The role of reverse time migration in imaging and model estimation

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This article covers recent developments in the depth-imaging technology known as reverse time migration (RTM). RTM will be compared to Kirchhoff, beam, and other wave-equation migration techniques. Special emphasis will be placed on the practical application of this technology to reduce exploration cycle time and risk. Recent trends such as TTI anisotropy and wide-azimuth applications will also be discussed.

RTM depth imaging is most applicable in geologic regimes that exhibit significant contrasts in velocity and steeply dipping features. Imaging below salt is a typical example where it is particularly appropriate. By using RTM for final imaging and model estimation, an accurate image of salt bodies and the targets beneath salt bodies can be developed. A fundamental conclusion from this article will be that using RTM throughout the imaging sequence will collapse the total cycle time of the project. In addition to getting the data faster, the total technical risk in the project will also be greatly reduced.

This subject is significant to both the geophysical and broader exploration community since the location and shape of salt bodies are critical in the hydrocarbon search. RTM is a tool that can help to greatly reduce exploration risk since it gives a more accurate image of those salt bodies. This better image, in turn, reduces the risk associated with well location. In addition to reducing the risk, the effective use of a full suite of imaging tools can increase the collapse of overall project turnaround time.

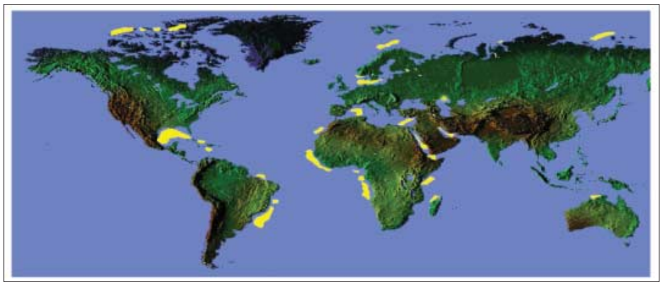

Figure 1. *Map showing salt basins around the world.*

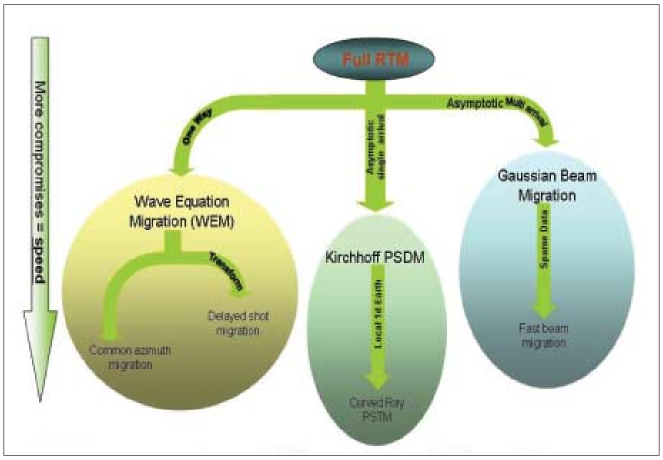

Figure 2. *Imaging tree categorizing different families of migration techniques.*

Subsalt imaging challenges

The challenges of subsalt imaging are daunting. Salt structures are formed when salt sheets intrude into higher-density sediments deposited above them. The resulting domes, walls, pillows, ridges, and fountains are complex. They can be free-floating or remain attached to the base salt layer as irregular, mushroom-shaped bodies called diapirs. The current area of interest is in deep water, where complex salt bodies provide geoscientists with significant imaging challenges. These steeply dipping traps can be extremely prolific, capable of being drained with relatively few high-rate wells—ideal for high-cost deepwater environments. The map in Figure 1 gives an indication of how common highly complex salt plays are in exploration. Note that almost all marine exploration involves some quantity of salt, as can be seen in Figure 1.

Imaging reservoirs beneath salt bodies or along their steep flanks poses two serious problems for conventional seismic imaging technologies. First, the seismic waves reflected off the steep flanks of subsurface features travel almost horizontally which is a problem for standard imaging algorithms. Second, the top of salt structure is often highly irregular (rugose) which scatters seismic waves into multiple paths. This is because seismic waves generally have a much higher velocity when traveling through low-density salt than through surrounding sediments. Unless the imaging process is able to reconstruct this scattered energy, information from any wave that passes through the top of the salt mass is effectively lost or only partially imaged. These factors, if not taken into consideration, can yield misleading information about the location and geometry of prospective formations and seldom provide sufficient information to properly locate an exploration well. Images of potential traps can emerge or disappear if a sufficiently good imaging technique is not used. In the 1980s, Kirchhoff depth migration was used to image seismic data. In the 1990s, wave-equation migration methods began to be used in combination with Kirchhoff methods to try to fully resolve structures not adequately resolved with Kirchhoff migration. Starting in 2005, reverse time migration became commercially viable in all phases of the imaging sequence.

Reverse time migration

The RTM algorithm is a simple migration technique that until recently was too compute-intensive to use in a commercial 3D or WAZ setting. It was first introduced or outlined by Dan Whitmore and others in the early 1980s. To understand the benefits of RTM relative to other migration methods, we first need to know how this migration technique works and contrast it to the other migration techniques that are in standard use.

Figure 2 shows the relationships between the different migration techniques. Broadly the four migration families are: RTM, one-way wave-equation migration (WEM), Kirchhoff migration, and beam migration. The ray-based or integral techniques propagate the source and the receiver wavefields down to each potential reflector in the subsurface using high-frequency ray-based approximations. The finite-difference-based migrations propagate the source and receiver wavefields down to each reflector using recursive techniques.

To be specific, RTM predicts the incident wavefield at each reflector using the wave equation and injecting the source signature into the model at the source position. This is standard forward modeling in which the wavefield is propagated forward in time—later time samples are predicted from earlier time samples. Now, just as we can run movies backwards on computers, we can also run the wave equation backwards in time; i.e., we can predict earlier times from later times. This is what is done to predict the reflected wavefield at each point in the subsurface. In this case, the recorded wavefield is reintroduced into the model at the receiver locations from late to early times. To predict the reflectivity at each position, the estimated incident and reflectivity wavefields are correlated at each location and for each shot and added to the output image cube. The key feature of this technique is that, once the source and receiver energy is injected into the propagation grid, there are no amplitude approximations. The wavefield is propagated as an acoustic wavefield, and there are no limitations on propagation with direction.

Standard one-way wave-equation methods use a similar technique to predict the source and receiver wavefields in the subsurface, but instead of propagating the wavefield in time, the wavefield is propagated in depth. The source wavefield is recursively propagated into the subsurface under the assumption that this wavefield always propagates downwards while the reflected wavefield is recursively propagated into the subsurface under the assumption that this wavefield always propagates upwards. If the wavefield propagation is closer to horizontal, an inferior estimate of that wavefield extrapolation will be computed. Notice also that this scheme will eliminate diving or turning energy, as this energy doesn't propagate only upward or downward before and after being reflected.

To demonstrate the potential of RTM in comparison to one-way wave-equation methods, consider the complex isotropic acoustic FD synthetic data example shown in Figure 3. Figure 3a shows the result of migrating the data with a one-way WE algorithm while Figure 3b shows the result of migrating the data with RTM. In the one-way image, the turning-ray energy that illuminates the overhanging and steep portions of the salt stem cannot be handled and often causes them to not be imaged (due to algorithmic dip limitation) or are not illuminated by the acquisition. Steep dips and the turning-wave energy, as well as energy from other two-way ray paths, are handled by RTM, producing a good image. The one-way migration examples shown in this paper were obtained using a split-step Fourier plus interpolation algorithm (SSFPI).

Kirchhoff and beam migration-based techniques propagate the source and receiver wavefields down to each potential

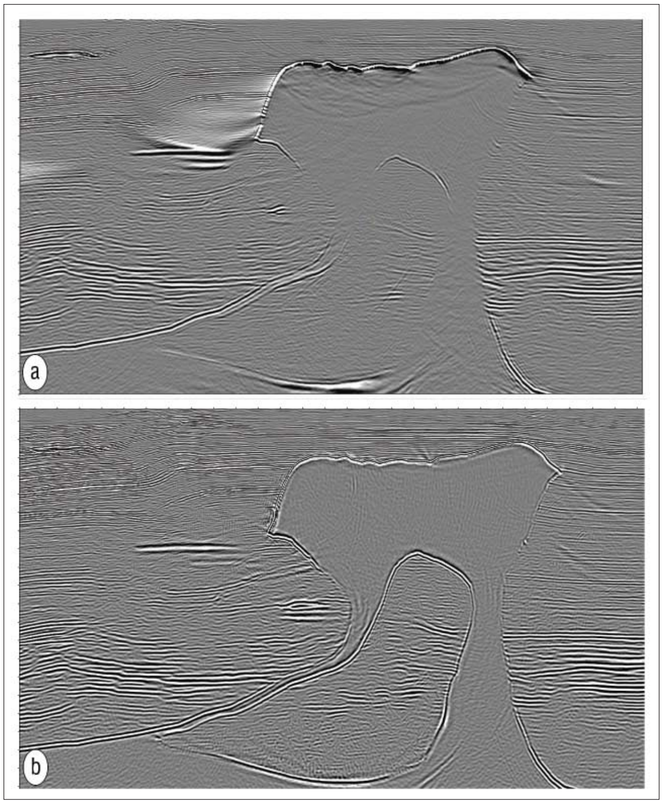

Figure 3. *(a) Synthetic data migrated with a one-way, wave-equation algorithm. (b) Synthetic data migrated with a two-way RTM algorithm.*

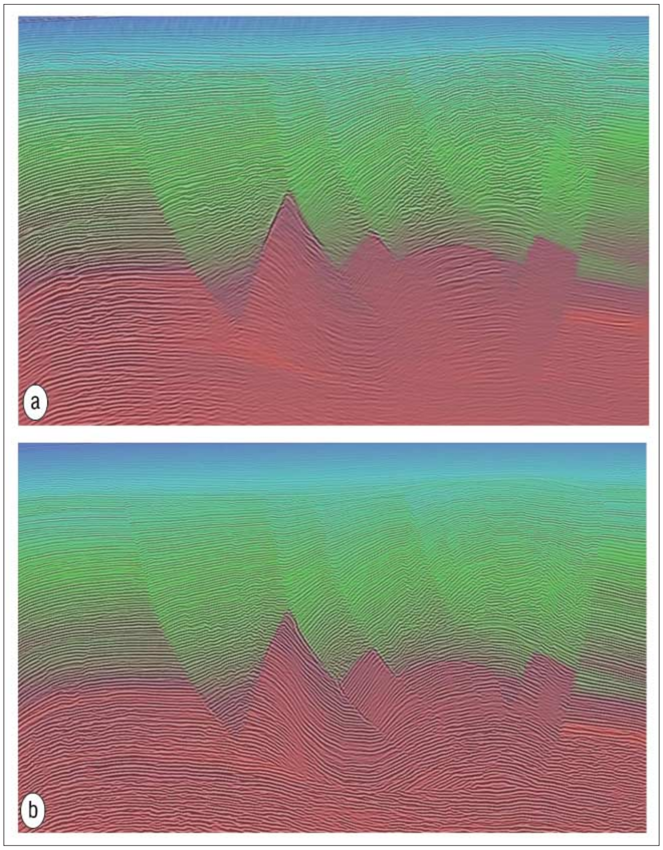

Figure 4. *(a) Beam migration of TTI synthetic model. (b) RTM of TTI synthetic model. Note the well-imaged faults and deeper structure below the complex fault blocks. (Data courtesy of BP.)*

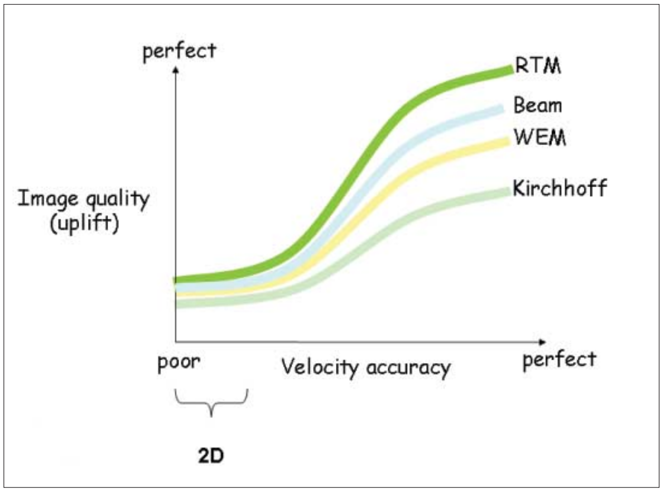

Figure 5. *Image quality versus velocity accuracy.*

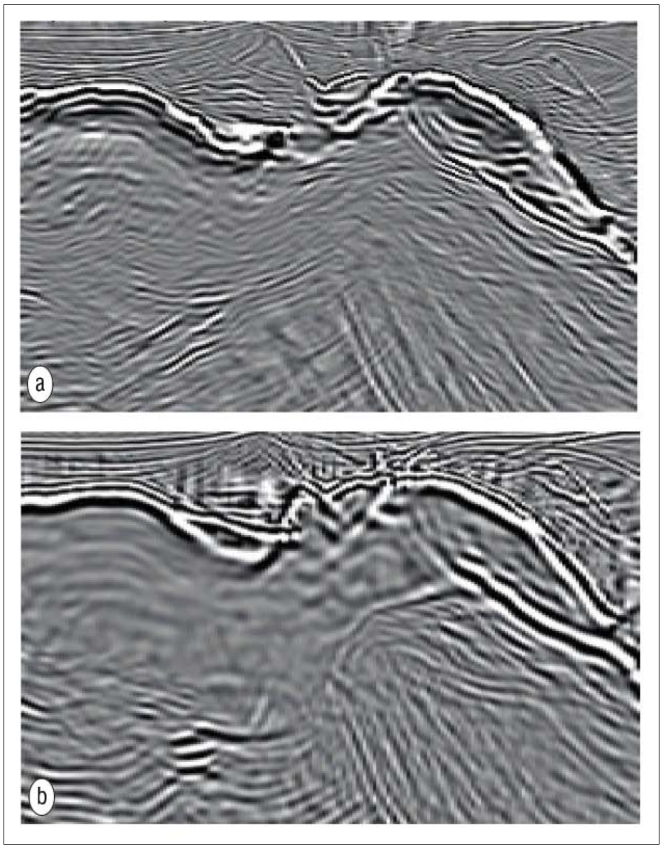

Figure 6. *WEM (a) and RTM (b) images of a salt body. The base of salt and subsalt reflections are far clearer on the RTM image than on the WEM image.*

Representative standard imaging workflow	*RTM-based imaging flow*
3D SRME multiple attenuation	3D SRME multiple attenuation
Kirchhoff-based tomography to establish sedimentary velocity field	Kirchhoff-based tomography to establish sedimentary velocity field
Kirchhoff sedimentary flood migration for top salt	RTM top salt
WEM flood for base of salt + Kirchhoff for steeply dipping areas of salt	RTM for bottom salt
Repeat two previous steps for recumbent salt interfaces	Repeat two previous for recumbent salt interfaces
WEM-based subsalt tomography or scans	RTM-based subsalt tomography
WEM and Kirchhoff final migrations	RTM final migration

Table 1. *Imaging workflow methods. This table contrasts traditional and the new RTM imaging workflows.*

reflection point using ray-based techniques. These techniques are based on high-frequency solutions to the wave equation. Typically, beam techniques support multivalued propagation of the source and receiver wave fields whereas Kirchhoff algorithms do not. These techniques are capable of imaging steep structure, which is the weakness of WEM techniques, but they are not able to image well below or near complex velocity structures, such as adjacent to or below salt bodies or faulted structures. Figure 4a and Figure 4b show the weakness of beam migration on model data provided by BP. The model is a TTI model that is designed to represent the offshore geology that might be found off the northern portions of South America. The anisotropic axis of symmetry in the model was perpendicular to the reflections in the model. It is clear that the RTM image in Figure 4b is superior to the beam migration image in Figure 4a. This is evident in the areas both above and in the faults.

Barriers to RTM adoption

Given the benefits of RTM migration relative to the other migration techniques and given that the RTM algorithm has been known for many years, why hasn't it been used very much?

One reason is the relative computational cost of the algorithm. Until recently compute demands of the algorithm were simply too great to make its use widespread. With the advent of cluster computing this barrier was eliminated, and this in turn lead to the development of new more efficient wavefield propagation techniques. Today large volumes of data can be efficiently processed with RTM without bandwidth limitations.

Another reason why the seismic industry has been cautious about RTM is the perception that it is more sensitive to model accuracy than the other migration techniques. Simply stated, there is a perception that unless we know the model to a high level of accuracy, which is greater than we can achieve with current technology, RTM will either produce inferior images or we won't see the benefit of applying it. Our experience, based on the large volume of RTM migrations that we have run, has shown that this perception is ill-founded. Figure

5 captures our experience to date with this technique. What we see is that, in an imaging project where we don't know the model very well, RTM does not yield significantly better images than other methods; but even with that poor model, RTM will image steep dips. However, as our knowledge of the model increases, the RTM images become significantly better than the images produced with the other techniques. Furthermore, based on our experience, we have never seen a case in which the RTM images are inferior to the images produced using the other algorithms independent of the accuracy with which the model is known.

What we have found is that the key to capitalizing on the benefits of RTM is to build better models by using RTM in the model-building phase of a project. This has lead to the generation of better models in a reduced amount of time. In the next section we will analyze the potential of RTM to collapse the imaging cycle.

Collapsing the imaging cycle

To see how RTM can be used to reduce or collapse the imaging cycle, we first need to look at the current imaging cycle. In comparing migration methods, it is not sufficient just to compare the migration outputs alone, the entire processing flow must be analyzed. Table 1 shows a representative of traditional processing and imaging workflow for a typical depth-imaging project in the Gulf of Mexico.

The typical flow consists of at least two iterations to define the salt—one for the top and one for the base. The base of salt iteration is typically done using a combination of Kirchhoff and WEM to overcome the limitations of each algorithm. For more complex or recumbent salt bodies, additional imaging iterations are required to define the salt that uses a combination of Kirchhoff and WEM. The last step is to generate WEM and Kirchhoff images with the final velocity model. A key point is that the traditional flow uses a combination of Kirchhoff and WEM due to their respective deficiencies to build the salt model. Generating, understanding, and forming a coherent model from two different images at each iteration is a lengthy process. Oil companies have limited staff to do this work so it puts significant strain on an exploration team, and model building slows the prospect generation process. To summarize, each migration takes a finite amount of time to run, and it takes time to understand each image and build a coherent interpretation from two separate sets of images. Additional time is also spent readying the data for interpretation.

In contrast, the current RTM-based model-building flow replaces two different migrations with a single imaging algorithm that is able to simultaneously resolve both complexity and steeply dipping interfaces. Not only is one migration run at each step, but no time is required to understand how to combine the interpretation of the two separate images. In addition, the quality of the RTM image will be superior to either the Kirchhoff or WEM images, and this will reduce the project cycle time.

Figure 6 clearly shows how RTM gives an improved image of the base of salt on a real data example. WEM fails to image the steep events that define the top of salt, as well as the base of salt. While these events are not perfectly clear on the WEM migration, these interfaces are clearly visible on the RTM image. The implication is that it would take an interpreter longer to understand and define the salt interfaces on the WEM image than on the RTM image.

To help see the impact that RTM has on cycle time reduction in a real world context, lets consider a small 1200 km^2 (approximately 50 OCS blocks) exploration project in the Gulf of Mexico.

First, consider the base of salt interpretation phase for the traditional flow. Let's assume that the WEM and Kirchhoff migrations both take one and a half weeks to run. For this analysis it is assumed that these runs are done sequentially, one after the other. The total time for migrations is around three weeks. A typical base of salt based on WEM and Kirchhoff images will take about four weeks. Thus the total amount of time to image the base of salt is about seven weeks using the traditional flow. In contrast, the time to image the base of salt with RTM takes about the same amount of time as either a WEM or a Kirchhoff migration, but the time taken to interpret the image is typically only about two thirds of the time, or, in this case, three weeks. Thus, the total time for the RTM-based flow is four and a half weeks versus seven weeks for the traditional Kirchhoff and WEM flows. We can speed up the traditional flow by running the WEM and the Kirchhoff migrations parallel, but the limiting factor in this process is the time it takes to interpret data. The key to reducing project cycle time is to reduce the time it takes to interpret and construct models.

At this stage it is worth adding an additional comment regarding the relative computational requirement of the imaging step for towed-streamer, wide-azimuth geometries. The computer power needed for Kirchhoff migration only depends on the number of traces falling within the migration aperture. Standard exploration towed-streamer wide-azimuth surveys have a high fold, even though they have a relatively low shot count. This makes it very cost-effective to image this type of data using shot-based migration algorithms, such as shot-domain RTM. As the objective of a survey moves from an exploration to a development phase, the fold count increases significantly while the shot effort still remains relatively low. For example, in rich azimuth acquisition techniques or node acquisition, the shot-domain migration algorithms become significantly less expensive than Kirchhoff migration techniques. This makes RTM even more attractive than any trace-by-trace technique, and there is no technical downside.

Reducing the time it takes to interpret the salt interfaces doesn't just depend on the quality of the migrated images. Most modern interpretation systems still assume that the top and base salt interfaces are relatively flat or nearly horizontal. In practice, salt interfaces are often steeply dipping, vertical, or recumbent. Interpreting such salt interfaces is very difficult with modern interpretation systems. The current approach is to break the interfaces into a series of simple grids that are combined in the model construction process. Further, even though the steep salt flanks are clearly visible on the RTM images, autopicking software designed to pick 1D wavelets simply cannot interpret these interfaces that are visible on these more accurate images. In order to further reduce cycle time, better interpretation and model construction systems need to be developed.

RTM trends

The two key trends examined in this section are wide-azimuth imaging and TTI anisotropy. Until recently, most marine data were acquired with narrow-azimuth acquisition geometries. The recent trend in exploration is to wide-azimuth collection geometries for improved illumination and better multiple attenuation. Furthermore, it has become more commonplace to combine multiple wide-azimuth or narrow-azimuth surveys in the same imaging project. Typically, these surveys will be either collected at different azimuths either by design or chance. In order to optimally image these data, recent case studies suggest that it may be necessary to include velocity anisotropy in the imaging step. A natural model for anisotropy is to assume that the symmetry axis is perpendicular to the bedding planes or dips of reflectors. This type of anisotropy is called TTI or tilted transverse anisotropy. It is a struggle for WEM techniques to deal with this type of anisotropy. For example, perturbation-based isotropic migration schemes such as PSPI or extended PSPI techniques typically extrapolate data using a number of reference velocities. When the medium is anisotropic but the symmetry axis is vertical, the number of reference media must increase because more parameters are needed to define the medium. In addition, the number of reference extrapolations may increase from 10 to over 40 or 50. The situation becomes even worse as the subsurface moves from a VTI to a TTI model. Techniques that directly use the wave equation to extrapolate wavefield, such as RTM that don't use a series of reference media, do not suffer from this explosion of reference media steps and become very cost-effective. The effectiveness of RTM to image a strongly TTI anisotropic image is shown in Figure 4a. Many of our recent RTM wide-azimuth projects are being processed with TTI anisotropic models.

Conclusions

Complex bodies such as salt domes are illuminated by many wave paths and cannot be imaged effectively using standard conventional one-way migration or ray-based migration algorithms. To overcome the limitations of these techniques, combinations of ray and one-way WEM techniques are often used. RTM migration in contrast, which uses a two-way WEM algorithm, can accurately image all the raypaths and can deliver a single image of all the raypaths.

This article discussed the adoption barriers for RTM and showed that due to increased compute power and algorithmic improvements, computational barriers no longer exist. Furthermore, the specious arguments regarding RTM's sensitivity to model errors is unfounded, and, in fact, it was natural to use RTM as an integral component of the model building work flow to develop more accurate models.

In order to produce better exploration results, such as more prospect leads and more accurate drilling decisions, we need to build reliable images in a timely fashion. To reach these results, we need better models faster. We have shown that because of RTM's superior dip-handling characteristics, the ideal way to build these models is by using RTM. Using RTM throughout the imaging cycle will lead to reduced exploration risks and a potential shortening of the exploration cycle.

Lastly, we have shown that RTM is more suitable for imaging anisotropic structures than either ray or one-way migration schemes. This will become increasingly more important in the context of wide-azimuth acquisition.

Suggested reading. "Application of reverse time migration to complex imaging problems" by Farmer et al. (*First Break*, 2006). "Reverse time migration" by Baysal et al. (Geophysics, 1983). *Classics of Elastic Wave Theory* (SEG Geophysics Reprint Series, 2007). "Iterative depth migration by backward time propagation" by Whitmore (SEG 1983 *Expanded Abstracts*). "Choice of scheme and parameters for optimal finite-difference migration in 2D" by Diet and Lailly (SEG 1984 *Expanded Abstracts*). TLE

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