

1 **METHODS FOR EARTH MODELING AND SEISMIC IMAGING**
2 **USING INTERACTIVE AND SELECTIVE UPDATING**

3
4 FIELD OF THE INVENTION

5
6 The present invention relates generally to methods for earth modeling and
7 seismic imaging, and more particularly, to methods which use beam migration
8 to create seismic images.

9
10 BACKGROUND OF THE INVENTION

11
12 Constructing accurate seismic images and corresponding earth models is
13 important in making decisions relating to exploration and reservoir
14 management. For example, earth scientists use seismic images to determine
15 where to place wells in subterranean regions containing hydrocarbon
16 reservoirs. They also use velocity or earth models to create reservoir models
17 suitable for reservoir fluid flow modeling. The quality of the decisions made
18 by the earth scientists is highly dependent on the quality of the seismic
19 images and earth models.

20
21 The quality of an earth model and the quality of a corresponding seismic
22 image are interrelated. An earth model is typically comprised of hundreds of
23 thousands or even millions of cells or elements which are used in a computer
24 simulation. An imaging program is used which simulates energy passing
25 through the elements of the earth model, constrained by seismic data, to
26 create a seismic image. An accurate earth model is often necessary for a
27 clear seismic image, and vice versa.

28
29 The earth model has various properties that will affect the computation of the
30 seismic image. For example, a seismic velocity field is specified within each
31 geologic layer in the earth model. The magnitude of the velocities and the
32 spatial variations within the velocity field affect the positioning and focusing of

1 energy propagation through the elements. Moreover, the shapes of the
2 boundaries between various geologic layers can greatly affect the propagation
3 direction of seismic energy as well. For example, an image beneath a
4 massive salt formation is greatly affected by the shape of the boundaries
5 between salt and sedimentary layers. Often, the velocities are not strongly
6 dependent on the direction of energy propagation and are approximately
7 specified as a simple isotropic scalar field. It is becoming common, however,
8 to build much more detailed earth models which specify detailed anisotropic
9 velocities with a tensor field.

10

11 The conventional practice for imaging complex geology is iterative refinement
12 of both the earth model and the seismic image. FIG. 1 shows a flowchart
13 outlining this conventional iterative process. A seismic survey is taken in **step**
14 **20** of a subterranean region which is to be modeled and imaged. A
15 geophysical/geological interpreter typically makes an initial determination of
16 an appropriate earth model in **step 30**. This earth model is based upon
17 information derived from well data, seismic surveys, geological outcrops, and
18 geologic structural concepts. Commercially available programs are often
19 used to construct such models. For example, GOCAD™ earth-modeling
20 software is available from Earth Decision Sciences of Houston, Texas.

21

22 The earth modeling software creates an earth model data file that contains the
23 particulars of the model. The time needed to prepare such a model depends
24 on the size and complexity of model. Commonly, the time needed to prepare
25 the initial model ranges on the order of 5 days to 5 weeks. The technical
26 expertise required for creating an earth model is usually provided by
27 collaboration between a person skilled in geology and another skilled in
28 computer-aided design, especially of earth-model representations.

29

30 A seismic imaging expert, often a geophysicist, generates in **step 40** images
31 of the earth by using imaging software known in the seismic industry as
32 migration software. An example of a migration program is ChevronTexaco's

1 proprietary GBMig software. This software uses Gaussian beam migration to
2 create seismic images. An example of a commercially available migration
3 program is included in modules of ProMax[®] software sold by Landmark
4 Graphics Corporation of Houston, Texas. These migration programs typically
5 receive as input seismic data and an earth model data file created by the
6 earth modeling software. The seismic imaging expert utilizes the earth model
7 and seismic data to create seismic images which are saved as seismic image
8 data files. The time required to create the initial seismic images is often on
9 the order of 1 day to 4 weeks.

10

11 Several different migration techniques may be used by the seismic imaging
12 programs. Examples of these techniques include non-recursive Kirchhoff and
13 Gaussian beam migration methods, recursive finite-difference and
14 phase-shift-plus-interpolation methods.

15

16 Seismic interpretation software is used in **step 50** to evaluate the seismic
17 image and to compare the seismic images with the initial earth model. An
18 example of such interpretation software is Seisworks[®] software available from
19 Landmark Graphics Corporation, Houston, Texas. The technical skills for this
20 evaluation and comparison include an understanding of structural geology
21 and seismic stratigraphy. Several different factors are considered during the
22 evaluation of the seismic image, including: (1) whether the earth model is
23 consistent with the seismic image; (2) whether the seismic image is
24 geologically plausible or even possible; and (3) whether the image is
25 well-focused or is blurred.

26

27 After evaluation of the current seismic image, the earth model is refined in
28 **step 60** in hopes of reducing observed deficiencies in the image in a next
29 round of imaging computations. A geophysical expert selects elements of the
30 original earth model and revises these elements in an effort to improve the
31 model. The updated model, containing the updated elements, is then saved

1 as an updated earth model data file. The time necessary for this step is often
2 several hours to several days.

3

4 The updated earth model data file is returned to the seismic imaging expert.
5 The imaging expert supplies the updated earth model to the migration
6 program to generate the next round of seismic images. This process takes
7 approximately a day or even weeks, depending on the complexity of the earth
8 model as it evolves. The updated seismic images are passed back to the
9 geologic expert for reevaluation, and the iterative loop of **steps 40-60**, as
10 seen in FIG. 1, continues until the seismic image is deemed satisfactory.

11

12 Many considerations affect the construction of the initial earth model. These
13 considerations will vary depending on the type of geology being represented.
14 For the example of sub-salt imaging in the Gulf of Mexico, an earth model is
15 often constructed in a top-down fashion, as will now be described.

16

17 An "interpreter" is a person skilled in geologic interpretation and is often
18 principally responsible for the development of an exploration prospect. The
19 first step for the interpreter is typically to specify the ocean depths over the
20 region of the recorded seismic data. These depths might be specified by the
21 recorded bathymetry, but more often the depths are mapped from a seismic
22 image while working in a seismic interpretation system, such as Landmark's
23 Seisworks® software. The initial seismic image used for identification of the
24 water bottom can be constructed by very rudimentary imaging method since
25 the travel paths to the water bottom are simple. Once the water bottom has
26 been mapped, this map is saved as a computer data file and given to a
27 geophysicist who is also skilled in computer-aided modeling of the earth. This
28 geophysicist will form a two-layer model, the upper layer being the ocean, and
29 the lower layer being a sedimentary layer. The velocities of the sedimentary
30 layer are at this point only roughly specified by converting initial stacking
31 velocities to interval velocities using a Dix conversion. The salt bodies are not
32 yet represented in the model.

1 The current two-layer "sediments only" model is used as the earth model input
2 to a depth migration imaging program, such as GBMig migration software
3 which uses beam migration to create seismic images. The imaging program
4 will produce an image of the sedimentary layers, but the image will not usually
5 be well focused everywhere because the sedimentary velocities are not
6 accurate and especially do not accurately represent lateral spatial velocity
7 variations, such as might be caused by the presence of gas. The magnitude
8 of the misfocusing is measured by the geophysicist and used as input to a
9 tomography module, such as is included in Landmark's ProMax[®] software.
10 This tomography program can estimate the corrections to the velocity field
11 that are needed to correct the misfocusing in future applications of the
12 imaging program. At this point, however, tomography is only appropriate for
13 finding velocity corrections for regions above massive salt layers; the salt itself
14 and regions below salt are generally too badly imaged to allow the use of
15 tomographic velocity calculations.
16
17 Once the tomographic corrections have been calculated for the regions above
18 the salt layers, these corrections are included in the earth model. The
19 imaging program is again applied to the seismic data using the updated
20 velocity or earth model. Since this updated model now has accurate
21 velocities at least down to the top of salt layers, the computed energy
22 propagation down to the top of salt should be accurate and result in an
23 accurate image of the top of salt.
24
25 This latest image is again sent to the interpreter, whose job is now to map the
26 top of salt. This round of mapping is not as easy as mapping the water
27 bottom because the top of salt is often rugose. In fact, the mapping of the top
28 of the salt is sometimes ambiguous, especially where the salt might be locally
29 overturned or where sedimentary country rock might be entrained in the salt.
30 Nevertheless, the top of salt is usually well imaged at this point because the
31 propagation paths from the earth's surface to the top of salt are relatively
32 simple.

1 The salt-top map is saved as a computer file and delivered to the
2 geophysicist. The geophysicist enters this salt-top map into the earth model
3 to form a three layered model, known as a "bottomless salt" model. The three
4 layers are the water layer, the sedimentary layer above salt, and the salt
5 layer. At this point, the salt layer extends to the bottom of the earth model.
6 The actual bottom of salt is not yet specified because it is generally not yet
7 well imaged. The seismic velocities within salt are usually modeled as a
8 constant value that is representative of what is observed in wells that
9 penetrate salt. The salt velocity value is also guided by values that were
10 successfully used in other sub-salt imaging projects.

11
12 Now that the boundary specifying top of salt is included in the earth model,
13 the imaging program can accurately compute the refraction of seismic energy
14 at the top of salt and form an image to greater depths. In particular, the
15 imaging program can now form an image of the salt bottom. The imaging
16 program is run once again with the current "bottomless salt" model. The
17 resulting image is again delivered to an interpreter, who must now map the
18 bottom of salt.

19
20 The mapping of the bottom of salt is sometimes easy because the boundary is
21 sometimes clearly imaged. Often, however, mapping the salt bottom is very
22 difficult and ambiguous. The salt bottom is not well illuminated everywhere
23 because the salt top refracts energy in other directions. There are often
24 suture boundaries within the salt that might be mistaken for the salt bottom.
25 Usually, the signal is weak because the salt top interface significantly reduces
26 the energy transmitted to illuminate deeper horizons. There can also be large
27 coherent noise caused by multiple reflections above the salt and by
28 conversion of the pressure-wave seismic energy to shear-wave seismic
29 energy. Although these factors make the identification of the salt bottom
30 difficult, the interpreter must nevertheless map the salt bottom and save this
31 map as a computer file.
32

1 The file containing the map of the salt bottom is delivered to the geophysicist,
2 who uses this map to complete the specification of the shape of salt in the
3 earth model. The geophysicist also specifies the velocities of sedimentary
4 layers beneath the salt. It is difficult to measure sedimentary velocities
5 beneath salt. Often, the velocity specification of sub-salt sediments is based
6 on velocities measured in similar sedimentary layers that are at similar depth
7 but are not beneath salt.

8
9 The imaging software is again applied to the seismic data, using the latest or
10 velocity or earth model. Since the velocity model is complete, the quality of
11 the resulting imaging is often sufficient for mapping sub-salt hydrocarbon
12 prospects.

13
14 The sub-salt example just given illustrates a case with a step-by-step recipe
15 for construction of the earth model. There is a clear-cut recipe because, in
16 one important respect, this example earth model is simple: it has smoothly
17 varying velocities within each layer. Only the boundaries between salt and
18 sediments are complicated, and the shape of these boundaries often can be
19 determined by the top-down recipe just described.

20
21 In many other cases, the construction of the velocity model is much more
22 complicated and cannot be described beforehand in a step-by-step recipe.
23 For example, in thrustbelt geology, there can be overturned layers for which it
24 is difficult to determine both the layer shapes and the velocities within the
25 layers. In other examples, anhydrates entrained in salt masses have a large
26 effect on the propagation of the seismic energy but are difficult to map from
27 the seismic image. Even for sub-salt imaging, the top-down recipe just
28 described only results in a sub-optimal provisional earth model, which could
29 be refined by further analysis.

30
31 There are many barriers to improving upon a suboptimal seismic image. First,
32 it is often not clear what changes should be made to the model to improve the

1 focusing of the image. Sophisticated tomographic inversion programs
2 analyze the misfocus of a seismic image to derive model corrections to
3 reduce this misfocus. Nevertheless, the resolution of these inversion
4 programs is limited. Many different model corrections will produce the same
5 degree of improvement of the image focus, although each different model will
6 produce an image with different apparent geologic structure. Furthermore, in
7 many seismic imaging problems, the seismic signal is weak and noise is
8 strong, making it difficult to discern whether the image is focused or not.

9
10 Geophysical measurements are usually not sufficient for obtaining an
11 accurate image of complex geology. Geologic considerations must constrain
12 the image. There are many examples of these constraints. A simple geologic
13 constraint would be that the image must agree with existing well data, which
14 might include the positions and dips of bedding that appears in the image.
15 Often, there is the geologic constraint that certain beds in the image should be
16 simple and flat. Another constraint is that fault-plane reflections should line up
17 with the image of bedding throw. Moreover, an image that exhibits
18 superimposed crossing geologic bedding cannot be correct. These are just a
19 few simple considerations, but advanced structural principles also constrain
20 the geology.

21
22 Combining geophysical inversion of the seismic data with geologic constraints
23 on the earth model is difficult to derive mathematically and to implement in
24 computer code. For example, the obvious constraint that geologic beds
25 cannot cross is beyond the current technical art of tomographic seismic
26 inversion. Only rudimentary constraints on the smoothness of the velocity
27 field and reflection horizons are part of the current inversion art. Even
28 smoothness constraints should not be imposed solely by the geologist or the
29 geophysicist. A well-focused image that is consistent with a geologic
30 framework should be the product of collaboration between geologic and
31 geophysical experts.

32

1 Revising a seismic image with geologic insight is difficult. Besides days or
2 weeks of computer time, revising an image requires coordination of an
3 assembly-line process in which different specialists perform the steps using
4 separate software applications in the process. Instead of constant
5 collaboration, experts mostly interact only when intermediate results are
6 transferred from one step to the next. FIG. 1 diagrams the geologic and
7 geophysical evaluation of the image as different steps. The interpreter
8 decides if the image is sufficient to map the geologic structure and, if it is not,
9 points out the deficiency of the image to geophysical experts and asks them
10 to improve the image. The interpreter generally does not get directly involved
11 in the geophysical analysis.

12

13 Decisions on how best to update the earth models and seismic images and
14 how to perform the seismic interpretation are generally not collaboratively
15 made by all the experts. This is largely due to the length of time it takes to
16 recompute updated data files, i.e., earth model data files, seismic image data
17 files, and topological subsurface bedding maps. Commonly, it takes many
18 hours or days for computers to compute these large updated files for each of
19 the earth modeling, seismic imaging, and seismic interpretation steps. As a
20 result, the earth modeling and seismic imaging iterative improvement is done
21 in the discrete steps described above rather than in a fully collaborative
22 fashion between experts from the various disciplines. All in all, this
23 discretized process of creating the separate data files which are repeatedly
24 passed back and forth between geologists, geophysicists and interpreters
25 may take months before arriving at a satisfactory seismic image and
26 corresponding earth model.

27

28 As described above, conventional methods of iteratively refining earth models
29 and seismic images have a number of shortcomings. First, the computational
30 efforts to update earth models, seismic images, and maps are great due to
31 the recomputing of the entire data files during iterations. Second, because
32 each of the updating steps in earth modeling, seismic imaging and seismic

1 interpretation is so time consuming, it is difficult for and unlikely that the
2 various experts will fully collaborate when decisions are made as how to
3 update the earth model and seismic images. Finally, the passing of numerous
4 data files back and forth between various experts and processing software
5 require great efforts and care to insure the data files are not corrupted or lost
6 during the enhancement process.

7
8 The present invention provides a time and computationally efficient method
9 for interactively and selectively updating earth models and seismic images.
10 As a consequence, collaboration between desired experts in geology,
11 geophysics, seismic interpretation, and computer modeling can be used
12 throughout the iterative process in updating the earth model and seismic
13 images. This leads to better quality models and images being prepared in a
14 relative short period of time, i.e., hours and days rather than days, weeks or
15 even months. Further, ideally an integrated program is used in this iterative
16 process which reduces chances for corrupting or losing data files used in the
17 iterative enhancement process.

18 19 SUMMARY OF THE INVENTION

20
21 One aspect of the present invention provides a method for creating an
22 enhanced depth-migrated seismic image, the method comprising:

23 (a) acquiring seismic data from a seismic survey conducted over a
24 subterranean region;

25 (b) transforming the seismic data into a set of energy components;

26 (c) creating an earth model having velocity model characterizations
27 therewithin representative of the subterranean region, the earth model
28 comprising a set of lens elements having propagation properties which affect
29 energy propagation through the lens elements;

30 (d) propagating the set of energy components through the lens
31 elements to form image components which are combined into a depth-

1 migrated seismic image;

2 (e) identifying a target in the seismic image for image enhancement;

3 (f) selecting a trial subset of less than all of the lens elements from

4 the set of lens elements and updating propagation properties of the trial

5 subset of lens elements which may affect imaging of the target without

6 updating the propagation properties of all the lens elements of the earth

7 model;

8 (g) selecting a trial subset of less than all of the energy components

9 from the set of energy components which may affect imaging of the target;

10 (h) propagating the trial subset, without propagating all, of the set of

11 energy components through the earth model to form updated image

12 components; and

13 (i) updating the seismic image by replacing image components of the

14 current seismic image with the updated image components without replacing all of

15 the image components to arrive at an enhanced seismic image.

1
2 Most preferably, the method for selecting the subset of energy components
3 which is to be propagated through the updated lens element to form the
4 updated image components is as follows. A trial set of energy components is
5 selected from the transformed seismic data. The selection criteria is that an
6 energy component have a corresponding ray path that passes within a
7 predetermined distance of a target of interest. Furthermore, it is preferred that
8 this ray path pass through at least one of the lens elements which is updated.
9 Ideally, this trial subset of energy components is further reduced. Ray paths
10 of the trial set of energy components are traced through the updated earth
11 model to create updated ray paths. No image components need be formed at
12 this time. Only those energy components who propagate and touch the target
13 and also whose updated ray path passes through one of the updated lens
14 elements is selected to be included in the subset of energy components which
15 is to be used to form the updated image components. These updated image
16 components will replace corresponding image component from the current
17 seismic image to create an updated seismic image.

1 Ray tracing may be used to select the trial set of lens elements to be updated
2 and also to select the trial set of energy components. The preferred energy
3 components are Gaussian beam components and the preferred propagation
4 or migration technique used is Gaussian beam migration. The iterative
5 updating of the seismic image is performed within a single application so that
6 data files do not have to be passed between separate software packages.

7

8 An alternate aspect of the present invention provides a method for enhancing a
9 depth-migrated seismic image comprising:

10 (a) propagating a set of seismic energy components through an earth
11 model having velocity model characterizations therewithin comprising a set of lens
12 elements to form a set of image components which are summed to form a depth-
13 migrated seismic image;

14 (b) identifying a target in the seismic image which is to be enhanced;

15 (c) updating a trial subset of lens elements of less than all of the lens
16 elements from the set of lens elements to update the earth model without updating all
17 of the lens elements of the earth model;

18 (d) selecting a trial subset of energy components of less than all of the
19 energy components from the energy components of step (a);

20 (e) propagating the trial subset of energy components through the
21 updated earth model without propagating all of the set of energy components through
22 the updated earth model to create updated image components; and

23 (f) replacing current image components with the updated image
24 components and not replacing those image components that were not updated to
25 create an enhanced seismic image.

26

27 A further aspect of the present invention provides a method for enhancing a
28 depth-migrated seismic image comprising:

29 (a) creating a depth-migrated seismic image using an earth model having
30 velocity model characterizations therewithin comprising a set of lens elements and
31 using seismic data, the seismic image comprising a set of image components, the

1 seismic image including a target which is to be enhanced;

2 (b) updating a trial subset of less than all of the lens elements selected
3 from the set of lens elements in the earth model;

4 (c) updating those image components in the seismic image which are
5 associated with changes in the trial subset of lens elements of the earth model which
6 affect the seismic imaging of the target; and

7 (d) subtracting image components in the seismic image and adding in
8 their place updated image components without replacing all of the image
9 components to enhance the seismic image.

10

11 An additional aspect of the present invention provides a method for enhancing a
12 depth-migrated seismic image comprising:

13 a) propagating a set of seismic energy components through a velocity
14 model, comprising a set of lens elements, to form a set of image components which
15 are summed to form an original depth-migrated seismic image;

16 b) updating at least some of the lens elements to update the velocity
17 model;

18 c) selecting a trial subset of energy components of less than all of the
19 energy components from the set of energy components of step (a);

20 d) propagating the trial subset, without propagating all, of the energy
21 components through the updated velocity model to create updated image
22 components; and

23 e) subtracting image components from the original seismic image and
24 adding in their place updated image components, without replacing all of the image
25 components of the original seismic image, to arrive at an updated enhanced seismic
26 image.

27

28 Embodiments of the present invention to provide an integrated workflow in
29 earth modeling and seismic imaging program wherein the computational time
30 required to update earth models and seismic images is sufficiently short that
31 this workflow can be accomplished interactively in minutes or hours rather
32 than using discretized programs and analyses which

1 require weeks or months to complete.

2

3 Alternate embodiments incrementally update depth migrated images by
4 recomputing only those targeted image components associated with the latest
5 changes in the earth model.

6

7 Further embodiments provide an interpretation-depth migration scheme
8 wherein select elements of a earth model are updated and only a subset of a
9 corresponding portion of the seismic image need be updated in providing an
10 enhanced seismic image.

11

12 Additional embodiments update an earth model using not only information
13 from structural patterns emerging in the image but also by a quick ray-trace
14 analysis of imaging focusing.

15

16 BRIEF DESCRIPTION OF THE DRAWINGS

17

18 These and other objects, features and advantages of the present invention
19 will become better understood with regard to the following description,
20 pending claims and accompanying drawings where

- 1 FIG. 1 is a flowchart showing steps conventionally used in iteratively
2 enhancing seismic images and earth models;
3
- 4 FIG. 2 is a flowchart of a preferred embodiment of the present invention
5 showing a workflow for creating seismic images and earth models;
6
- 7 FIG. 3 is a flow chart describing ray tracing techniques which may be used to
8 select lens elements which are to have their propagation properties, such as
9 shape or velocity field, updated;
10
- 11 FIG. 4 shows preferred steps used to select a subset of energy components
12 which are to be propagated through an updated earth model to form updated
13 image components;
14
- 15 FIG. 5 illustrates seismic data processed into a Common-Offset Section or
16 approximated to what would be recorded at zero offset;
17
- 18 FIG. 6 depicts a single beam energy component, i.e., a Gaussian beam,
19 which is projected into the earth along a ray path;
20
- 21 FIG. 7 illustrates a seismic image of a subterranean salt dome which is
22 comprised of summed image components;
23
- 24 FIG. 8 illustrates the transformation of seismic data into beam components
25 showing (A) a transform separating events near location L having dip p^m ; and
26 (B) these events being projected back into the earth along all shot-detector
27 ray path pairs that have dips summing to p^m ;
28
- 29 FIG. 9 shows a display used to analyze the problem of crossing reflectors in a
30 seismic image;
31

1 FIGS. 10A and 10B illustrate a focusing analysis using a two-point ray search
2 of a faulty image wherein energy components have traveled along different
3 ray paths and focus at different locations, indicating a problem with the earth
4 model; and

5

6 FIG. 11 shows lens elements of an earth model being modified with a portion
7 of an earth surface being interactively dragged with the change in the focusing
8 of the lens element being immediately updated.

9

10 DETAILED DESCRIPTION OF THE INVENTION

11

12 An exemplary and preferred embodiment of a method for creating an
13 enhanced seismic image, made in accordance with the present invention, is
14 shown in FIG. 2. FIGS. 3 and 4 show sub-steps of steps 160 and 170 of
15 FIG. 2. The method concurrently optimizes an earth model along with the
16 seismic image.

17

18 In **step 110**, seismic data are obtained from a seismic survey of a
19 subterranean region of interest. The seismic data, if so desired, can be
20 organized into data sets which facilitate further analysis. In this exemplary
21 embodiment, the seismic data is organized into common-offset sections
22 (COS). Alternatively, these seismic data may be used in a raw form by using
23 the recorded organization of the seismic data, i.e., common shot gathers. Or
24 else, the seismic data may be organized into other data sets such as
25 common-midpoint gathers or common-receiver data.

26

27 FIG. 5 shows a two-dimensional example of a COS data set, which, for this
28 particular example, happens to be for zero offset. Each COS data set
29 includes only traces that were recorded at a particular offset vector. An offset
30 vector is the spatial vector between the seismic source and the seismic
31 detector for a trace. A trace at a particular offset vector might be available
32 directly from a recorded data set. If this offset is not directly available, then

1 the desired traces can be approximated by applying standard processing
2 steps (such as move-out and stack) to traces recorded at some other offset
3 vectors. Within each COS data set, the seismic traces are ordered into a
4 three-dimensional array of values. The first axis of the three-dimensional
5 array is the recorded time. The origin of the first axis is the initiation time of
6 the seismic source. The other two axes are the X and Y spatial positions of
7 the midpoint between the source and detector for each trace.

8
9 In **step 120**, these data sets are transformed into energy components. For
10 the purposes of this specification, the term "energy components" refers to a
11 set of components into which the recorded seismic data is analyzed or
12 transformed. The energy components may include any partitioning of the
13 seismic data including shot profiles, common offset data, common midpoint
14 data and plane wave energy components.

15
16 In this preferred embodiment, the seismic data sets are transformed in energy
17 components, referred to as beam components, and more preferably Gaussian
18 beam components. In the case of beam components, the energy propagates
19 approximately along a single ray path. Several physical energy sources, for
20 example, air guns, contribute to each of the beam components traveling along
21 their respective ray paths. By way of example and not limitation, other
22 examples of energy components into which seismic data can be
23 mathematically analyzed or decomposed include shot gathers or simple
24 mathematical transformations such as plane-wave transforms (F-K
25 transforms). In the case of shot gathers, the transformation can be
26 considered to be simply an identity transform on the recorded data which
27 results in the original shot gathers.

28
29 Each seismic data set, i.e., COS, is mathematically transformed in **step 120**
30 into a corresponding set of energy components, in this case Gaussian beam
31 components. This transformation is ideally carried out as described in Hill,

1 N.R., *Prestack Gaussian Beam Migration*, Geophysics, Volume 66,
2 pp. 1240-50 (2001), and as will be further described in detail below.

3
4 Although not as preferred, the transformation into beam components could
5 also be performed in accordance with the transformation method described in
6 U. S. Patent 5,274,605, entitled "Depth Migration Method Using Gaussian
7 Beams", the teachings of which are hereby incorporated by reference in its
8 entirety. A further transformation method is also described in Hill, N.R.,
9 *Gaussian Beam Migration*, Geophysics, Volume 55, pp. 1416-28, (1990).
10 Both of the aforementioned publications to N.R. Hill are also incorporated
11 herein by reference for their descriptions regarding Gaussian beams.

12
13 In the present preferred method (Hill, 2001), the transformation of the COS
14 data sets into corresponding beam components is performed using the
15 following mathematical expression:

$$17 \quad D_{\mathbf{h}}(\mathbf{L}, \mathbf{p}', \omega) = \left| \frac{\omega}{\omega_l} \right|^3 \iint \frac{dx' dy'}{4\pi^2} D_{\mathbf{h}}(\mathbf{r}', \omega) \exp \left[i \omega \mathbf{p}' \cdot (\mathbf{r}' - \mathbf{L}) - \left| \frac{\omega}{\omega_l} \right| \frac{|\mathbf{r}' - \mathbf{L}|^2}{2w_l^2} \right] \quad (1)$$

18
19 where $D_{\mathbf{h}}(\mathbf{r}', \omega)$ are the data recorded at vector offset $\mathbf{h}$ after being Fourier
20 transformed into the frequency (ω) domain, and where w_l is the initial width
21 of the beam at reference frequency ω_l . The transformed data are $D_{\mathbf{h}}(\mathbf{L}, \mathbf{p}', \omega)$,
22 where vectors $\mathbf{L}$ and $\mathbf{p}'$ are the surface locations and directions of the beam
23 components. Transform Equation (1) is similar to a windowed Fourier
24 transform and to a Gabor transform. Each of the beam components is the
25 component of the seismic energy that travels through the earth approximately
26 along a particular ray path. FIG. 6 shows an example of one beam
27 component projected into the earth. In this instance, the offset happens to be
28 zero.

29

1 A provisional earth model is constructed in **step 130** which is representative
2 of a subterranean region which contains or is prospective for hydrocarbons.
3 For example, the preferred earth modeling program may be the GOCAD™
4 software which was discussed above.

5
6 The earth model is made of many cells, perhaps even hundreds of thousands
7 or millions of cells. The velocity properties of the cells in the earth model
8 affect the direction of seismic energy propagation. Accordingly, for the
9 purposes of this specification and claims, these cells shall be referred to as
10 "lens elements" as these cells direct energy similar to the manner in which an
11 optical lens directs light. That is, the lens elements refract energy passing
12 there through. The refractions of energy through the lens elements are
13 dependent upon the propagation properties of the individual lens elements
14 comprising the earth model. More particularly, these propagation properties
15 may include, but are not limited to, the geometric shape, the velocity field,
16 including anisotropic specification of the velocity field, and the compressional
17 and shear velocities.

18
19 A migrated seismic image is generated in **step 140** utilizing the earth model
20 and the energy components, i.e., Gaussian beam components, in this
21 exemplary embodiment. More particularly, the set of beam components are
22 ideally propagated through the lens elements using Gaussian beam migration
23 to form image components which are combined or summed to form a seismic
24 image. This Gaussian beam migration is preferably carried out as described
25 in Hill, N.R., *Prestack Gaussian Beam Migration*, Geophysics, Volume 66,
26 pp. 1240-50 (2001). Although not as preferred, the migration could also be
27 performed in accordance with the method described in U.S. Patent 5,274,605,
28 entitled "Depth Migration Method Using Gaussian Beams", which has
29 previously been mentioned above. For a zero-offset case, the method
30 described in Hill, N.R., *Gaussian Beam Migration*, Geophysics, Volume 55,
31 pp. 1416-28, (1990) can also be used. Appendices A and B describe,

1 respectively, theory behind Gaussian Beams and the representation of a point
2 source by Gaussian beam summation.

3

4 FIG. 6 shows a beam component after energy has been projected into the
5 earth and the energy is received back along coincident ray paths. The vertical
6 axis displays depth in kilometers and horizontal axis is horizontal position.
7 The angle Θ is representative of the angle of departure and arrival for the
8 beam component. The seismic image of the subsurface is obtained by
9 projecting all beam components along their respective ray paths and summing
10 their contributions to the image in the manner described in Hill (2001). The
11 resulting seismic image, as shown in FIG. 7, displays a subterranean salt
12 dome 290. The single beam component depicted in FIG. 6 contributes to the
13 seismic image of the steep flank 292 of the dome. The salt dome flank 292 is
14 contained within the rectangular box 294 of FIG. 7.

15

16 The most preferred Gaussian beam migration uses the up-down imaging
17 principle described in Claerbout, J.F., *Coarse Grid Calculations of Waves in*
18 *Inhomogeneous Media with Applications to Delineation of Complicated*
19 *Seismic Structures: Geophysics*, 35, 407-418 (1970) and Claerbout, J.F.,
20 *Fundamentals of Geophysical Data Processing: McGraw-Hill*, (1976). The
21 up-down imaging principle states that an image is formed by cross-correlating
22 the downward-continued, recorded wavefield and the forward-modeled source
23 wavefield. In the Fourier domain, this cross correlation of the two wavefields
24 corresponds to summing over frequency the product of the downward-
25 continued wavefield and the complex conjugate of the source wavefield. The
26 boundary-value integral:

27

$$28 \quad \phi(\mathbf{r}, \omega) = \frac{-1}{2\pi} \iint dx' dy' \frac{\partial G^*(\mathbf{r}, \mathbf{r}', \omega)}{\partial z'} \phi(\mathbf{r}', \omega) \quad (2)$$

29

30 provides the downward-continued recorded wavefield, where $\mathbf{r}' = (x', y', 0)$ is
31 the detector positions at the earth's surface $z' = 0$. A Green's function

1 $G(\mathbf{r}, \mathbf{r}', \omega)$ is the response at point $\mathbf{r}$ to a source at point $\mathbf{r}'$. Gaussian beams
 2 enter the current derivation by expressing a Green's function as a Gaussian-
 3 beam summation. Appendices A and B show that a high-frequency
 4 representation of the field at point $\mathbf{r}$ caused by source at point $\mathbf{r}'$ is:

$$6 \quad G(\mathbf{r}, \mathbf{r}', \omega) \approx \frac{i\omega}{2\pi} \iint \frac{dp'_x dp'_y}{p'_z} u_{GB}(\mathbf{r}; \mathbf{r}', \mathbf{p}'; \omega) \quad (3)$$

7
 8 where $u_{GB}(\mathbf{r}; \mathbf{r}', \mathbf{p}'; \omega)$ is the normalized beam (A.9) with initial conditions
 9 (A.10) and (A.11). The ray path for beam $u_{GB}(\mathbf{r}; \mathbf{r}', \mathbf{p}'; \omega)$ radiates from point
 10 $\mathbf{r}'$ with ray vector $\mathbf{p}'$.

11
 12 Green's function Equation (3) requires that the source point coincides with the
 13 initial point of the rays. Since seismic reflection surveys have closely spaced
 14 sources and detectors, however, Equation (3) should be modified so that the
 15 source point $\mathbf{r}'$ can be different from the initial point of the rays $\mathbf{r}_0$. A simple
 16 way to do this modification is to insert a factor in the integrand of Equation (3)
 17 to compensate for the phase change from points $\mathbf{r}_0$ to $\mathbf{r}'$:

$$19 \quad G(\mathbf{r}, \mathbf{r}', \omega) \approx \frac{i\omega}{2\pi} \iint \frac{dp'_x dp'_y}{p'_z} u_{GB}(\mathbf{r}; \mathbf{r}_0, \mathbf{p}'; \omega) \cdot \exp[-i\omega \mathbf{p}' \cdot (\mathbf{r}' - \mathbf{r}_0)] \quad (4)$$

20
 21 Equation (4) is valid for source points $\mathbf{r}'$ in some neighborhood of the ray
 22 initial point $\mathbf{r}_0$. Since an additional phase factor has been introduced into the
 23 integrand, the saddle-point integration in Appendix B should also include the
 24 additional phase factor. These modifications, however, do not result in large
 25 corrections and make little difference in migrated images. This derivation
 26 proceeds by using the simple approximation in Equation (4).

27
 28 Summing contributions from all sources results in the image:

$$I(\mathbf{r}) = \frac{-1}{2\pi} \int d\omega \iint dx_d dy_d \iint dx_s dy_s \frac{\partial G^*(\mathbf{r}, \mathbf{r}_d; \omega)}{\partial z_d} G^*(\mathbf{r}, \mathbf{r}_s; \omega) D(\mathbf{r}_d, \mathbf{r}_s, \omega) \quad (5)$$

2

3 Function $D(\mathbf{r}_d, \mathbf{r}_s, \omega)$ is the field recorded by a detector at point4 $\mathbf{r}_d = (x_d, y_d, 0)$ when the source is located at $\mathbf{r}_s = (x_s, y_s, 0)$.

5

6 Instead of summing directly over source and detector positions, as in

7 Equation (5), the present formulation emphasizes the application of the

8 imaging operation to common-offset sections. Accordingly, the integration

9 variables are changed to midpoint $\mathbf{r}_m$ and offset $\mathbf{h}$ coordinates:

10

$$\begin{aligned} \mathbf{r}_m &= \frac{1}{2}(\mathbf{r}_d + \mathbf{r}_s) \\ \mathbf{h} &= \frac{1}{2}(\mathbf{r}_d - \mathbf{r}_s) \end{aligned} \quad (6)$$

12

13 Equation (5) becomes:

14

$$I(\mathbf{r}) = \iint d\mathbf{h}_x d\mathbf{h}_y I_{\mathbf{h}}(\mathbf{r}) \quad (7)$$

16

$$I_{\mathbf{h}}(\mathbf{r}) = \frac{-2}{\pi} \int d\omega \iint dx_m dy_m D_{\mathbf{h}}(\mathbf{r}_m, \omega) \frac{\partial G^*(\mathbf{r}, \mathbf{r}_d; \omega)}{\partial z_d} G^*(\mathbf{r}, \mathbf{r}_s; \omega) \quad (8)$$

18

19 where $D_{\mathbf{h}}(\mathbf{r}_m, \omega)$ is the field recorded at midpoint $\mathbf{r}_m$ and offset $\mathbf{h}$. The

20 summation Equation (8) is the seismic image from data collected at the

21 common-offset specified by the offset vector $\mathbf{h}$. The integral Equation (7)

22 sums the results of common-offset migrations (8) into a final image.

23

24 To use the Green's function representation of Equation (4) in integral

25 Equation (8), the integrand must be partitioned. This partitioning is

1 accomplished by inserting into the integrand of Equation (8) overlapping
 2 Gaussian functions that sum approximately to unity for any x and y :
 3

$$4 \quad \frac{\sqrt{3}}{4\pi} \left| \frac{\omega}{\omega_l} \right| \left(\frac{a}{w_l} \right)^2 \sum_{\mathbf{L}} \exp \left[- \left| \frac{\omega}{\omega_l} \right| \frac{|\mathbf{r}' - \mathbf{L}|^2}{2w_l^2} \right] \approx 1 \quad (9)$$

5
 6 Vector $\mathbf{L} = (L_x, L_y, 0)$ ranges over a two-dimensional lattice of points that spans
 7 the range of the recorded seismic data. The Gaussian width w_l is the same
 8 as the initial beam width (see Appendix A). Constant a is the distance
 9 between nearest-neighbor lattice points. The normalization factor in
 10 Equation (9) is appropriate for a hexagonal lattice, which optimizes the
 11 approximation. Within each partitioned region, the ray origins for
 12 $G(\mathbf{r}, \mathbf{r}_d; \omega)$ and $G(\mathbf{r}, \mathbf{r}_s; \omega)$ are chosen to be at $\mathbf{r}_0 = \mathbf{L} + \mathbf{h}$ and $\mathbf{r}_0 = \mathbf{L} - \mathbf{h}$ (see
 13 FIG. 8B). These steps result in:

$$15 \quad I_h(\mathbf{r}) \approx \frac{2i\omega}{\pi} C_0 \sum_{\mathbf{L}} \int d\omega \iint dp_x^d dp_y^d \iint \frac{dp_x^s dp_y^s}{p_z^s} u_{GB}^*(\mathbf{r}; \mathbf{L} + \mathbf{h}, \mathbf{p}^d; \omega) u_{GB}^*(\mathbf{r}; \mathbf{L} - \mathbf{h}, \mathbf{p}^s; \omega) D_h(\mathbf{L}, \mathbf{p}^d + \mathbf{p}^s, \omega) \quad (10)$$

17
 18 Equation (10) becomes more manageable if the integration variables are
 19 changed to new variables $\mathbf{p}^m = (p_x^m, p_y^m)$ and $\mathbf{p}^h = (p_x^h, p_y^h)$, such that:

$$21 \quad \begin{aligned} p_x^m &= p_x^d + p_x^s \\ p_y^m &= p_y^d + p_y^s \\ p_x^h &= p_x^d - p_x^s \\ p_y^h &= p_y^d - p_y^s \end{aligned} \quad (11)$$

22
 23 The new variables correspond to the time dip in common offset and common
 24 midpoint gathers. With these variable changes, Equation (10) becomes:

1

$$I_{\mathbf{h}}(\mathbf{r}) \approx -C_0 \sum_{\mathbf{L}} \int d\omega \int dp_x^m dp_y^m U_{\mathbf{h}}(\mathbf{r}; \mathbf{L}, \mathbf{p}^m; \omega) D_{\mathbf{h}}(\mathbf{L}, \mathbf{p}^m, \omega) \quad (12)$$

3

4 where $D_{\mathbf{h}}(\mathbf{L}, \mathbf{p}^m, \omega)$ is the transformation Equation (1) for data of offset $\mathbf{h}$, and

5

$$U_{\mathbf{h}}(\mathbf{r}; \mathbf{L}, \mathbf{p}^m; \omega) = \frac{-i\omega}{2\pi} \iint \frac{dp_x^h dp_y^h}{p_z^s} u_{GB}^*(\mathbf{r}; \mathbf{L} + \mathbf{h}, \mathbf{p}^d; \omega) u_{GB}^*(\mathbf{r}; \mathbf{L} - \mathbf{h}, \mathbf{p}^s; \omega) \quad (13)$$

7

8 describes the propagation of wavefield component $D_{\mathbf{h}}(\mathbf{L}, \mathbf{p}^m, \omega)$. The sum and

9 difference of the two-dimensional vectors $\mathbf{p}^m$ and $\mathbf{p}^h$ determine the initial

10 directions $\mathbf{p}^d$ and $\mathbf{p}^s$ of the beam components in the integrand of

11 Equation (13).

12

13 The propagation described by Equation (13) includes all pairs of ray paths

14 from the source and detector such that their dips are in accord with

15 Equation (11). As depicted in FIGS. 8A and 8B, the dips of the shot ray and

16 the detector ray must sum to $\mathbf{p}^m$, which is equal to the dip of the data

17 component $D_{\mathbf{h}}(\mathbf{L}, \mathbf{p}^m, \omega)$.

18

19 Efficient evaluation of summation Equation (13) is important to pre-stack

20 Gaussian beam migration. This summation over the product of source and

21 detector beams does not depend on the recorded data, suggesting that travel

22 time description is the essential role of Equation (13). Large contributions to

23 the summation occur if both the beams pass near the point $\mathbf{r}$ for the same

24 value of $\mathbf{p}^h$ (see FIG. 8B). In general, the ray paths of both beams will not

25 pass through $\mathbf{r}$ at the same value of $\mathbf{p}^h$. Contributions to the summation

26 Equation (13) could be evaluated by the method of steepest descents.

27 Equation (13) may be written as:

28

$$U_h(\mathbf{r}; \mathbf{L}, \mathbf{p}^m; \omega) = \frac{-i\omega}{2\pi} \iint \frac{dp_x^h dp_y^h}{p_z^s} A(\mathbf{r}; \mathbf{p}^m, \mathbf{p}^h) \exp[i\omega T(\mathbf{r}; \mathbf{p}^m, \mathbf{p}^h)] \quad (14)$$

2

3 by using (A9). Function $A(\mathbf{r}; \mathbf{p}^m, \mathbf{p}^h)$ is the product of amplitudes of the two
4 beams; $T(\mathbf{r}; \mathbf{p}^m, \mathbf{p}^h)$ is the sum of the complex travel times:

5

$$T(\mathbf{r}; \mathbf{p}^m, \mathbf{p}^h) = T_d(\mathbf{r}; \mathbf{p}^d) + T_s(\mathbf{r}; \mathbf{p}^s) \quad (15)$$

7

8 where $T_d(\mathbf{r}; \mathbf{p}^d)$ and $T_s(\mathbf{r}; \mathbf{p}^s)$ are the complex travel times for the beams
9 coming from detector and source points $\mathbf{r}_d$ and $\mathbf{r}_s$ with initial ray-vectors $\mathbf{p}^d$
10 and $\mathbf{p}^s$. Steepest-descent evaluation would result in:

11

$$U_h(\mathbf{r}; \mathbf{L}, \mathbf{p}^m; \omega) \approx A_0 \exp[i\omega T_0] \quad (16)$$

13

14 where T_0 is the complex travel time Equation (15) evaluated at the saddle
15 point and A_0 is a complex amplitude. The amplitude A_0 does not depend on
16 frequency because the steepest-descent evaluation of the two-dimensional
17 integral generates a factor ω^{-1} that cancels the factor ω appearing in
18 Equation (14). A steepest-descent evaluation of Equation (14) would
19 determine A_0 from a second-order expansion of $T(\mathbf{r}; \mathbf{p}^m, \mathbf{p}^h)$ about its saddle
20 points. This expansion could be achieved by using the same dynamic-ray-
21 tracing information used to construct the Gaussian beams. This added effort
22 to determine A_0 is unwarranted in the present theory, however, because the
23 imaging principle used is only kinematically correct.

24

25 The present goal of Gaussian beam migration is to form structurally correct
26 images; the image amplitudes are secondary. For this limited goal, the
27 following method provides a simple, fast evaluation of Equation (13). The first
28 step is to assume that Equation (13) can be reduced to the form of

1 Equation (16), which is tantamount to assuming the integral is dominated by
2 contributions near an isolated saddle point. To further simplify the evaluation
3 of Equation (13), the second step is to assume that the saddle point of
4 $T(\mathbf{r}; \mathbf{p}^m, \mathbf{p}^h)$ occurs at real $\mathbf{p}^h$. In that case, the saddle point can be located by
5 scanning all real values of $\mathbf{p}^h$ for the value that minimizes the imaginary part
6 of $T(\mathbf{r}; \mathbf{p}^m, \mathbf{p}^h)$. The last step is to use the geometric average of the amplitude
7 of the two beams for the value of A_0 . An advantage of this A_0 is that the
8 pre-stack and post-stack migrations will give similar results when applied to a
9 zero-offset gather.

10

11 Of course, the complex time Equation (15) will not always have the isolated
12 saddle points that are supposed by the approximation Equation (16).
13 Approximation Equation (16) will not be valid in some cases where there are
14 multi-valued travel times. Nevertheless, since Equation (11) restricts the
15 domain of the travel times included in Equation (14), it also restricts multi-path
16 contributions to this integral, although it does not eliminate these
17 contributions. There is an advantage of searching for the minimum imaginary
18 part of the travel time instead of the maximum real part. Although these two
19 points will coincide at a saddle point, using the minimum imaginary part tends
20 to select the most significant saddle point, when there are contributions from
21 more than one.

22

23 Typically, the initial seismic image generated by the migration of **step 140** will
24 need iterative refinement. In **step 150**, one or more zones of interest or
25 "targets" are identified in the seismic image which are to be enhanced by
26 iterative refinement. A "target" shall mean a portion of the overall image
27 selected for enhancement. Usually, the target will be a small sub-volume of
28 the complete seismic image generated in **step 140**. For example, the target
29 may be the indicated portion of the seismic image enclosed by rectangle 294
30 in FIG. 7. A particular target may be selected because that portion of the
31 image is key to delineating a reservoir.

1 If the image is in some way deficient, then the earth model is evaluated and
2 modified. Geologic and geophysical aspects of the image are concurrently
3 examined. Parts of the image that are regarded by a geologist as deficient or
4 questionable can be probed interactively for geologic and geophysical
5 integrity by using techniques such as those illustrated by the following
6 example.

7
8 In **step 160**, an interpreter and a geophysicist who are ideally experienced in
9 migration of seismic data then select a trial set of trial lens elements from the
10 earth model. This trial set of lens elements is to be modified in an attempt to
11 enhance the earth model and resulting seismic image. The trial set of lens
12 elements are lens elements that might affect the imaging in the region of the
13 target. Ray tracing techniques are preferably used to provide guidance in this
14 selection process, as is illustrated in FIGS. 9 and 10, and will be described
15 below. Also, FIG. 3 shows a flowchart describing these ray tracing
16 techniques. Other methods for selection of the trial set of lens element to be
17 updated may also be used. For example, the selection may be made by
18 simple visual inspection.

19
20 FIG. 9 shows an image 302 superimposed over an earth model 304. Image
21 302 was formed by migrating synthetic seismic data and is superimposed in
22 space over the earth model 304. Note that the surface 305 in earth model
23 304 contains a model anticline 306, i.e., an upwardly protruding "bump."
24 Image 302 also shows an image anticline 310, although the model anticline
25 306 and image anticline 310 do not exactly match. For this synthetic data set,
26 the surface 305 of the earth model 304 and the surface of image 302 should
27 be flat; the erroneous anticline 310 in the image 302 is likely caused by the
28 erroneous anticline 306 in the earth model 304.

29
30 There are several ways to test if the initial image 302 and the earth model 304
31 are correct. For example, image 302 is suspect because of crossing
32 reflectors 312a and 312b at the boundaries of several layers. A suspect

1 portion is identified by graphically positioning in **step 161** (FIG. 3) a test disk
2 314 over a suspect portion of the earth model/image, i.e., one of the two
3 crossing reflectors 312a. This disk 314 becomes a temporary reflecting
4 surface in earth model 304. After a geophysicist interactively positions this
5 reflecting disk 314 upon this feature in the image 302, a ray path 316 is traced
6 in **step 162** normally from the center of disk 314 through lens elements to a
7 recording datum (not shown) of the earth model 304. The recording datum is
8 the surface from which the seismic survey was recorded. This normal ray 316
9 describes the seismic data recorded at zero offset. For zero offset, most
10 energy travels along coincident paths in the upward and downward directions.
11 The path of the ray 316 extends through lens elements where there might be
12 problems in the earth model 304 that are responsible for the erroneous image
13 of crossing reflectors 312a and 312b. For example, the ray 316 in FIG. 9
14 intersects a portion of the anticline 306 in the model. If this anticline 306 is
15 incorrect, it might be the cause of the faulty image 302. Accordingly, lens
16 elements that are proximate normal ray 316 are selected in step 166 as a trial
17 set of lens elements which are to be updated in the hopes of improving the
18 image of the target.

19
20 A second geophysical test is shown in FIG. 10A. Again, a reflecting disk 332
21 is placed and adjusted in **step 161** over a suspect portion of an earth
22 model/image. The disk 332 is adjusted by using three-dimensional computer
23 graphics to drag the disk into the desired location and orientation. Ideally, the
24 disk is oriented sub-parallel to the bedding shown in the image or where
25 bedding is anticipated to be in the image. In **step 163**, many different
26 specular ray paths 330a-j are projected which reflect off reflecting disk 332.
27 For each of these specular rays 330a-j, the angle of incidence to the disk
28 surface 332 equals angle of reflection, as depicted in FIG. 10A. These
29 reflected rays intercept spaced-apart locations on the recording datum. The
30 intercept locations are compared against the actual locations of the sources
31 and detectors used in the seismic survey of **step 110**.

32

1 A two-point ray trace search, which is well known to those skilled in the art of
 2 seismic ray theory, is performed in **step 164** to match the intercept locations
 3 of these rays to the seismic survey geometry. The specular opening angles
 4 and azimuths are individually and iteratively adjusted at the specular reflection
 5 points until the ray source and detector intercepts are coincident with the
 6 actual locations of the survey sources and detectors. The display in FIG. 10A
 7 shows rays 330a-j determined by this search procedure for all the offsets
 8 utilized provided in **step 110**.

9
 10 Once rays in FIG. 10A are determined, the image can be checked for
 11 misfocusing in **step 165** by retrieving the energy which travels along each of
 12 these rays 330a-j. The energy traveling along each ray 330a-j will correspond
 13 to one of the energy components provided in **step 120**. To help explain this,
 14 FIGS. 8A and 8B show the relation between an exemplary pair of source rays
 15 336 and detector rays 338 and their energy components, i.e., beam
 16 components in the preferred exemplary embodiment. The emerging angles of
 17 the detector and source rays 336, 338 define the ray vectors $\mathbf{p}^d$ and $\mathbf{p}^s$. As is
 18 illustrated in FIGS. 8A and 8B, energy traveling along this path will appear in a
 19 COS as events that slope at a rate $p_x^m = p_x^d + p_x^s$ in the x direction and
 20 $p_y^m = p_y^d + p_y^s$ in the y direction (see Equation 11). Moreover, energy
 21 propagation along this travel path will appear in a COS as events located near
 22 the midpoint coordinates $x_m = \frac{1}{2}(x_d + x_s)$, $y_m = \frac{1}{2}(y_d + y_s)$. The location
 23 (x_m, y_m) and slope (p_x^m, p_y^m) determine which beam data component contains
 24 the energy traveling along this ray path. In particular, the location and slope
 25 determine the arguments L and p' appearing on the left side of Equation (1).
 26 All ω samples for this (L, p') pair are retrieved from beamed data provided in
 27 **step 110** and inverse Fourier transformed to the time domain. The beam
 28 components are often transformed to the time domain before storage, in
 29 which case the time samples are directly retrieved from a beam file. The
 30 location (x_m, y_m) and slope (p_x^m, p_y^m) will not, in general, fall exactly upon the

1 sampled values of L and p' used when performing the transform computations
2 prescribed by (1). The parameters L and p' are sampled as prescribed in Hill
3 (2001) and are sufficiently dense for accurately interpolating values between
4 samples. The time series of sampled values obtained by this retrieval will be
5 referred to as a beam trace. This beam trace contains the waveform
6 information of the energy that traveled along a ray path.

7
8 A beam trace is retrieved for each of the ray paths in FIG. 10A. Each beam
9 trace is displayed to show how it contributes to the image near the disk.
10 FIG. 10B shows a beamed trace for each ray path. A small window of each
11 trace has been plotted after having been delayed in time by the travel time
12 along each ray. If the earth model were exactly correct, there would be no
13 shift in the reflection event from trace to trace because the ray-trace travel
14 time would exactly be the arrival time of the reflected event. An event is a
15 lineup on a number of traces of the arrival of new seismic energy, indicated by
16 a systematic phase or amplitude change on a seismic record. In the case in
17 FIG. 10B, however, there is a shift, indicating that the earth model is incorrect
18 along the travel paths indicated in FIG. 10A. In particular, if the earth model
19 were correct, then the travel-times computed by ray tracing would be larger at
20 the larger offsets or less at the small offsets, or both. The incorrect focusing
21 of the energy appearing in FIG. 10B causes degradation of the image in
22 FIG. 10A because the contributions from the different ray paths do not add
23 together constructively.

24
25 A geophysicist observes that the rays which illuminate a faulty part of the
26 image pass through portions of the earth model that are suspect. For
27 example, the ray paths in the synthetic data of FIGS. 9 and 10 pass through
28 the bump or anticline 306 in the earth surface 322. The geologist and
29 geophysicist analyzing the image might suspect that the bump is incorrect,
30 perhaps because the mapping of this part of the image was ambiguous. The
31 misfocusing observed in FIG. 10B is further evidence that some of the lens
32 elements falling along the rays paths in Fig 10A are incorrect and should be

1 adjusted. Therefore, the lens elements that are intercepted by the rays shown
2 in FIG. 10A may be selected in **step 166** as candidates for the trial set of lens
3 elements which is to be updated in hopes of improving the image in the region
4 of the target.

5

6 Another consideration during the selection of trial lens elements is that some
7 portions of the image and model might be more credible than others. For
8 instance, some portions of the current earth model might be constrained by
9 well data. Other portions of the earth model are subject to revision because
10 those portions were constructed based upon a degraded or ambiguous
11 seismic image.

12

13 FIG. 11 shows an example of an image 402 superimposed upon an earth
14 model 404. A sub-volume of lens elements 406 is graphically selected as a
15 trial set of lens elements which touch or are contained within this sub-volume.
16 In this case, the lens elements 406 are comprised of the boundary shape of
17 the highlighted surface region shown in FIG. 11. A bump 410 in the surface
18 region is identified as the likely cause of misfocusing because bump 410 is
19 geologically suspect and because rays passing through bump 410 are
20 misfocused. This surface region is repositioned by using 3D computer
21 graphics tools. The geologist and geophysicist modify the earth model by
22 using 3D computer graphics to drag surfaces of the selected lens elements
23 406 into different positions to change the propagation properties, in particular
24 the shapes, of these lens elements 406. Alternatively, the propagation
25 properties of these lens elements could be modified or updated by changing
26 the velocity field within this region. Or else, both the geometric shapes and
27 the velocity fields could be updated.

28

29 The propagation properties of the selected subset of lens elements are then
30 updated. These updates are largely trial and error but the trials are informed
31 by the ray trace analysis described with respect to FIGS. 9 and 10. Ideally, a
32 geophysicist/migration expert will collaborate with a geologist to determine

1 how best to update the selected subset of lens elements. This collaboration
2 should ideally result in changes to the lens elements which enhance the
3 geophysical focus about the target(s) in the various seismic images and also
4 produce seismic images which are geologically plausible. Examples of
5 propagation properties which might be updated include the velocity field of the
6 selected subset of lens elements and the shape of those lens elements. This
7 shape can be updated geographically by moving surfaces of the suspect lens
8 elements. Other properties which may be changed in an effort to enhance the
9 seismic image may include, by way of example and not limitation, the
10 anisotropic model specifications of the velocities.

11
12 Before actually updating the image, the geophysicist can quickly estimate the
13 likely effects of the modifications to the earth model. By ray tracing through
14 the modified model, the new position of the disk in FIG. 9 can be instantly
15 determined by map migration. This repositioning of the disk is a good
16 indication of the repositioning of the reflection events that will occur when the
17 image is revised with the modified model. Furthermore, the alignment of the
18 reflection events in FIG. 10B also can be instantly updated according to the
19 modified model by computing the change in travel time along the specular
20 rays. Although FIGS. 9 and 10 show only one disk, many disks can exist at
21 once in an image and corresponding model.

22
23 Preferably, only a subset of the original energy components computed in
24 **step 120** must be repropagated to form updated image components to be
25 used in updating the image. FIG. 4 shows a flowchart describing a preferred
26 method for selecting this subset of energy components. First a reduced, but
27 preferably overly inclusive, trial set of energy components which may
28 contribute to the image near the target is sought. Ray paths of those energy
29 components computed in **step 120** are checked to in **step 171**. Rays
30 corresponding to each energy component are traced downward from the
31 surface and only energy components having rays that pass within some
32 predetermined distance from the target are candidates for this trial set of lens

1 elements. This predetermined distance should be larger than the beam width
2 to include beams that may move into or out of the targeted image because of
3 updates to the propagation properties of the lens elements. A second check
4 is to see whether the ray paths pass through at least one of the updated lens
5 elements. Energy components whose ray paths meet both of these criteria
6 are then selected for inclusion in the trial set of lens elements.

7
8 In **step 172**, ray paths are traced through the updated earth model for each of
9 the trial set of energy components. The step recomputing updated image
10 components, which is computationally intensive, need not be incurred at this
11 time. To further reduce the number of energy components which must be
12 used to compute updated image components, the updated ray paths of the
13 trial set of energy components are analyzed in **step 173**. First, the ray paths
14 must have beams that touch the target. Second, the ray paths must also pass
15 through at least one of the updated lens elements. Those energy
16 components which have updated ray paths meeting these two criteria are
17 then included for inclusion in the subset of energy components used to
18 compute updated image components.

19
20 Those skilled in the art will appreciate that other criteria could be used to
21 reduce the number of energy components which are to be used to form
22 update image components. By way of example, and not limitation, only
23 energy components which pass within the predetermined distance of the
24 target might be selected and the other selection criteria ignored. Again, those
25 skilled in the art will appreciate that other methods of choosing the subset of
26 energy components can be used and are within the scope of this invention.

27
28 In **step 180**, the subset of energy components, or beam components in the
29 preferred embodiment, is propagated through the updated earth model to
30 form updated image components. The ray paths of these beam components
31 will be changed due to the change in propagation properties of the updated
32 lens elements. Similarly, the updated image components will also be revised.

1 The seismic images are updated in **step 190**. Only the image components
2 belonging to the subset of energy components identified in **step 170** are
3 updated in an image data file computed in **step 140**. Each of these image
4 components computed according to the previous earth model is replaced with
5 one computed according to the current earth model. That is, the image
6 components associated with the old energy components are subtracted from
7 the image and the image components associated with the new energy
8 components are added.

9

10 Although it is not essential for the current invention, the computer time
11 required for **step 170** can be reduced by using limited aperture methods,
12 which are in some ways similar to methods described by Carroll, R.J. et. al, A
13 *Directed-Aperture Kirchhoff Migration*, et al., in *Geophysical Imaging*,
14 *Symposium of Geophysical Society of Tulsa*; Tulsa SEG, pp. 151-165 and by
15 Krebs, J.R. in U. S. Patent 5,640,368, entitled "Migration Velocity Analysis
16 Using Limited-Aperture and Monte Carlo Migration". For example, the ray
17 tracing computations in **step 170** can be reduced by only testing beam ray
18 paths that are in the neighborhood of rays reflecting from one of the disks
19 used in **step 160** (see FIG. 10A).

20

21 This neighborhood is determined as follows. Test rays of **step 170** must
22 depart from the earth's surface within some predetermined spatial distance
23 from one of the rays reflecting from one of the disks. Also, the direction of the
24 departing test ray must be within some predetermined angular distance from
25 one of the rays reflecting from one of the disks. Limiting the ray tracing in this
26 way is similar to the limited aperture methods named above in that the chosen
27 subset of input data used in the migration is based upon interpretively
28 identifying reflection events within the seismic data. The current method,
29 however, limits the input data not only to components falling within some
30 small spatial aperture identified by ray tracing, but also to beam components
31 that propagate in directions also identified by ray tracing. Moreover, the
32 alternative methods named above compute the image solely from data

1 components within the limited spatial aperture. In contrast, the current
2 method updates an existing image by replacing data components within some
3 limited spatial and angular aperture.
4

5 In **step 200**, the earth model and the seismic image are then evaluated to
6 determine if they are satisfactory or not. Factors as previously discussed are
7 evaluated including: (1) whether the earth model is consistent with the seismic
8 image; (2) whether the seismic image is geologically plausible or even
9 possible; and (3) whether the image is well-focused or is blurred.
10

11 If the image quality is judged by the interpreter as sufficient for accurately
12 delineating the subterranean geology, the current image is used for mapping
13 prospects, planning wells, estimating reserves and for other technical and
14 business decisions. If not, the iteration of **steps 150-190** are repeated until a
15 satisfactory seismic image and earth model are created.
16

17 The present invention overcomes many of the shortcomings in conventional
18 iterative methods of constructing earth models and seismic images. First, the
19 invention greatly reduces computation time by ideally incrementally updating
20 only the portions of the seismic image that are affected by the latest earth
21 model updates. Second, the invention preferably integrates software (earth
22 modeling, seismic imaging and seismic interpretation) corresponding to the
23 **steps 30-50** in FIG.1 into a single software application. This helps eliminate
24 problems associated with the repeated transfer of data files between discrete
25 software packages. This integrated application ideally links three-dimensional
26 desk-top graphics with high performance computer engines so that the cycle
27 time for revision of the earth model and seismic image often takes less than
28 an hour.
29

30 Beam migration methods promote quick turnaround through incremental
31 updates. This quick turnaround and the integrated software fosters

1 collaboration between geologic and geophysical experts during the iterative
2 updating of the seismic image and earth model.

3

4 Geologic insights guide trial-and-error corrections to an earth model and
5 seismic image. The trial modifications of the earth model, however, can be
6 informed not only by structural patterns emerging in the image but also by
7 quick ray-trace analysis of imaging focusing. Detailed analysis is promoted
8 because energy is analyzed into components that travel along ray paths. This
9 analysis can include locating problems in the earth model, point and click
10 velocity measurements, and quick identification of coherent events that are
11 not primary compression waves.

12

13 While in the foregoing specification this invention has been described in
14 relation to certain preferred embodiments thereof, and many details have
15 been set forth for purposes of illustration, it will be apparent to those skilled in
16 the art that the invention is susceptible to alteration and that certain other
17 details described herein can vary considerably without departing from the
18 basic principles of the invention.

APPENDIX A

GAUSSIAN BEAMS

This appendix summarizes three-dimensional Gaussian beams and presents a simple beam parameterization that is used for the migration method used in this specification. A full description of Gaussian beams in the context of dynamic ray theory appears in a review by Cerveny, V., *The application of ray tracing to the propagation of shear waves in complex media*, in Dohr, G.P. Ed. Handbook of Geophysical Exploration: Seismic shear waves: Geophysical Press, pp. 1-240 (1985). Another publication describing ray tracing is Cerveny, V., *Seismic Ray Theory*, Cambridge University Press (2000).

In the neighborhood of a ray path, the expansion of the travel time field to second order in ray-centered coordinates is:

$$T(q_1, q_2, s) \approx \tau(s) + \frac{1}{2} \mathbf{q}^T \mathbf{M}(s) \mathbf{q} \quad (\text{A.1})$$

where s is arc length along the ray and q_1 and q_2 are coordinates along the axes $\hat{e}_1$ and $\hat{e}_2$ that lie in a plane perpendicular to the ray at point s (see Cerveny, 1985). The axes $\hat{e}_1$ and $\hat{e}_2$ are constructed such that the coordinates (q_1, q_2, s) form a right-handed, orthogonal, curvilinear system. Function $\tau(s)$ is travel time along the ray path:

$$\tau(s) = T(0, 0, s) \quad (\text{A.2})$$

Vector $\mathbf{q}$ is a two-dimensional vector,

$$\mathbf{q}^T = (q_1, q_2) \quad (\text{A.3})$$

1 The elements of the 2x2 matrix $\mathbf{M}(s)$ are the second derivative of the travel
 2 time field with respect to the coordinates q_1 and q_2 :

$$3 \quad M_{IJ}(s) = \left[\frac{\partial^2 T(q_1, q_2, s)}{\partial q_I \partial q_J} \right]_{q_1=q_2=0} \quad (\text{A.4})$$

5
 6 Expansion (A.1) contains no first order derivatives because, for the isotropic
 7 case considered in this paper, constant travel time surfaces are perpendicular
 8 to rays.

9
 10 A way to determine the matrix $\mathbf{M}(s)$ is to substitute (A.1) into the eikonal
 11 equation written in ray-centered coordinates. This step yields a non-linear,
 12 ordinary differential equation for $\mathbf{M}(s)$. The standard procedure of dynamic
 13 ray tracing is to reduce this equation to the linear system:

$$14 \quad \frac{d\mathbf{Q}(s)}{ds} = v(s)\mathbf{P}(s) \quad (\text{A.5})$$

$$16 \quad \frac{d\mathbf{P}(s)}{ds} = v^{-2}(s)\mathbf{V}(s)\mathbf{Q}(s) \quad (\text{A.6})$$

18
 19 where $\mathbf{P}(s)$ and $\mathbf{Q}(s)$ are 2x2 matrices such that:

$$20 \quad \mathbf{M}(s) = \mathbf{P}(s)\mathbf{Q}^{-1}(s) \quad (\text{A.7})$$

22
 23 Matrix $\mathbf{V}(s)$ is a 2×2 matrix of second derivative of the velocity field:

$$24 \quad V_{IJ} = \frac{\partial^2 v}{\partial q_I \partial q_J} \quad (\text{A.8})$$

26

1 Since the travel time field (A.1) satisfies the eikonal equation in the vicinity of
 2 the ray path, the transport equation can then be invoked to determine the
 3 amplitudes of a high-frequency solution to the scalar wave equation (1). The
 4 resulting solution is:

$$5 \quad \sqrt{\frac{v(s) \det \mathbf{Q}(s_0)}{v(s_0) \det \mathbf{Q}(s)}} \exp \left\{ i\omega \left[\tau(s) + \frac{1}{2} \mathbf{q}^T \mathbf{M}(s) \mathbf{q} \right] \right\} \quad (\text{A.9})$$

7
 8 normalized to unity at $s = s_0$.

9
 10 The character of solution (A.9) is determined by the initial conditions chosen
 11 for matrix functions $\mathbf{P}$ and $\mathbf{Q}$. For any choice of real $\mathbf{P}$ and $\mathbf{Q}$, there might be
 12 points along the ray path where solution (A.9) fails because $\det \mathbf{Q} = 0$. On the
 13 other hand, complex initial values of $\mathbf{P}$ and $\mathbf{Q}$ can be chosen so that (A.9) is
 14 always a bounded, high frequency solution of the scalar wave equation. If
 15 choice of complex initial values is such that $\text{Im} \{ \mathbf{P} \mathbf{Q}^{-1} \}$ is positive definite and
 16 $\det \mathbf{Q} \neq 0$, then these qualities hold everywhere along the ray path. In this
 17 case, (A.9) is the well-known Gaussian-beam asymptotic solution to the wave
 18 equation (Cerveny, 1985). The particular initial-value choice:

$$19 \quad \mathbf{P}_0 = \begin{pmatrix} i/V_0 & 0 \\ 0 & i/V_0 \end{pmatrix} \quad (\text{A.10})$$

$$21 \quad \mathbf{Q}_0 = \begin{pmatrix} \omega_i w_i^2 / V_0 & 0 \\ 0 & \omega_i w_i^2 / V_0 \end{pmatrix} \quad (\text{A.11})$$

23
 24 results in a beam with initial width w_i at frequency ω_i . Quantity V_0 is the
 25 seismic velocity at the ray's initial point s_0 .

26

APPENDIX B
REPRESENTATION OF A POINT SOURCE
BY GAUSSIAN BEAM SUMMATION

The field from a point source at $\mathbf{r}'$ is approximated by the Gaussian beam summation:

$$G(\mathbf{r}, \mathbf{r}'; \omega) = \int d\Omega \Psi(\Omega) u_{GB}(\mathbf{r}; \mathbf{r}', \Omega; \omega) \quad (\text{B.1})$$

where function u_{GB} is the value at point $\mathbf{r}$ of a Gaussian beam that departs from point $\mathbf{r}'$ at angle $\Omega = (\theta, \phi)$, and $d\Omega$ is the solid angle $\sin \theta \cdot d\theta d\phi$. The spherical coordinates are such that point $\mathbf{r}'$ is at the origin and point $\mathbf{r}$ is on the axis $\theta = 0$. Function $\Psi(\Omega)$ must be determined. If the velocity field is constant $v(\mathbf{r}) = V_0$, then by symmetry, this function is constant, $\Psi(\Omega) = \Psi_0$. This constant Ψ_0 will also be appropriate if the actual medium is nearly constant for a few wavelengths about the source, but is more complicated elsewhere.

In a constant velocity medium, the Gaussian beam given by Equations (A.9) to (A.11) simplifies to:

$$u_{GB} = \frac{\omega_l w_l^2}{V_0} \left(\frac{\omega_l w_l^2}{V_0} + is \right)^{-1} \exp \left\{ i\omega \left[\frac{s}{V_0} + \frac{i}{2} \frac{q_1^2 + q_2^2}{\omega_l w_l^2 + iV_0 s} \right] \right\} \quad (\text{B.2})$$

Then equation (B.1) becomes:

$$G = \Psi_0 \int_0^{2\pi} d\phi \int_0^\pi \sin \theta \cdot d\theta \frac{\omega_l w_l^2}{\omega_l w_l^2 + iV_0 R \cos \theta} \exp \left\{ i\omega \left[\frac{R \cos \theta}{V_0} + \frac{i}{2} \frac{R^2 \sin^2 \theta}{\omega_l w_l^2 + iV_0 R \cos \theta} \right] \right\} \quad (\text{B.3})$$

1 where $R = |\mathbf{r} - \mathbf{r}'|$. A stationary point of the integral occurs at $\theta = 0$. Since for
 2 large ω , the principal contribution to the integral occur near this stationary
 3 point, (B.3) can be approximated as:

$$4 \quad G = 2\pi \Psi_0 \left(\frac{\omega_l w_l^2}{\omega_l w_l^2 + iV_0 R} \right) \exp(i\omega R/V_0) \cdot \int_0^\infty \theta \exp \left\{ \frac{-i\omega R}{2 V_0} \left[\frac{\omega_l w_l^2}{\omega_l w_l^2 + iV_0 R} \right] \theta^2 \right\} d\theta$$

6 (B.5)

7
 8 Evaluation of the definite integral results in:

$$10 \quad G = \Psi_0 \left(\frac{-2\pi i V_0}{\omega} \right) \frac{\exp(i\omega R/V_0)}{R} \quad (B.6)$$

11
 12 Equation (B.6) is the well-known response for a constant velocity if:

$$14 \quad \Psi_0 = \frac{i\omega}{2\pi V_0} \quad (B.7)$$

15
 16 For the present derivation, it is more convenient to change integration
 17 variables from θ and ϕ to ray-parameters p'_x and p'_y :

$$18 \quad p'_x = \frac{1}{V_0} \sin \theta \cos \phi$$

$$19 \quad p'_y = \frac{1}{V_0} \sin \theta \sin \phi \quad (B.8)$$

$$20 \quad p'_z = \frac{1}{V_0} \cos \theta$$

21 With these variable changes and (B.7), the Green's function (B.1) becomes:

22

$$1 \quad G(\mathbf{r}, \mathbf{r}'; \omega) = \frac{i\omega}{2\pi} \int \frac{dp'_x dp'_y}{p'_z} u_{GB}(\mathbf{r}; \mathbf{r}', \mathbf{p}'; \omega) \quad (\text{B.9})$$

CLAIMS:

1. A method for creating an enhanced depth-migrated seismic image, the method comprising:

(a) acquiring seismic data from a seismic survey conducted over a subterranean region;

(b) transforming the seismic data into a set of energy components;

(c) creating an earth model having velocity model characterizations therewithin representative of the subterranean region, the earth model comprising a set of lens elements having propagation properties which affect energy propagation through the lens elements;

(d) propagating the set of energy components through the lens elements to form image components which are combined into a depth-migrated seismic image;

(e) identifying a target in the seismic image for image enhancement;

(f) selecting a trial subset of less than all of the lens elements from the set of lens elements and updating propagation properties of the trial subset of lens elements which may affect imaging of the target without updating the propagation properties of all the lens elements of the earth model;

(g) selecting a trial subset of less than all of the energy components from the set of energy components which may affect imaging of the target;

(h) propagating the trial subset, without propagating all, of the set of energy components through the earth model to form updated image components; and

(i) updating the seismic image by replacing image components of the current seismic image with the updated image components without replacing all of the image components to arrive at an enhanced seismic image.

2. The method of claim 1 wherein:

the energy components are beam components.

3. The method of claim 2 wherein:

the beam components are Gaussian beam components.

4. The method of claim 1 wherein:

the set of energy components includes any partitioning of the seismic data including shot profiles, common offset data, common midpoint data and plane wave energy components.

5. The method of claim 1 wherein:
the propagation of the energy components through the lens elements to form image components is computed using beam migration.
6. The method of claim 1 wherein:
the trial subset of lens elements is selected using ray tracing.
7. The method of claim 6 wherein:
the ray tracing utilizes a two-point ray trace search.
8. The method of claim 6 wherein:
the ray tracing utilizes normal ray tracing.
9. The method of claim 1 wherein:
the trial subset of lens elements is selected by visual inspection.
10. The method of claim 1 wherein:
the trial subset of energy components is selected using a directed-aperture.
11. The method of claim 1 wherein:
the trial subset of energy components is selected using a migration aperture.
12. The method of claim 1 wherein:
the trial subset of energy components is selected using ray tracing.
13. The method of claim 1 wherein:
the step of selecting a trial subset of energy components includes selecting a subset of energy components that have ray paths that pass within a predetermined distance of the target prior to updating of the lens elements.
14. The method of claim 1 wherein:
the step of selecting a trial subset of energy components includes selecting a subset of energy components each having a ray path that passes through at least one of the updated lens elements.

15. The method of claim 1 wherein:

the step of selecting a trial subset of energy components includes selecting a subset of energy components that each have a ray path that passes within a predetermined distance of the target and each ray path passes through at least one of the updated lens elements.

16. The method of claim 1 wherein:

the step of selecting a trial subset of energy components includes propagating the trial subset of energy components through the updated earth model to create updated ray paths for the trial subset of energy components.

17. The method of claim 16 wherein:

the trial subset of energy components is selected from the energy components which touch the target and have ray paths that pass through at least one of the updated lens elements.

18. The method of claim 1 wherein:

the steps (e)-(i) are computed within a single interactive software application.

19. The method of claim 1 wherein:

steps (e)-(i) are repeated at least one more time.

20. The method of claim 1 wherein:

the earth model is a velocity model.

21. The method of claim 1 wherein step (d) further comprises:

generating the depth-migrated seismic image with depth migration software.

22. The method of claim 1 wherein step (d) further comprises:

generating the depth-migrated seismic image with depth-migration imaging software responsive to the earth model having velocity model characterizations therewithin.

23. The method of claim 20 wherein step (d) further comprises:

generating the depth-migrated seismic image with depth-migration imaging software responsive to the velocity model.

24. A method for enhancing a depth-migrated seismic image comprising:

(a) propagating a set of seismic energy components through an earth model having velocity model characterizations therewithin comprising a set of lens elements to form a set of image components which are summed to form a depth-migrated seismic image;

(b) identifying a target in the seismic image which is to be enhanced;

(c) updating a trial subset of lens elements of less than all of the lens elements from the set of lens elements to update the earth model without updating all of the lens elements of the earth model;

(d) selecting a trial subset of energy components of less than all of the energy components from the energy components of step (a);

(e) propagating the trial subset of energy components through the updated earth model without propagating all of the set of energy components through the updated earth model to create updated image components; and

(f) replacing current image components with the updated image components and not replacing those image components that were not updated to create an enhanced seismic image.

25. The method of claim 24 wherein:

the energy components are beam components.

26. A method for enhancing a depth-migrated seismic image comprising:

(a) creating a depth-migrated seismic image using an earth model having velocity model characterizations therewithin comprising a set of lens elements and using seismic data,

the seismic image comprising a set of image components, the seismic image including a target which is to be enhanced;

(b) updating a trial subset of less than all of the lens elements selected from the set of lens elements in the earth model;

(c) updating those image components in the seismic image which are associated with changes in the trial subset of lens elements of the earth model which affect the seismic imaging of the target; and

(d) subtracting image components in the seismic image and adding in their place updated image components without replacing all of the image components to enhance the seismic image.

27. A method for enhancing a depth-migrated seismic image comprising:

a) propagating a set of seismic energy components through a velocity model, comprising a set of lens elements, to form a set of image components which are summed to form an original depth-migrated seismic image;

b) updating at least some of the lens elements to update the velocity model;

c) selecting a trial subset of energy components of less than all of the energy components from the set of energy components of step (a);

d) propagating the trial subset, without propagating all, of the energy components through the updated velocity model to create updated image components; and

e) subtracting image components from the original seismic image and adding in their place updated image components, without replacing all of the image components of the original seismic image, to arrive at an updated enhanced seismic image.

28. The method of claim 27 wherein:

less than all of the lens elements are updated in step b) to update the velocity model.

29. The method of claim 27 wherein:

the trial subset of lens elements is selected by visual inspection.

30. The method of claim 27 wherein:

the trial subset of energy components is selected using a directed-aperture.

31. The method of claim 27 wherein:
the trial subset of energy components is selected using a migration aperture.
32. The method of claim 27 wherein:
the updated image components of the enhanced seismic image replace corresponding image components from the original seismic image and image components for which no updated image components were created in step d) remain the same between the updated seismic image and the original seismic image.
33. The method of claim 27 wherein:
a target is selected in the current original seismic image which is to be enhanced.
34. The method of claim 33 wherein:
the step of selecting a trial subset of energy components of less than all of the energy components uses ray tracing and selects energy components which may affect imaging of the target.
35. The method of claim 34 wherein:
the ray tracing uses a two-point ray trace search.
36. The method of claim 34 wherein:
the ray tracing utilizes normal ray tracing.
37. The method of claim 34 wherein:
the step of selecting a trial subset of energy components includes selecting energy components that have ray paths that pass within a predetermined distance of the target prior to updating of the lens elements.

38. The method of claim 34 wherein:

the step of selecting a trial subset of energy components includes selecting energy components each having a ray path that passes through at least one of the updated lens elements.

39. The method of claim 34 wherein:

the step of selecting a trial subset of energy components includes selecting energy components that each have a ray path that passes within a predetermined distance of the target and passes through at least one of the updated lens elements.

40. The method of claim 34 wherein:

the trial subset of energy components is selected from the energy components which have ray paths that touch the target and pass through at least one of the updated lens elements.