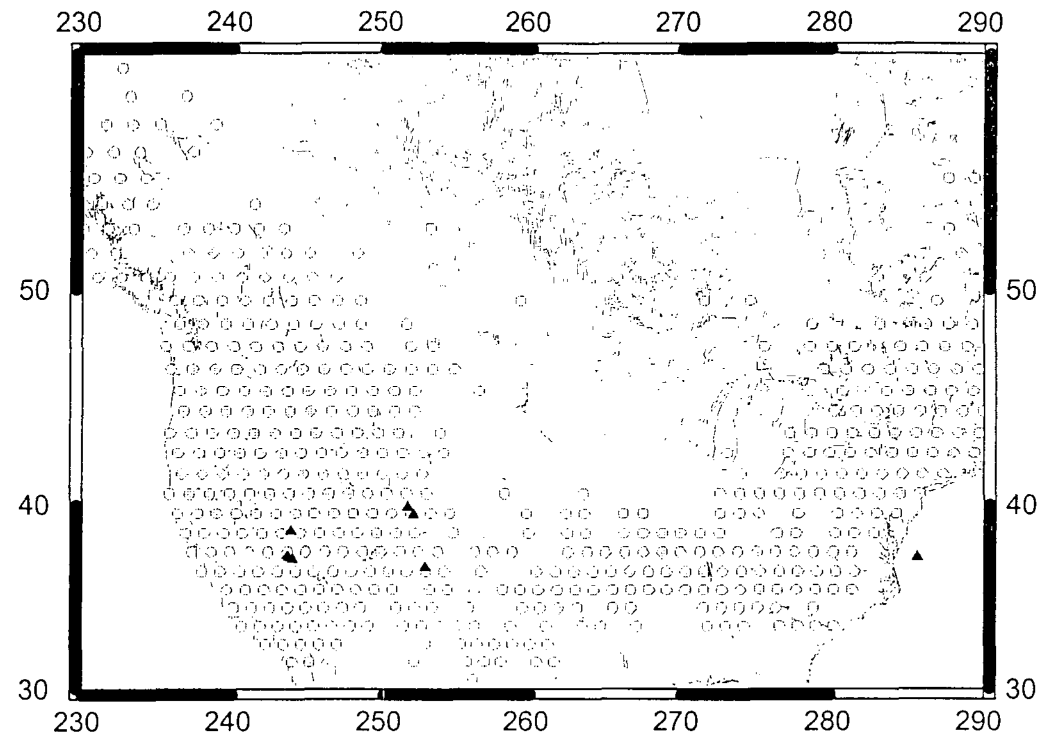

Figure 2 **shows the US distribution of Pn velocity estimates in the model of Smith and Ekstrom (1999). Triangles show the locations of PNEs used in Smith and Ekstrom (1996).**

Table 1 shows the RMS misfit using isotropic, laterally heterogeneous, and anisotropic models. Although this table suggests a general location improvement using the anisotropic structures we note that the majority of this improvement is seen in the locations for the western most events. This is explicable by examination of Figures 2 and 3 which demonstrate that for the eastern most event all regional arrivals are from similar azimuths, and so the 3 models converge to the same answer. It is notable that these improvements are minimal and given the liminted test-bed perhaps not statistically significant. Possible explanations for this minimal level of improvement are in use of direct raypaths as opposed to calculating the true raypath predicted by our model, and also dependence on the crustal model.

Model	RMS Misfit to Known Location (km)
isotropic	12.1
heterogeneous	11.6
anisotropic	10.9

Table 1: **Results of relocation using different velocity models**

Table 2 shows the results of experiments where we have relocated the events but only using travel-times from more distant stations (> 6 degrees). Although this reduces the number of travel-times the significance of accounting for correct uppermost mantle velocities increases.

Model	RMS Misfit to Known Location (km)
isotropic	14.1
heterogeneous	13.8
anisotropic	11.4

Table 2: **Results of relocation using different velocity models and restricting distance range to arrivals > 6°**

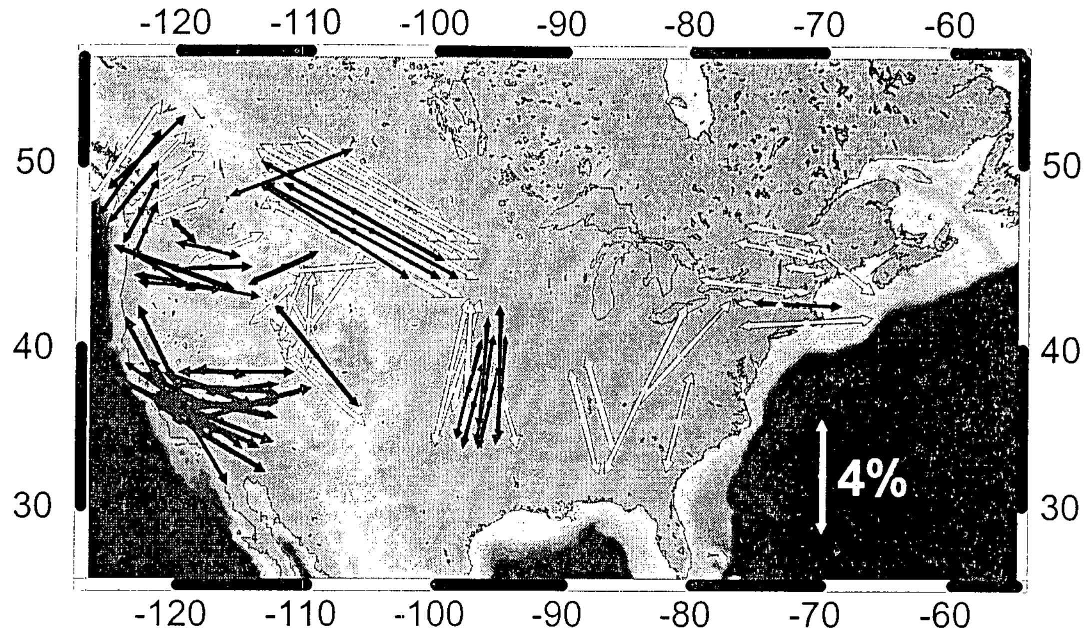

Figure 3 **Pn anisotropy estimates in the US. Arrows show the fast anisotropic direction and are proportional to the size of anisotropy. A 4% arrow is shows for scale.**

Investigation of Raypath Effects

We also developed and tested methods to quantify the effect of anisotropic velocity variations on raypath deviations from the great-circle path and the subsequent effect on Pn travel times. In this part of the work raypaths were allowed to deviate in the horizontal plane away from the great-circle path but not in the vertical plane. This limitation was imposed as a reflection of both the model and reality: if the wave were allowed to dive it would no longer be a Pn arrival but instead a diving wave, and as the model had no gradient in the vertical direction there was no physical basis for inferring deviations from the horizontal plane. Of course some deviation will exist in the real world due to slight moho variations and the existence of strong velocity gradients in some regions. Initial raypaths were calculated as being along the great circle path and then a 'bending' algorithm applied where the ray was allowed deviate from the great-circle path if small deviations allowed a faster route. Travel-times were then calculated using these new raypaths and the relocations repeated using them.

In practice the bending only produced occasional, and small deviations from the great-circle path. This may in part be due to the resolution of the model compared to the overall pathlength of Pn. The Pn velocity model is constructed from measurements with resolution of 1.5-3 degree radius caps and therefore a diameter of 3 to 6 degrees. Pn only propagates from 2-14 degrees and to avoid diving rays we have limited our Pn to 11 degrees distance. The relative resolution therefore may be limiting our ability to accurately reproduce strong raypath effects.

A second consideration is that even when a range of raypaths at a particular azimuth did show strong deviations due to the large number of raypaths included in the relocations the overall relocation was rarely affected to a great degree. The statistical analysis of the relocations using non-great-circle path raypaths is shown in the table below. Clearly a much stronger effect is noted from introduction of the anisotropic model on overall velocity and travel time rather than with raypath effects.

Model	RMS Misfit to Known Location (km)
isotropic	12.1
heterogeneous	11.6
Anisotropic with Ray bending	10.9

Table 3: Results of relocation using different velocity models

In the final part of our investigation we expanded our list of ground truth events to incorporate earthquakes that had been well located (Kennett and Engdahl, 1991). This produced some interesting results. Although the relocation improvement provided by incorporation of an anisotropic velocity model was limited for the preliminary list of nuclear explosions the improvement not only remained, but increased for earthquakes. The explanation for this is two-fold. First, our model shows the strongest variations in anisotropy and the greatest magnitude of anisotropy near actively deforming regions. Thus it is not surprising that for these regions, where earthquakes characteristically happen, as opposed to continental interiors where the majority of nuclear tests occur the accurate mapping of anisotropy becomes more important. The second reason is due to sampling. Where a great many events have appeared in the past our anisotropic Pn models are inevitably better constrained than where we have much more limited data and they therefore do a better job of predicting travel times and providing relocations in these regions. The table below shows the statistical comparison of relocations for isotropic, laterally heterogeneous, and anisotropic (non-great circle path) models.

Model	RMS Misfit to Known Location (km)
isotropic	17.3
heterogeneous	16.8
Anisotropic with ray bending	11.2

Table 4: Results of relocation using different velocity models for earthquake events

CONCLUSIONS AND RECOMMENDATIONS

Our current study clearly indicates that inclusion of more precise models, incorporating both heterogeneity and anisotropy at the regional scale, can improve the location accuracy. In continental interiors, the improvements obtained are not as striking as one might expect given the level of anisotropy and heterogeneity in the current models. However, near plate boundaries where anisotropic variations in Pn are noted to be at their most variable and highest magnitude the inclusion of anisotropic velocity models gives significant improvements.

Use of approximate raypaths as opposed to calculating the raypaths predicted by our model does not appear to give significantly different results on average. However, their remains a possible source of error in the calculation of the crustal leg of the traveltime. At greater distances this portion of the travel time becomes a less significant percentage of the overall traveltime and this is reflected in the increased significance in the improvement obtained at when considering longer raypaths.. In addition both the distribution of Pn velocity estimates available, and the azimuthal distribution of travel-times for the event being tested appears to have a critical effect on the improvement possible.

In conclusion it seems that the new anisotropic models can provide improvements in event location. However, at current model resolutions the improvement is likely as large for approximate great-circle paths as for the computationally more intensive situation of non-GCP raypaths. When locating events where the raypaths are closer to actively deforming regions the models are better and the anisotropic signal stronger and thus even greater improvements in relocation are seen. Many of the countries currently developing nuclear weapons are in such tectonic regions and so application of anisotropic corrections may be of significant importance in a CTBT context.

Conclusion of Work

All work has been completed as outlined in the `Statement of Work' initially proposed in the contract. These are expanded on in the same itemization order below.

1. A list of historical events for which "ground truth" has been determined by non-seismological data was established and these events used in the analysis of this approach. The events largely consisted of nuclear explosions as used by Smith and Ekstrom (1996).
2. Pn arrival times for the above dataset were extracted from the ISC catalog with obvious outliers, misidentifications and timing errors discarded.
3. A grid search algorithm was developed and applied to these events using the Pn velocity model.
4. Relocations were performed using isotropic, laterally heterogeneous and anisotropic Pn velocity models.
5. Derived and ground truth locations were compared to identify systematic relocation differences
6. Comparison of the different locations showed that the anisotropic model provided the best location over other velocity models.
7. Raypaths were allowed to vary from straight line raypaths and the effects on travel times examined.
8. The travel-times based on these raypaths were then used to perform new relocations
9. Comparison of the different locations showed similar results to earlier: that the anisotropic model provided the best location over other velocity models.
10. Use of newer "ground truth" events eg the earthquake data-set of Kennett and Engdahl (1991) was incorporated as much as possible.
11. Assessment of the practicality of this application was performed given the relative improvements provided to the increased time needed to incorporate such calculations in standard relocation work

Contractual/Administrative actions:

No changes in personnel, organization or operational methods occurred during the fulfillment of this contract. Dr Smith was promoted to Senior Research Staff but shortfall in salary from the new salary level was covered via alternative sources from within the University with no detrimental affect in time or effort on the current contract.

Properties Acquired:

No properties were acquired.

Travel

Travels covered under the entire contract included trips to the annual Seismic Research Reviews conference for Dr Smith to facilitate reporting of results and exchange of data and ideas. No new travel has occurred on this contract since the last report.

Reports, Articles and Presentations

Presentation of this work has been made at various of the annual Seismic Research Reviews conference by Dr Smith

Plan(s) for Next Reporting Period

This is the final report for reporting on this contract. All items of the original statement of work have been completed as outlined earlier (see section *Conclusion of Work*). No further work is scheduled or planned under the current contract.

Other Activities

Dr Smith's time has been covered at 50% by the DTRA contract. His other 50% has been covered under NSF contracts developing new understanding and mappings of anisotropy and its effect on raypaths and travel times. This other research has resulted in significant synergistic contributions to the current study of the effect of anisotropy on regional locations.

Finances

"Of the total funds authorized for the duration of this contract, 100% have been spent; 100% of the work has been completed."

All financial resources of this contract since last reporting have been expended on covering the salary of Dr Smith in accordance, and at the rates, covered under the original contract. The extra time to complete this contract has been covered by the university.

REFERENCES

Bamford, D., 1977. Pn velocity anisotropy in a continental upper mantle, Geophys. J. Roy. Astron. Soc., 49, 29-48.

Beghoul, N., and M. Barazangi, 1990. Azimuthal anisotropy of velocity in the mantle lid beneath the Basin and Range, Nature, 348, 536-538.

Carder, D.S., 1962. The Gnome Symposium. Bull. Seism. Soc. Am., 52, 977-979.

Christensen, N. I., 1966. Elasticity of ultrabasic rocks. J. Geophys. Res., 71, 5921-5932.

Crosson, R. S., 1976. Crustal structure modeling of earthquake data 1. Simultaneous least squares estimation of hypocenter and velocity parameters, J. Geophys. Res., 81, 3036-3046.

Dziewonski, A. M, 1984. Mapping the lower mantle: determination of lateral heterogeneity in P velocity up to degree and order 6, J. Geophys. Res., 89, 5929-5952.

Dziewonski, A. M., and D. L. Anderson, 1981. Preliminary Reference Earth Model. Phys. Earth and Planet. Int., 25, 297-356..

Engdahl, E. R., and S. Billington, 1986. Focal depth determination of Central Aleutian Earthquakes, Bull. Seism. Soc. Am., 76, 77-93.

Engdahl, E. R., N. H. Sleep, and M.-T. Lin, 1977. Plate effects in North Pacific subduction zones, Tectonophys., 37, 95-116.

Forsyth, D. W, The early structural evolution and anisotropy of the oceanic upper mantle, Geophys. J. Roy. Astr. Soc., 43, 103—162, 1975

Fuchs, K., 1977. Seismic anisotropy of the subcrustal lithosphere as evidence for dynamical processes in the upper mantle, Geophys. J. Roy. Astron. Soc., 49, 167-179.

Hearn, T., 1996. Anisotropic Pn tomography in the Western United States, J. Geophys. Res., 101, 8403-8414.

Herrin, E., 1968. Seismological tables for P-phases, Bull. Seism. Soc. Am., 60, 461-489.

Herrin, E. and J. Taggart, 1968. Regional variations in P travel times. Bull. Seism. Soc. Am., 58, 1325-1337.

Herrin, E. and J. Taggart, 1962. Regional Variations in Pn velocity and their effect on the location of epicenters, Bull. Seism. Soc. Am., 52, 1037-1046.

Herrin, E., W. Tucker, J. Taggart, D. W. Gordon, and J. L. Lobdell, 1968. Estimation of surface focus P travel times, Bull. Seism. Soc. Am., 58, 1273-1291.

Hess, H. H, Seismic anisotropy of the uppermost mantle under oceans, Nature, 203, 629—631,1964

Hirn, A., 1977. Anisotropy of the continental upper mantle: possible evidence from explosion seismology, Geophys. J. Roy. Astron. Soc., 49, 49-58.

Jeffreys, H. and K. E. Bullen, 1940. Seismological Tables, British Association for the advancement of Science, London.

Kennett, B. L. N., and E. R. Engdahl, 1991. Traveltimes for global earthquake location and phase identification, Geophys. J. Int., 105, 429-465.

Kumazawa, M., and O. L. Anderson, 1969. Elastic moduli, pressure derivatives, and temperature derivatives of single crystal olivine and single crystal forsterite, J. Geophs. Res., 74, 5961-5972.

Raitt, R. W., G. G. Shor Jr., T. J. G. Francis, and G. B. Morris, Anisotropy of the Pacific upper mantle, J. Geophys. Res., 74, 3095--3109, 1969

Smith, Gideon P., and Goran Ekstrom, 1999. A global study of Pn anisotropy beneath continents, J. Geophys. Res., 99, NO. B12, 23,787-23,800.

Smith, Gideon P., and Goran Ekstrom, 1996. Improving teleseismic event locations using a 3-dimensional Earth model, Bull. Seism. Soc. Am., 86, 788-796.

Smith, Gideon P., and Goran Ekstrom, 1996b. Regional Phases in global Earth models, abstarct EOS Trans., 77, Fall Meet. Suppl., F489.

Su. W. and A. M. Dziewonski, 1993. Joint 3-D inversion for P- and S- velocity in the mantle, EOS, 74, 557.

Tanimoto, T. and D. L. Anderson, Mapping convection in the mantle, Geophys. Res. Lett., 11, 287--290, 1984

Vetter, U., and J.-B. Minster, 1981. Pn velocity anisotropy in southern California, Bull. Seis. Soc. Am., 71, 1511-1530.

DISTRIBUTION LIST
DTRA-TR-03-34

DEPARTMENT OF DEFENSE

DEFENSE TECHNICAL INFORMATION CENTER
8725 JOHN J. KINGMAN ROAD,
SUITE 0944
FT. BELVOIR, VA 22060-0944
2 CYS ATTN: DTIC/OCA

DEFENSE THREAT REDUCTION AGENCY
8725 JOHN J. KINGMAN ROAD MS 6201
FT. BELVOIR, VA 22060-6218
2 CYS ATTN: TDND/ D. BARBER

DEPARTMENT OF DEFENSE CONTRACTORS

ITT INDUSTRIES
ITT SYSTEMS CORPORATION
1680 TEXAS STREET, SE
KIRTLAND AFB, NM 87117-5669
2 CYS ATTN: DTRIAC
ATTN: DARE

WASHINGTON UNIVERSITY
ONE BROOKINGS DRIVE
ST. LOUIS, MO 63130-4899
ATTN: G. P. SMITH